PROCEEDINGS OF THE F. D. HOLLAND, JR., GEOLOGICAL SYMPOSIUM

Edited by

J. Mark Erickson and John W. Hoganson

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EDITORS' PREFACE

When we learned that Bud Holland was planning to retire from the Department of Geology and Geological Engineering at the University of North Dakota there was no doubt in our minds that some honorary celebration was in order. We knew it would be much in keeping with Bud's pedagogy if we were to produce a festschrift in his honor, yet that seemed to accomplish only a portion of our wishes for such works can be compiled these days without convening the celebrants - without the "fest" as it were. Our hope was to gather friends together to celebrate Bud with the science he has fostered in the place which his vision helped to create--"within the matrix of geological education at UND"-- is how we phrased it at the time. A geological symposium at Leonard Hall seemed in order.

From the instant we proposed it to Frank Karner, Department Chairman, we had the enthusiastic support of colleagues and staff at the University and the North Dakota Geological Survey. Preparations for the symposium and the banquet which followed were aided by many individuals and organizations whom we wish to acknowledge here. Frank Karner, John Reid, Gloria Pederson who gave administrative and clerical support and who made contacts with various university officials and press; Dexter Perkins, heading the "FOGS" Lecture Committee, and Sigma Xi at UND both of which sponsored the keynote speaker; Alan Cvancara, Tim Kroeger and the members of Beta Zeta Chapter of Sigma Gamma Epsilon who shared their Spring Banquet with us (attended by 150 celebrants); John Bluemle and the North Dakota Geological Survey for supporting publication of the symposium proceedings; and Dr. Frank Karner, Dean Alan Fletcher, UND President Thomas Clifford and the North Dakota Board of Higher Education for honoring Bud with their special recognitions.

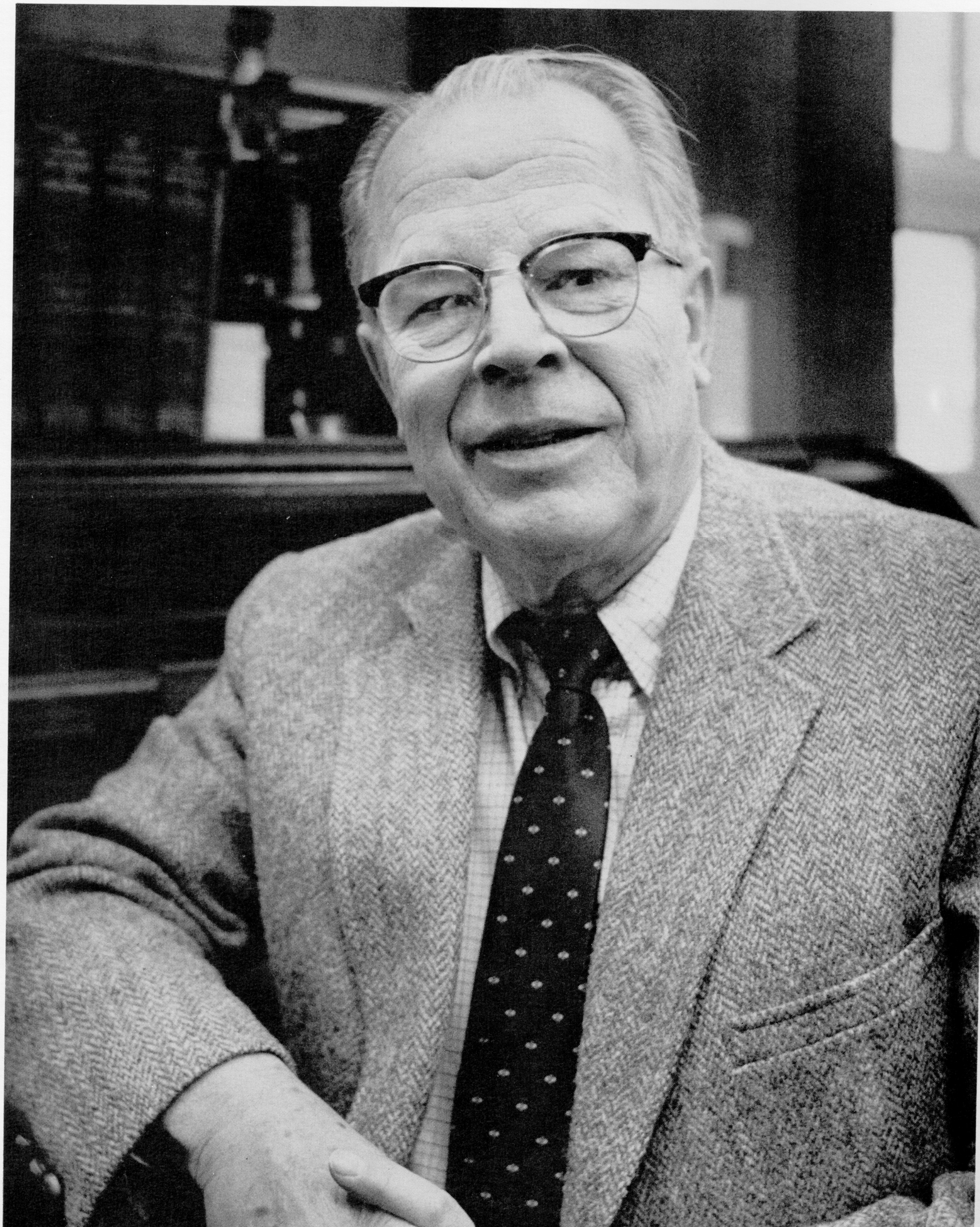
The F. D. Holland, Jr., Geological Symposium convened April 14, 1989 with 16 speakers and an audience that pretty well filled the 200-seat lecture bowl at Leonard Hall. The special recognition ceremony that culminated the meeting found listeners standing three rows deep in the rear of the hall! Abstracts of papers presented at the symposium are reprinted along with the program in this volume as a record of participants.

It is obvious that substantial time has passed since the symposium was convened. We acknowledge the tardiness of this publication and apologize to authors whose works have been delayed to their detriment, but we found many unexpected barriers to be overcome on this mission. It is our belief that this volume honoring Bud is better for these efforts and for the patience shown by its authors. We hope you agree.

All but one of the papers presented at the Holland Symposium are included. The topics span a wide range of the discipline, perhaps reflecting Bud's diverse interests as much as those of his colleagues and students. Two papers included here were not presented at the symposium, and we are pleased to insert them for completeness. Both of us have been involved in the editing process while one of us (JWH) has had the added responsibility for supervising the computerization of manuscripts and arrangements for publication. For errors we accept equal blame; if there should be any praise after this lengthy hiatus, we will gladly share that as well. The real praise and thanks, however, belong to Bud Holland for giving us the inspiration and desire to begin this project in the first place!

J. Mark Erickson
John W. Hoganson
Co-Conveners and
Co-Editors

April 30, 1992



Professor Emeritus F. D. "Bud" Holland, Jr.--1989

A DEDICATION TO F. D. HOLLAND, JR., PRAIRIE PALEONTOLOGIST, FROM FORMER STUDENTS AND COLLEAGUES

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Papers comprising this dedicatory volume have been created and submitted by former students and colleagues of Dr. Frank D. (Bud) Holland, Jr. at the time of his retirement after 35 years of selfless, dedicated, inspiring teaching of paleontology and geology at the university of our northern plains, the University of North Dakota, Grand Forks. It has been the intent of the authors, and the celebrants who attended the F.D. Holland, Jr. Geological Symposium on April 14, 1989, that their efforts should honor Bud for his contributions to students and to our science. He has opened many eyes and minds to worlds both past and present.

We feel that it is important to tell something of the man who is the reason for our gathering. To that end I have been encouraged to present the remarks that follow, however incomplete they may be.

In the mid 1880's his paternal grandparents, Laura Huffman and Oscar Brown Holland, had homesteaded adjacent quarter sections one mile northwest of Brampton in Sargent County, North Dakota. O. B. Holland was a County Commissioner there in 1886. Bud's father was born at the homestead in 1890, and lived there until 1903, when the family relocated to Pleasanton, in eastern Kansas. J. R. Bell, Holland's maternal grandfather, had been a land surveyor there following the Civil War. Bud was born on March 6, 1924 to Francys Eola Bell Holland and Frank Delno Holland in Leavenworth, Kansas. It is not surprising that a naturalist's love of the plains and prairies developed in him. Nor is it surprising that he found an interest in invertebrate paleontology given the chain of developments that surrounded his arrival when he stepped off the train in Lawrence to bound to enroll at the University of Kansas.

This was 1942, and he was met at the station by an uncle, Dr. E. Lee Treece, a bacteriologist on the University of Kansas faculty with whom he was staying until he got settled. That evening as they sat in his living room Treece said, "Well, Bud, what are you interested in studying?" Bud replied that he thought he'd like to be an archeologist!

"That's interesting," Treece responded, "because we have no archeology department at the university! But, I think tomorrow you should go and speak with my friend Dr. Laudon in the geology department." Bud did just that the next day.

After some searching he found Dr. Lowell R. Laudon seated behind his desk in a long narrow office piled high with books and specimens. He introduced himself, was invited in, and told to, "park his butt in that bookshelf" opposite Laudon's desk, and, by doing so and putting his feet on the front of the desk, Bud was able to converse with Laudon at some ease telling him of his interest in archeology. Soon this elicited the following response.

"Think of the Empire State Building with a nickel and a cigarette paper on top. The nickel and paper are the time humans have been on earth, and the cigarette paper is the length of recorded history. Now, why would you want to study a nickel and a cigarette paper if you could study the Empire State Building?"

Apparently this made the appropriate impression, for Bud devoted himself to the study of the "Empire State Building" from that moment on!

At that instant a taller-than-average freshman walked into the office and introduced himself to Laudon as James M. Parks and declared his intent to study geology. Laudon offered another bookcase to Parks, and he proceeded to advise them both. That was the start of two influential friendships and a career for Bud.

However, the war was on and Bud's education was interrupted when he went to Oberlin for training in the Navy V-12 program. At Oberlin, he was taught by Erwin C. Stumm and mastered many elements of cnidarian paleontology. As a lieutenant (j. g.) in the naval reserve he visited both the Atlantic and Pacific theaters between 1942 and 1946.

On his return Bud married Margine C. McVey whom students and colleagues alike know as "Mardi," the graceous hostess of the Holland household, whose wisdom sustained many of us amidst the post-review doldrums of our first thesis drafts! Mardi's patience no doubt fluorished while Bud completed the B.S. as a

"Jayhawker" at the University of Kansas (1948).

Others who influenced Bud at K. U. included John C. Frye, Arthur L. Bowsher, Cecil G. Lalicker and R. C. Moore. Graduate work in paleontology and stratigraphy led first to the University of Missouri, Columbia (A.M., 1950), where Laudon was currently located, and then to the University of Cincinnati (Ph.D., 1958), where he became a doctoral student of Kenneth E. Caster.

It was at this time that Bud established himself as a scholar of Devono-Mississippian stratigraphy and brachiopod paleontology, interests that he has passed on to several generations of his graduate students at UND. His masters thesis describing the Leatham Formation, a newly recognized shale unit lying unconformably on the Devonian Jefferson Dolostone and beneath a lower basal black shale of the Madison Limestone at Leatham Hollow, Utah, piqued Bud's interest in the Devono-Mississippian transition. Doctoral study with Caster, to which I shall allude again below, saw him working in rocks of similar age in Pennsylvania and New York where he focused on the stratigraphy and brachiopod paleontology of the Oswayo and Knapp Formations of the Penn-York Embayment.

Work on Bud's dissertation was interrupted by a call from Wilson M. Laird, another of Caster's former students, who was in need of a paleontologist for UND where Laird was department chairman. Caster thought that, "Holland would be OK," and Laird hired him to return to North Dakota thus completing the family's three-generation circle of the midwest. Bud started teaching as assistant professor in 1954, saw promotion to associate professor in 1959, and advanced to full professor in 1965. He taught without sabbatical and with only one interruption until retirement in 1989! Remarkably, during that time he served under only two presidents, George C. Starcher and Thomas J. Clifford.

Initiating paleontological research at the University of North Dakota, Holland's publications on the topic of Devono-Mississippian stratigraphy and paleontology began with papers in The Compass (Holland, 1951), and the AAPG Bulletin (Holland, 1952) and have continued to his most recent contribution with Hayes, Thrasher and Huber in 1987. A bibliography of Holland's works to date is appended hereto, and descriptions of his several types of contribution to geological literature have been included elsewhere in this volume (Scott and Lerud, herein). It is of note that most of the published chronostratigraphic and biostratigraphic knowledge of the Devono- Mississippian boundary in the Williston Basin has resulted from work by Bud and his students.

The other dimensions of Bud's character and background have been equally important to his students, the university and to geologic education at large. He and Mardi have raised two sons, Frank D., III, and Erik Lee Holland. As Bud had been a Star Scout, lacking only one badge for Eagle and Life Scout, Del and Erik, too, aspired to and reached Eagle status. The formative years for his family were formative for him, also, as he was building a philosophy of education, service, and institutional loyalty. It is that philosophy, cast in the light of today's practices, that makes Bud Holland's career unusual, even remarkable. One measure of a man may be taken by knowing the qualities and values that he holds dear. His Kansas upbringing, his family, his respect for knowledge and the history of knowledge, his membership in the Society of Friends, his scouting, and his interest in students and colleagues provided a focus to Bud's career that led him to think deeply about his mission as geologist-educator-humanist. Those of us who know him well can recognize this blend of influences in his accomplishments.

Exemplary of both his belief in professionalism and his interest in nurturing the breadth of students was Bud's service for more than 30 years as faculty advisor to Beta Zeta Chapter of Sigma Gamma Epsilon. He was always encouraging of its activities at UND, editing two chapter issues of The Compass, 1964 and 1970 (saying "Never again!" each time), and seeing many students publish their first papers in that journal (see Scott and Lerud herein). Beta Zeta members named the F.D. Holland, Jr. Service Award in his honor because of his example. His many contributions were summarized in the dedication of the Beta Zeta issue of The Compass (Anonymous, 1970).

Because Beta Zeta was an active chapter, Holland's influence helped to further improve the society. Beta Zeta delegates drafted and moved through convention (at Cincinnati) the by-law language changes making women's participation in Sigma Gamma Epsilon explicit and Beta Zeta Chapter quickly initiated women under that amendment. Beta Zeta delegates also proposed the membership categories of Alumni Member and Life Member. The first Life Member was Frank. D. Holland, Bud's father, who had been a member of the first initiation class of Alpha Chapter at the University of Kansas.

Bud's belief in the scholarly goals that Sigma Gamma Epsilon promoted and his great interest in the students it represented led to his nomination to the National Council. After serving as Regional Vice President, he was elected National President (1970-75) by student delegates in convention. In that office Holland influenced the educations and careers of a great many students in this country. In recognition for his steadfast support Bud was elected to Honorary Life Membership in Sigma Gamma Epsilon in 1978.

As a member of the Society of Friends, Bud shared understanding and wisdom with students who were asking their own ethical and moral questions in the late 1960's. As already mentioned, in the late 60's and early 70's Bud's philosophy of education influenced, and was influenced by, the humanist movement in geological education, perhaps because that philosophy voiced many tenets about the inter-personal interactions of mentors and students that Bud had grown to practice himself. Thorough and careful advisement of his students -- undergraduate and graduate alike -- was a hallmark of his teaching career. He listened to students and reacted to what he heard, much as he is doing in Figure 1.

When an Associate Director of the NSF-sponsored Academic Year Institutes at UND between 1966 and 1970 Holland taught geology to many of the region's elementary and high school teachers, and he learned how they were teaching. He expressed his ideas in print (Holland and Erickson, 1969) and became involved in a national undertaking to improve Earth Science education throughout the country. This led to his only hiatus from active teaching which came between 1970 and 1972 while he served as Director of the Council on Education in the Geological Sciences and as Director of Education and Manpower for the American Geological Institute. In that position he visited geology departments throughout the country, encouraging a greater role for students in the processes of their education while also seeking ways to expand minority participation in the science. He returned to teaching at UND in Fall of 1972.

By his example Bud's students grew to recognize the premium he placed upon service to his university and to his discipline. He was elected to 16 international, national, and regional scholarly societies including membership in the Geological Society of France, Fellowship in the Geological Society of America and the Honorary Life Membership in Sigma Gamma Epsilon to name a few. Significantly, he was elected President of four of these including National Sigma Gamma Epsilon, UND Chapter of Sigma Xi, North Dakota Academy of Science, and the North Dakota Natural Science Society. On his return from Washington, Bud resumed advisorship of Beta Zeta and helped plan the establishment of a substantial endowment which continues to work in support of student research and field study. His record of service to his institution, where he had been elected to the faculty senate, was similarly strong. Bud took on many committee chairmanships and held numerous committee memberships on behalf of UND.

Two such committee assignments have allowed him to make his unique mark on the University of North Dakota. For the benefit of all its students, Bud championed the development of both Chester Fritz Library and the Geology Library at UND as a member

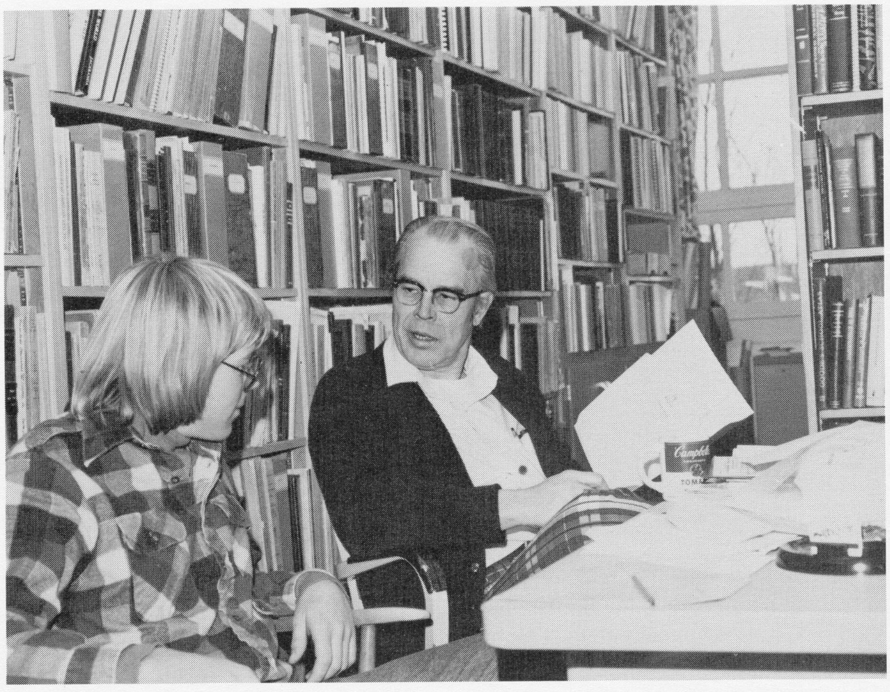

Figure 1-Bud Holland discusses course selection and academic plans with Frank Forsgren in 1985 at Bud's office in Leonard Hall.

of the Library Committee from 1976-1983. As I said when we honored him at the Holland Symposium, "Bud loves books and the things found in books". His careful nurturing of the geological library over 35 years helped make it one of the truly great collections of the upper mid-west, and it includes many items donated by Bud from his personal library. In recognition and gratitude for that service the Geology Library at UND was dedicated as the F.D. Holland, Jr. Geological Library by Dean Alan Fletcher on behalf of the Board of Higher Education. Figure 2 illustrates the dedication plaque placed in the newly renovated library on the third floor of Leonard Hall.

This dedication is doubly fitting because of Holland's roll in the planning of Leonard Hall, itself. At the request of Wilson Laird, then State Geologist and Department Chairman, Holland chaired the Leonard Hall Building Committee between 1960 and 1965, when the completed structure was dedicated as one of the most advanced geology buildings in the mid-continent. The unique expressiveness of the structure made it a joy for faculty and students alike. The building truly reflects Holland's creativity and feeling for the discipline as it echoes "geology" at every turn. Ground breaking for the edifice is pictured in Figure 3. When completed under Bud's careful supervision, the result was an "holistic" structure, one which has "an education in its walls" (Holland, 1966).

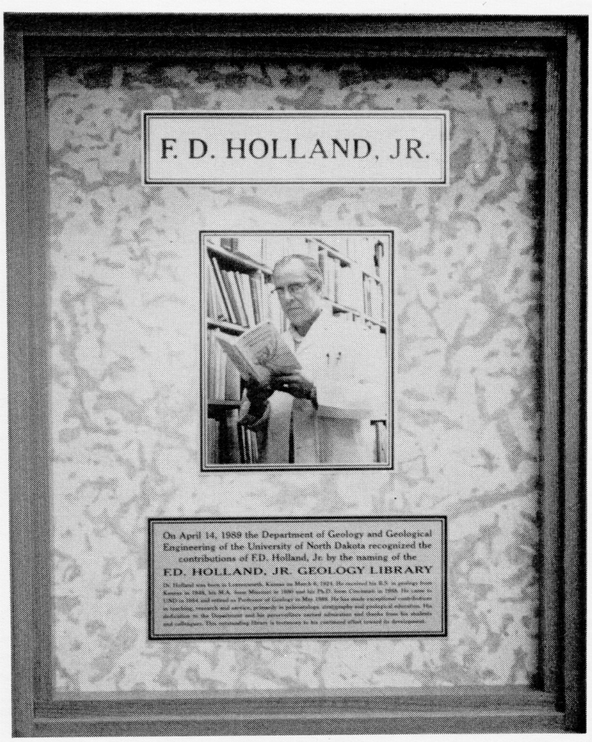

Figure 2-The labor of a career dedicated to developing and maintaining an excellent library system, including a geological library, at the University of North Dakota was recognized by UND President Tom Clifford and Dean Alan Fletcher during the F. D. Holland, Jr. Geological Symposium by unveiling this plaque formally naming the geological library on the third floor of Leonard Hall in Holland's honor.

Together these efforts and achievements deservedly earn this man recognition of his colleagues and peers at UND. However, while important to him, I think Bud would count two other aspects of his life yet more important. Firstly, he would credit his wife Mardi for the loving support she has selflessly contributed and his sons Erik and Del for the inspiration they have given. Secondly, Bud would credit his students for their roles in challenging his academic practices and for turning his scholarly activities in directions he might not otherwise have chosen. He saw the Ph.D. program in geology begin at UND, and he chaired 24 masters and 9 doctoral committees during his career while serving on numerous committees chaired by others. The diversity of his students' work is reflected in this volume. It is also indicative of the breadth of Holland's paleontological interests and abilities which are not bounded, ranging from microfossils, through the invertebrate phyla to the collection, preparation and exhibition of the UND *Triceratops* skull in Leonard Hall. By research with his students, he has documented the occurrences of numerous fossil taxa newly known from North Dakota and has described two genera and four species new to science. Furthermore, four species have been named in his honor by his doctoral graduates.

Bud Holland is a scholar of stratigraphy as well as paleontology; he is able to command and unite the two in a fashion that is no longer common among today's students. He likes the rocks as much as he likes their fossilized contents and his works have demonstrated that predilection from the time of his description of the Leatham Formation. In the context of the present writing, more than the geology presented in that particular paper is of interest. The footnotes(Holland, 1952, p.1697 & 1699) reflect many of Bud's personal qualities, as well as expressing relationships to people who had influenced his persona up to that time. In particular there are juxtaposed the names of Lowell Laudon (geologist/mentor), A. K. Unklesbay (geologist/mentor), Frank D. Holland (father), James M. Parks (fellow student), and Margine M. Holland (spouse). And in the second footnote (p. 1699), added in proof, is an insight to the relationship that he was then developing at Cincinnati both with K. E. Caster and with his intended dissertation study of the brachiopods of the Penn-York embayment (Holland,1959). Caster imparted to his many students more than mere

Figure 3-A momentous day for UND, for the Geology Department and for the North Dakota Geological Survey was the ground-breaking ceremony for Leonard hall pictured here on September 19, 1962. From left to right in the photo are Myron Denbrook, architect, F. D. Holland, Jr., chairman of faculty building committee, Sulho Norri, superintendent with Lenci and Englund, contractors, and UND President George C. Starcher, all of whom are watching department chairman and state geologist Wilson M. Laird doing the spade work. The magnificant structure that resulted gave birth to a new era of science education and achievement for North Dakotans in many spheres of scientific and economic activity.

knowledge, as do many mentors, but Caster has been truly unique to his students in ways expressed in Holland's recent paper (1989 [1990]), a work that reflects as much about its author as it does about his subject. I encourage its reading by those interested in tracing the thread of this academic geneology, but I will not belabor the point longer here.

Finally, in a lighter vein, I would be remiss if I did not point out a singular honor conferred upon Bud Holland by colleagues of the Geology Department and the North Dakota Geological Survey. For a most memorable goof Bud was bestowed the Glotkin award, the most uncoveted accolade to be bestowed upon many a UND geologist. In Bud's case he was distinguished for emptying the chamber of his 45 automatic through the driver's door of his trusty, but oddly-colored, Plymouth. Fortunately, the window was rolled up at the time so that only a bit of bondo and pinkish-orange paint were needed to cover the indiscretion. The car, however, never truly forgave him, and, soon after, it began to burn oil mercilessly! We know that Bud regarded the Glotkin as a learning experience for he hung the citation in his office nearby his doctoral diploma from the University of Cincinnati. Perhaps he considers it as another advanced degree; we all thought it was - and well-earned at that!

By convening the F. D. Holland, Jr. Geological Symposium and by publishing its procedings, the participants wish to acknowledge the influence of this teacher/colleague on their lives, as well. Equally at home in the lab, library, field (Figure 4) or office various of us prefer to remember his mentorship in one or another of those settings. Always a challenge, frequently fun, our advice to Bud during his retirement as Professor Emeritus of Geology would echo through the halls of Leonard, "Go! Go! Go!" Thanks for that encouragment, Doc.

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Figure 4-Pictured here with Holland are Jeremy Reiskind, John Hoganson, Nancy Perrin, three of FDH's doctoral students, and Charles Kerans, a MS student, as they were participating in Bud's advanced Paleozoic faunas two-week-long field trip through seven upper midwestern states in May, 1978.

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PROGRAM AND ABSTRACTS OF THE F. D. HOLLAND, JR., GEOLOGICAL SYMPOSIUM

PROGRAM

LEONARD HALL
UNIVERSITY OF NORTH DAKOTA
GRAND FORKS, NORTH DAKOTA

Friday, April 14, 1989

REGISTRATION - 8:00 a.m. - Leonard Hall

9:00 - 10:45 a.m. **FIRST SESSION**

INTRODUCTION - 9:00 a.m. -- J. Mark Erickson, St. Lawrence University, Canton, N. Y.

- Frank R. Karner, Chairman, Geology and Geological Engineering, UND

- Thomas J. Clifford, President, UND

9:30 a.m. -- Volcanic Tuffs in North Dakota. -- **N. F. Forsman.**

9:45 a.m. -- Zoned Crystals. -- **G. L. Bell.**

10:00 a.m. -- Petroleum Development in North Dakota. -- **C. G. Carlson.**

10:15 a.m. -- Stratigraphic Controls on Gold Mineralization, Carlin Trend, Nevada. -- **O. D. Christensen.**

10:30 a.m. -- Characterization of Water Percolation in Tuffs in the Unsaturated Zone, Yucca Mountain, Nye Co., Nevada -- **J. Kume*** and **J. P. Rousseau.**

BREAK - 10:50 - 11:50 a.m. - Lunch

KEYNOTE ADDRESS - 12 - 1:00 p.m. - **John R. Horner -- "Transgression, Regression, and Evolution of Dinosaurs"**

1:15 - 4:00 p.m. **SECOND SESSION**

1:15 p.m. -- Ordovician Corals of the Red River-Stony Mountain Province. -- **F. P. Caramanica.**

1:30 p.m. -- Algae in the Winnipegosis Fm. (Middle Devonian), Williston Basin, North Dakota. -- **N. Perrin.**

1:45 p.m. -- The Paleoecology of ***Echinocaris randalli*** Beecher from the Vicinity of Drake's Well, Titusville, Pa. -- **R. M. Feldmann*, J. T. Hannibal, D. J. Mullett, B. A. Schwimmer, D. Tshudy, A. B. Tucker,** and **R. W. Weider.**

2:00 p.m. -- Petroleum Source Rocks and Stratigraphy of the Bakken Formation in North Dakota. -- **R. L. Webster.**

2:15 p.m. -- ***Tylericaris hollandi*** n. gen., n. sp. (Malacostraca: Tealliocarididae) from the Tyler Fm. (Pennsylvanian) of North Dakota. -- **J. C. Grenda.**

2:30 p.m. -- Biostratigraphy and Taphonomy of the Calcareous Nannoplankton of the Niobrara Fm., North-eastern North Dakota. -- **J. Reiskind.**

2:45 p.m. COFFEE BREAK

3:00 p.m. -- Paleoenvironments and Stratigraphy of the Fox Hills Fm. (Maastrichtian: Late Cretaceous) of the Missouri Valley - Toward a More Holistic View. -- **J. M. Erickson.**

3:15 p.m. -- Vertebrate Fossil Record, Age and Depositional Environments of the Brule Fm. (Oligocene) in North Dakota. -- **J. W. Hoganson*** and **G. E. Lammers.**

3:30 p.m. -- A Late Quaternary Insect Fauna from the Missouri Coteau, North Dakota. -- **A. Ashworth*** and **D. Schwert.**

3:45 p.m. -- The Impact of F. D. Holland, Jr. on Geological Literature. -- **M. W. Scott** and **J. Lerud*.**

SPECIAL RECOGNITION CEREMONY - 4:00 - 5:00 p.m.

ADJOURN - 5:00 p.m.

SGE/FDH SYMPOSIUM BANQUET -- WESTWARD HO - Social Hour 5:30 - 6:30 - Dinner 6:30.

* -- INDICATES SPEAKER

ABSTRACTS

VOLCANIC TUFFS IN NORTH DAKOTA

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The list of known occurrences of volcanic tuff in North Dakota has been greatly expanded during the 1980's. Many of these tuffs seem remarkably well preserved, in spite of the claim by many geologists that vitric tuffs must alter relatively rapidly to more stable, crystalline forms and so cannot be geologically old. Distinct tuff layers occur in the Fox Hills Formation, the Hell Creek Formation, the Sentinel Butte Formation, the Brule Formation, and in Killdeer Mountains strata. The quality of preservation of these tuffs is evidence of the inherent stability of natural glasses, and is evidence that volcanic ash does not alter as a function of time alone. Volcanic tuffs are of particularly great value to science.

Volcanic tuffs are useful indicators of depositional environments and processes: Their presence suggests a rapidly aggrading environment with most ash eventually being rinsed into low-lying areas, and sedimentary structures in tuff provide additional environmental clues. Samples from tuff units may provide absolute age information through radiometric or fission-track dating methods. Absolute age information of itself is extremely useful to geologists and it also improves the utility of paleontologic, paleomagnetic and other information. Volcanic tuffs serve as isochronographic units that facilitate correlation of strata. Well preserved tuffs are especially useful for this purpose. They may bear chemical or petrographic signatures that allow correlation of strata that are separated by many hundred kilometers. Thus, tuffs in North Dakota may provide important paleogeographic and paleotectonic information that will improve understanding of Laramide and post-Laramide events. Projects are underway utilizing volcanic tuffs in North Dakota and the broader region to obtain such information.

ZONED CRYSTALS

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Crystals that are coated or rimmed by different colored minerals are classed as zoned crystals. Molten material called magma in the earth's crust is host to the various stages of crystallization. The sequence of crystallization in a magma is called the Bowen reaction series. One series is discontinuous in descending order of temperature and pressure from olivine to pyroxene to amphibole, then mica and quartz, as indicated by the reaction rims or coronas. The other series or sequence is continuous from high temperature calcic plagioclase to albite at the sodium end. One mineral grows around another mineral as its nucleus. Feldspar crystals with calcic cores and sodic shells are normal constituent minerals in most lava dikes and flows.

Garnets are especially susceptible to zonal intergrowths with other minerals. Several occurrences of zoned garnets, feldspar crystals, mica and related minerals are given.

PETROLEUM DEVELOPMENT IN NORTH DAKOTA
A STRATIGRAPHIC AND HISTORICAL REVIEW

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Petroleum development in North Dakota may conveniently be divided into two cycles. The first cycle began with discovery in an unexplored basin in April, 1951, and ended with the Arab Oil Embargo in 1973. During the first cycle, drilling activity peaked with 454 completions in 1958; and oil production peaked at 27.1 million barrels in 1966. Activity levels reflected restricted markets and relatively low prices. About 5,000 wells were drilled during the cycle.

The second cycle has been marked by an explosive rise and then a collapse of oil prices. Drilling activity peaked with 834 completions in 1981, and an additional 6,500 wells having been drilled. Oil production peaked at 50.7 million barrels of oil in 1984.

The main emphasis of exploration during the first cycle was the Madison (Mississippian) reservoirs which accounted for about 80 percent of the production. The Duperow (Devonian) reservoirs accounted for 7 percent of the production, primarily from the Beaver Lodge initial discovery pool. Average depths of wells was about 6,700 feet.

The second cycle was marked by exploration of the deeper horizons. This was fueled by the economics of $28-to $35-a-barrel oil, improved seismic techniques, and the multiple pays in the central basin area. This combination led to a wildcat success ratio of 21 to 30 percent and an average depth of wells of about 9,000 feet for the period from 1978 through 1983.

The American Association of Petroleum Geologists classifies oil fields on the basis of ultimate recovery. Class A fields are defined as greater than 50 million barrrels, Class B - 25 to 50 million, Class C - 10 to 25 million, Class D - 1 to 10 million, Class E - less than 1 million and Class F - abandoned within one year of discovery. Using this classification, 5 Class A, 4 Class B, 22 Class C, and 106 Class D pools have been found in North Dakota. Three of the Class A and 4 of the Class B pools were found in the initial 1951 to 1958 surge of exploration. The other 2 Class A pools were found in the second cycle. Stratigraphically, Madison reservoirs account for 4 Class A and 2 Class B pools while one Class B pool is defined as a Spearfish-Madison pool. The other Class A pool is from the Duperow Formation, and the other Class B pool is from the Tyler Formation(Pennsylvanian).

STRATIGRAPHIC CONTROLS ON GOLD
MINERALIZATION, CARLIN TREND, NEVADA

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The Carlin Trend is a 60 km-long northwest alignment of epithermal, sediment-hosted, disseminated gold deposits. Since 1965, more than 8 million troy ounces of gold have been produced; current identified geologic resources in 20 deposits exceed 53 million ounces.

Gold deposits occur within rocks ranging in age from Ordovician through Mississippian deposited across the

Paleozoic continental margin. Lithologically dissimilar units were juxtaposed along the regionally significant, Mississippian-aged, Roberts Mountains Thrust Fault. These rocks constitute three distinct stratigraphic packages: autochthonous miogeoclinal carbonates; allochthonous eugeoclinal chert, shale, siltstone and sandstone; and an overlying coarse clastic overlap assemblage deposited on both upper and lower plate packages at the leading edge of the thrust. Deposits occur within all three rock packages.

Gold mineralization was both structurally and stratigraphically controlled, with economic concentrations localized at structural and stratigraphic settings similar to those which characterize petroleum traps; effective permeability was apparently of critical importance in channeling and focussing the flow of gold-mineralizing fluids. Along structural breaks, gold is selectively concentrated within favorable stratigraphic units. These include silty dolomite of the Silurian-Devonian Roberts Mountains Formation (Carlin deposit), limestone depositional breccia of the Devonian Popovich Formation (Post deposit) and siltstone of the Mississippian Webb Formation (Rain deposit).

Host stratigraphy controls the character of the ore, including average grade, grade variability, physical properties and metallurgical response. For example, the Gold Quarry deposit, with reserves exceeding 10 million ounces, consists of two distinct zones. The Main zone, hosted within highly fractured siliciclastic rocks is a low rade, highly variable, metallurgically amenable orebody. The Deep West zone, a stratabound concentration at the underlying limestone-clastic contact, has a relatively uniform grade approximately twice that of the Main ore zone but is metallurgically refractory.

Detailed stratigraphic mapping and logging play a critical role in exploration and geologic mine planning from Carlin-type gold deposits.

CHARACTERIZATION OF WATER PERCOLATION IN TUFFS IN THE UNSATURATED ZONE, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

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A surface-based borehole investigation is currently in progress to characterize water percolation in tuffs in the unsaturated zone, Yucca Mountain, Nye County, Nevada. This investigation will determine, through active in-situ testing and passive in-situ monitoring, an estimation of the present day water percolation (flux). The unsaturated zone consists of a gently dipping sequence of fine-grained, fractured, mostly welded ash-flow tuffs that are interbedded with ash-flow and ash-fall, nonwelded, sparsely fractured tuffs that, near the water table, are partly vitric and zeolitized. Primary objectives are to define the potential field within the unsaturated zone and to determine the in-situ bulk permeability and bulk hydrologic properties of the unsaturated tuffs. Borehole testing will be conducted to determine the magnitude and spatial distribution of physical and hydrologic properties of the hydrogeologic units together with their associated potential fields. System-analysis and integration studies of the unsaturated zone needed to develop a final unsaturated-zone model for the site will depend on these data as well as on data collected during other activities that characterize the hydrologic system of the site. The study area is restricted to that part of Yucca Mountain immediately overlying and within the boundaries of the perimeter drift of a proposed mined, geologic, high-level radioactive-waste repository. Vertically the study area extends from near the ground surface of Yucca Mountain to the underlying water table, some 500-750 meters below the ground surface.

This investigation involves dry drilling and coring of 1 horizontal and 19 vertical boreholes, ranging in length and depth from 60 to 760 meters, for a total of about 6,850 meters. The investigation also involves borehole studies consisting of in-situ pneumatic testing and vertical seismic profiling. Other activities related to and supported by this drilling program include matrix-hydrologic-property testing, physical-rock-property testing, age dating of contained pore water, geologic and lithologic logging, neutron-moisture logging and monitoring, geophysical logging, fracture mapping, and gas-flow evaluation.

The unique attribute of this proposed site is that the welded and nonwelded tuffs comprising and immediately surrounding the proposed geologic repository are unsaturated. The average distance between the proposed repository and the underlying water table is about 250 meters. The concept of waste disposal in a well-drained, unsaturated environment has great appeal because percolating water is not expected to have ready access to the waste-package environment after repository closure.

ORDOVICIAN CORALS OF THE RED RIVER-STONY MOUNTAIN PROVINCE

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Tabulate and rugose coral species of the Ordovician-age Red River and Stony Mountain Formations of southern Manitoba exhibit microskeletal morphologic features that show those corals occurring within the Selkirk Member of the Red River Formation to be more primitive than those occurring in the Gunn and Penitentiary Members of the Stony Mountain Formation. This was not recognized previously because many of the cerioid colonial forms of the tabulate and rugose corals occurring in the Selkirk Member were misidentified. Study of the microskeletal features of these corals showed that *Paleofavosites* occurs no lower in the Ordovician section than the Fort Garry Member of the Red River and *Favosites* occurs no lower than the Gunn Member. Those genera commonly identified as *Paleofavosites* or *Favosites* from the Selkirk are cerioid rugosa such as *Favistina* or *Crenulites*.

Extension of the "Flower Model" from *Favistina* shows that the solitary genera arose through *Palaeophyllum* to *Streptelasma*, which in turn gave rise to other genera such as *Lobocorallium*, *Grewingkia*, and *Deiracorallium*. Other, more restrictive models at the species level show that *L. trilobatum* (Whiteaves) arose from *Streptelasma* through *G. robusta* (Whiteaves) and *G. goniophylloides* (Teichert), and that species of *Bighornia* arose from *Streptelasma* without an intermediate ancestral genus.

New species of corals were described from study areas in Manitoba and Wyoming, based on descriptions using thin section microscopy with plane- and cross-polarized light to delineate microskeletal features. These features in the new and other, previously-described species show that the tabulate and rugose corals can be subdivided into "primitive" and "advanced" forms based on the evolutionary status of these features. The primitive forms predominate in the faunas occurring in the Red River and the advanced forms are most common in the Stony Mountain.

There is a clear relationship between dominance of coral genera with a specific corallum type and the type of sedimentation. Massive cerioid and phacelloid colonial forms flourished under conditions of carbonate deposition accompanied by low rates of sedimentation of terrigenous clastics, whereas the solitary forms were most abundant in stratigraphic units where deposition of these clastics predominated.

ALGAE IN THE WINNIPEGOSIS FORMATION (MIDDLE DEVONIAN), WILLISTON BASIN, NORTH DAKOTA

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The Winnipegosis Formation was deposited in the Williston-Elk Point Basin during the Middle Devonian (upper Eifelian - lower Givetian). The Winnipegosis Formation is composed of limestone, dolostone and anhydrite in a "shallowing-upward" sequence. During initial deposition of the Winnipegosis, a uniform, shallow marine environment covered the entire basin. Then, associated with a rise in sea level, the basin differentiated into a deep basin that received limited sediment and an encompassing shallow marine shelf. A variety of depositional environments developed at this time that included deep-basin, deep-shelf, reef, lagoon, and tidal-flat environments. Pinnacle reefs developed in the deep basin; and patch reefs developed at both the shelf margin and shoaling areas on the shelf. The reef rim that developed at the windward edge of pinnacle reefs sheltered a back-reef lagoon. Shelf lagoons were also associated with patch reefs.

In North Dakota, algae thrived in many of these shallow-water environments. Blue-green algal filaments contributed to the binding of the pinnacle-reef rims and the patch reefs. Blue-green algae encrusted a variety of different organisms, thriving especially in association with stromatoporoids in this reef environment. Codiacean algae (*Litanaia*, *Lanicula*) and calcispheres (?dasycladacean algae) dominated pinnacle-reef lagoons; whereas, segmented red algae (*Parachaetetes*), dendroid stromatoporoids (*Amphipora*), and calcispheres (?dasycladacean algae) dominated shelf lagoons.

The Elk Point Basin extended from northwestern North Dakota/northeastern Montana northwestward into Manitoba, across Saskatchewan to northern Alberta. The distribution of the various types of algae in the Winnipegosis in North Dakota is in some ways unlike the distribution of these types of algae in the Winnipegosis and its correlative Keg River Formation of Alberta. The lagoons in western Canada were dominated by dasycladacean algae (*Vermiporella*) and by dendroid stromatoporoids (*Amphipora*), with minor occurrences of codiacean algae, red algae, and calcispheres. The western Canadian lagoons apparently were more restricted than the lagoons in North Dakota. Although blue-green algal filaments seldom have been reported from the literature in Canada, they were probably distributed as extensively in reef rocks there as in North Dakota.

THE PALEOECOLOGY OF *ECHINOCARIS RANDALLII* BEECHER FROM THE VICINITY OF DRAKE'S WELL, TITUSVILLE, PENNSYLVANIA

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Echinocaris randallii Beecher is reported for the first time in interbedded coarse to fine clastic rocks cropping out at Drake's Well, Titusville, Pennsylvania. The rocks have been identified as belonging to the Corry Sandstone by recent workers, although this determination is not certain. However, the presence of *Cyrtospirifer* Fredericks in these rocks and the absence of *Paraphorhynchus* Weller firmly establishes the age of the rocks as Late Devonian --

not Mississippian; thus, there are no unequivocal Mississippian occurrences of *Echinocaris randallii*. By contrast with "typical" occurrences of species of *Echinocaris*, *E. randalli* occurs in association with a diverse, assemblage of megainvertebrates including sponges, brachiopods, pelecypods, gastropods, and cephalopods as well as trace fossils, including *Teichichnus* Seilacher and *Palaeophycus* Hall. This association probably represents a benthic community developed on medium to fine clastic, inner shelf substrata which were periodically interrupted by rapid influxes of coarser sediments.

PETROLEUM SOURCE ROCKS AND STRATIGRAPHY OF THE BAKKEN FORMATION IN NORTH DAKOTA

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The Bakken Formation (Devonian and Mississippian) of North Dakota consists of upper and lower black, organic-rich shales separated by a calcareous siltstone member. The formation is a relatively thin unit (maximum thickness of 145 ft (44.2 m)) with the lower shale attaining a maximum thickness of 50 ft (15.2 m) and the upper shale a thickness of 23 ft (7 m). The shales are hard, siliceous, pyritic, fissile, and noncalcareous. They contain abundant conodonts and tasmanites and have planar laminations accented by pyrite. The upper and lower shales were apparently deposited in an offshore, marine, anoxic environment where anoxic conditions were probably caused by a stratified water column resulting from restricted circulation. Organic matter deposited in the black shales was derived mostly from planktonic algae.

Organic geochemical analyses used to evaluate the Bakken shales as petroleum source rocks include organic measurements, chromatagraphic analysis of organic extracts, pyrolysis, vitrinite reflectance, and visual kerogen typing. The Bakken shales are very organic rich (avg. of 11.33 wt% organic carbon) and contain predominantly amorphous kerogen which is inferred to be sapropelic. The onset of hydrocarbon generation occurred at an average depth of 9,000 ft (2,740 m) based on interpreting depth plots and maps of various geochemical parameters (e.g. ratios of hydrocarbon to nonhydrocarbon organic compounds contained in solvent extracts, pyrolytic hydrocarbon to organic carbon, and the pyrolysis production index). Yet the relation of depth and source rock maturity is not uniform across the basin. The Bakken shales can be immature at depths of 10,000 ft (3,050 m) and mature at depths of 8,000 ft (2,440 m) depending on differences in paleo heat flow (paleo-geothermal gradients) in different parts of the basin. The effective source area of the Bakken lies mostly in McKenzie, Williams, Dunn, and Billings counties. Oil generation in the shales probably began about 75 million years ago (Late Cretaceous time) at a temperature of about 100 degrees C and initial expulsion of oil probably occurred 70 million years ago.

Vertical fracture systems, located primarily along the Nesson Anticline, Antelope oil field, and the Billings Anticline seem to be the most reasonable pathways for migration of oil to occur from the Bakken. The amount of oil generated by the Bakken in North Dakota, as calculated from pyrolysis data, is 92 billion barrels of oil. If only 10% of this oil was actually expelled from the shales it could easily account for the 3 billion barrels of known type two oil reserves in the Williston Basin.

TYLERICARIS HOLLANDI N. GEN., N. SP. (MALACOSTRACA: TEALLIOCARIDIDAE) FROM THE TYLER FORMATION (PENNSYLVANIA) OF NORTH DAKOTA

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A new genus and species of pygocephalomorph malacostracan is described from the Tyler Formation (Pennsylvanian) of North Dakota. The species extends the stratigraphic and geographic ranges of the family Tealliocarididae known previously only from the Mississippian of France and Scotland. It is the first reported tealliocarid of Pennsylvanian age and the first occurrence of the family in North America. The new species, *Tylericaris hollandi*, is named in honor of F.D. Holland, Jr. who encouraged paleontologic studies in these rocks.

BIOSTRATIGRAPHY AND TAPHONOMY OF THE CALCAREOUS NANNOPLANKTON OF THE NIOBRARA FORMATION, NORTHEASTERN NORTH DAKOTA

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The Niobrara Formation in northeastern North Dakota is approximately 200 feet thick and consists of two members: a lower, calcareous shale member and an upper, chalky member. Each member contains laminated as well as bioturbated intervals. Calcareous nannoplankton have been found in varying abundances throughout the section. The basal occurrence of the ammonite, *Clioscaphites saxitonianus septentrionalis*, and the occurrence of the nannofossil, *Arkhangelskiella specillata*, indicate an age of Santonian (Upper Cretaceous) for the entire section. The Niobrara in northeastern North Dakota represents a much briefer time interval than the much thicker sequence in Kansas.

The occurrences and relative abundances of calcareous nannoplankton species are related to initial abundances and to the degree of alteration due to early diagenesis. This diagenesis, in turn, is related to the original carbonate content of the sediment and to the degree of bioturbation that the sediment has undergone. In bioturbated, slightly carcareous shales there is a significant loss of species due to dissolution, with a consequent increase in the relative abundance of species more resistant to dissolution, such as *Micula staurophora*. On the other hand, the bioturbated, higly calcareous chalk exhibits some alteration of coccolith morphology due to recalcification. The taxonomy of calcareous nannoplankton must take these possible alterations into account. The best preserved, least altered species occur in the non-bioturbated, moderately calcareous intervals.

PALEOENVIRONMENTS AND STRATIGRAPHY OF THE FOX HILLS FORMATION (MAASTRICHTIAN: LATE CRETACEOUS) OF THE MISSOURI VALLEY - TOWARD A MORE HOLISTIC VIEW

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Studies of the Late Cretaceous Fox Hills Formation in the Missouri Valley Region have led to conflicting interpretations regarding its age, stratigraphic succession, physical correlation and faunal content ever since its first exploration before the birth of North Dakota. A modest, but steady, flow of studies about the region demonstrates the continued significance of this, and related rock units, particularly as aquifers. Comparing data from several studies with field relationships and with subsurface information serves to demonstrate that our understanding of the Fox Hills Formation is as yet imperfect.

Vagaries of pre-glacial and glacial erosion, coupled with fortuitous distribution of a barrier island sandstone lithosome (Timber Lake Mem.) and subtle syndepositional structural influences upon local lithofacies have combined to present field geologists with a distinctly unrepresentative record of Fox Hills deposition in and adjacent to the type area. Apparent simplicity of stratigraphic relationships in outcrop exposures in the Missouri Valley region belies the complexity of paralic facies that lie concealed beneath Hell Creek strata only a few tens of miles westward from the Fox Hills outcrop belt. A monotonous and more homogeneous set of facies characterizes Fox Hills deposition eastward from Emmons County. Substantial channelization across Emmons County has left a dissected patchwork of Fox Hills exposures having an as yet misunderstood relationship to western strata. In the Linton area sand facies lateral to the Timber Lake lie on a disconformity, broadly u-shaped in cross-section, that reaches to the Pierre Shale. This contact appears to represent an erosional interval rather than a depositional hiatus, although it is superimposed upon a Fox Hills section that may have been already-thinned (structurally).

Cross-sections and isopachous and lithofacies maps of various intervals in western Sioux, Grant, Morton and Adams Counties demonstrate exceptional thinning of the formation (or reason for re-evaluating its contacts and boundaries). Facies not exposed in outcrop include thin limestones, lignite and variegated siltstone and shale that represent interdistributary bay sedimentation dominated by delta-top systems distal to the barrier. These bayhead deposits replicate some aspects of the Stoneville facies of South Dakota. Interdistributary silts and clays, peat swamps, crevasse splay sandy silts, bar finger sands and perhaps chennier sands are represented among Fox Hills deposits in the region. This facies complex resulted from deactivation of distributaries and from compaction of delta platform clays and marine re-invasion. None of these facies has been recognized in the type area, but each is part of a more holistic environmental setting for the formation as a distributary-associated sequence of marine and bay deposits.

Regionally, Fox Hills sediments thin toward the southeast, but decisive relationships are eroded. There they represent the sea level deposits of the Dakota Isthmus which was emerging in late "Fox Hills" time. If they mimic older rock units, sediments forming the Dakota Isthmus probably existed from central Logan and McIntosh Counties southeastward to the axis of the Sioux Arch. This unusual sea-level, intertidal-to-supratidal flat lithotope of ten involved a brackish regime and thus was not an hospitable habitat for the "normal" Fox Hills fauna although it hosted both marine and brackish communities, some among mangrove swamps, at various times. The isthmus influenced both biotic and sedimentologic patterns within the formation eastward and southward from the type area. Further study throughout the region is warranted, particularly if we anticipate accurately understanding these important aquifer systems.

VERTEBRATE FOSSIL RECORD, AGE AND DEPOSITIONAL ENVIRONMENTS OF THE BRULE FORMATION (OLIGOCENE) IN NORTH DAKOTA

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Very few studies of fossils from the Brule Formation have been undertaken in North Dakota compared to stratigraphically equivalent units in other areas of the mid continent (e.g., Big Badlands of South Dakota). This ispartly because of the limited number of fossil-bearing outcrops of the Brule Fm. in North Dakota. Outcrops of the Brule, uppermost formation in the White River Group, are primarily restricted to the eastern Little Badlands and outlying buttes in Stark County and Chalky Buttes including White Butte in Slope County. The Brule Fm. has been informally divided into two members. The lower member consists of complexly interbedded lithologies of calcareous claystone, silty claystone, siltstone and crossbedded sandstone (Fitterer bed) intercalated, at times, with tuffs and limestones. Alternating beds of noncalcareous claystone, silty claystone and siltstone comprise the upper member. The upper member exhibits banded weathering and is cliff-forming whereas the slopes of the lower member are fluted.

Five classes of vertebrates (Osteichthyes, Amphibia, Reptilia, Aves and Mammalia) are represented by fossils in the Brule Formation in North Dakota. Mammalia, by far the largest group, contains taxa from 28 families in 10 orders. A list of vertebrate taxa recorded from the North Dakota Brule is presented. Vertebrate fossils are found as isolated occurrences throughout the lower member of the Brule and have been collected from areas of high concentrations in the fluvial sandstone facies. The upper member is mostly unfossiliferous. Collectively, mammal taxa recovered from the lower Brule in North Dakota indicate an Orellan North American Land Mammal Age. A possible Whitneyan age for the upper Brule has been inferred by others but no evidence was found during this study to substantiate that inference.

Lithologies characterizing the Brule Formation in North Dakota represent deposition by a dynamic fluvial system in which sluggish, loosely sinuous aggrading streams, flanked by low-relief levees, transected a broad floodplain containing small ponds and/or ephemeral swampy areas. This depositional setting provided a mosaic of habitats. Open savannah plains were inhabited primarily by small animals such as rabbits (*Palaeolagus*), deerlike ruminants (*Leptomeryx*), camels (*Poebrotherium*), hypertragulids and rodents (e.g., *Eumys* and *Ischyromys*). *Caenopus* (rhinoceros), *Archaeotherium* (entelodont), *Bothriodon* (anthracotheriid), *Merycoidodon* (oreodon), and *Mesohippus* (equid) were probably the dominant mammals in the near-stream woodlands containing hackberry trees. Most of these taxa also roamed the open plains but must have frequented the riparian forests. Carnivores and insectivores, although uncommon, were apparently ubiquitous. Shallow ponds or ephemeral swamps containing algae, fish, ostracods and gastropods developed, at times, in the inter-stream, open plain areas. Large mammals were occasionally stranded on sand bars where they were dismembered by scavengers or their bones disassociated by decomposition before burial by lateral stream migration. Frequently, floodwaters deposited fine-grained sediments over the alluvial plain burying recently dead and decaying carcasses and partially disintegrated bones. Interludes of non-deposition of unknown duration occurred between the flooding events.

A LATE QUATERNARY INSECT FAUNA FROM THE MISSOURI COTEAU, NORTH DAKOTA

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Sections on the Johns Lake site, located in SW1/4, SW1/4, NE1/4, Sec. 16, T. 145 N., R. 77 W., Sheridan County, North Dakota, were exposed during the construction of the McClusky Canal in 1973. The stratigraphy from the lake bed downwards consisted of 340 cm gray silty clay, 15 cm of clayey silt with abundant molluscs, 15 cm laminated marls, 9 cm moss peat (*Calliergon richardsonii*, *Drepanocladus aduncus*, *Scorpidium scorpioides*), 8 cm peat with wood and spruce cones, 37 cm organic clayey silt with occasional boulders, all overlying a gravel. Wood from the lower peat has a radiocarbon age of 10,820 +/- 150 yr B.P. (I-9556). The chitinous remains of insects were particularly abundant with lower peat. The fossil assemblage is dominated by aquatic and semi-aquatic beetles that presently are typical of marsh habitats in the boreal forest. Included in this component is the hydrophilid *Helophorus tuberculatus*, the staphylinids *Olophrum boreale*, and the micropeplid *Micropeplus sculptus*. A diverse assemblage of bark beetles associated with conifers, particularly spuce, were also present. Included in this component were *Ips borealis*, *Scolytus piceae*, *Phloeotribus piceae*, *Polygraphus rufipennis*, *Orthotomicus caelatus*, *Carphoborus carri*, and the "northwestern" scolytid *C. andersoni*. In species composition, the Johns Lake assemblage is similar to fossil faunas that have been described from sediments proximal to decaying ice elsewhere within the midcontinent. The scarabaeid species *Micraegialia pusilla*, very rare at the present, was a member of this fauna. There is evidence from species of ground beetles, such as *Dicaelus sculptilis*, that the climate was similar to that of the southern parts of the boreal forest at the present day.

THE IMPACT OF F.D. HOLLAND, JR. ON GEOLOGICAL LITERATURE

Mary W. Scott

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The impact of F. D. Holland, Jr. on geological literature is evidenced by his 59 publications covering 38 years, the publications of his 29 graduate students and the range of journals these have appeared in and the expanded range over which these papers have been cited. The publications of over 150 other graduate students plus scores of undergraduate majors who came in contact with Dr. Holland are a hidden element in this impact study.

ORDOVICIAN CORALS OF THE RED RIVER-STONY MOUNTAIN PROVINCE

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ABSTRACT

Tabulate and rugose coral species of the Ordovician-age Red River and Stony Mountain Formations of southern Manitoba exhibit microskeletal morphologic features that show those corals occurring within the Selkirk Member of the Red River Formation to be more primitive than those occurring in the Gunn and Penitentiary Members of the Stony Mountain Formation. This was not recognized previously because many of the cerioid colonial forms of the tabulate and rugose corals occurring in the Selkirk Member were misidentified. Study of the microskeletal features of these corals showed that *Paleofavosites* occurs no lower in the Ordovician section than the Fort Garry Member of the Red River and *Favosites* occurs no lower than the Gunn Member. Those genera commonly identified as *Paleofavosites* or *Favosites* from the Selkirk are cerioid Rugosa such as *Favistina* or *Crenulites*.

Extension of the "Flower Model" from *Favistina* shows that the solitary genera arose through *Palaeophyllum* to *Streptelasma*, which in turn gave rise to other genera such as *Grewingkia*, *Deiracorallium*, and *Lobocorallium*. Other, more-restrictive models at the species level show that *L. trilobatum* (Whiteaves) arose from *Streptelasma* through *G. robusta* (Whiteaves) and *G. goniophylloides* (Teichert), and that species of *Bighornia* arose from *Streptelasma*.

Six new species of tabulates and four new species of rugose corals are described herein. Within the Tabulata, *Trabeculites manitobensis* n. sp. and *Nyctopora fissisepta* n. sp. occur in the Selkirk Member of the Red River Formation in southern Manitoba, *Manipora bighornensis* n. sp. and *Angopora wyomingensis* n. sp. occur in the Hunt Mountain beds in the Bighorn Mountains of northern Wyoming, and *Favosites manitobensis* n. sp. occurs in the Gunn and Penitentiary Members of the Stony Mountain Formation in southern Manitoba. Within the Rugosa, *Streptelasma kelpinae* n. sp. occurs in the Gunn and Penitentiary Members, whereas *Streptelasma sheridanensis* n. sp., *Palaeophyllum sinclairi* n. sp., and *Cyathophylloides hollandi* n. sp. occur within or above the Hunt Mountain beds.

These new species of corals were based on descriptions using thin section microscopy with plane- and cross-polarized light to delineate microskeletal features. These features in the new and other, previously-described species show that the tabulate and rugose corals can be subdivided into "primitive" and "advanced" forms based on the evolutionary status of these features. The primitive forms predominate in the faunas occurring in the Red River and the advanced forms are most common in the Stony Mountain.

There is a clear relationship between dominance of coral genera with a specific corallum type and the type of sedimentation. Massive cerioid and phacelloid colonial forms flourished under conditions of carbonate deposition accompanied by low rates of sedimentation of terrigenous clastics, whereas the solitary forms were most abundant in stratigraphic units where deposition of these clastics predominated.

Proceedings of the F.D. Holland, Jr., geological symposium, 1992, J.M. Erickson and J.W. Hoganson, eds., North Dakota Geological Survey Miscellaneous Series No. 76.

INTRODUCTION

This study identifies Ordovician tabulate and rugose corals that have been collected from exposures of the Red River, Stony Mountain, and Stonewall Formations in southern Manitoba and the Bighorn Formation in northern Wyoming. The topics discussed herein are based on an earlier study (Caramanica, 1974) which dealt extensively with the entire coral faunas of the above formations. It is possible to determine the evolutionary advancement and relationships among tabulate and rugose coral genera based upon Flower's (1961) definitive work - the "Flower Model" which determined evolutionary relationships between genera of Ordovician tabulate and rugose colonial corals. This study extends the Flower Model from genera of cerioid rugosa to the solitary corals, and demonstrates that the solitary genera descendant from *Streptelasma* are related through it to its ancestral colonial genera *Palaeophyllum* and *Favistina*.

Study of the microskeletal features of the colonial and solitary corals demonstrates that they can be sorted into genera which exhibit "primitive" and "advanced" stages of evolution. There is a clear-cut ecological relationship between the colonial and solitary corals and the type of substrates they lived on, demonstrating the intolerance of certain genera for terrigenous sediments. This relationship is very likely related to the ability of the polyps to rid themselves of terrigenous clastic particles and their ability to utilize the metabolic products of their symbiotic organisms. New species of Ordovician corals are delineated due to their unique skeletal features which set them apart from previously described forms.

DEDICATION

The "blame" for this exposition of a portion of the overall body of scientific knowledge must be laid at the feet of an individual who shepherded the writer through the pitfalls and pratfalls of the doctoral program. Few individuals have the patience and perseverence to guide and counsel two generations of struggling graduate students through the rigors of defining an original scientific problem and carrying it to a solution and synthesis.

Dr. F. D. (Bud) Holland is one of those rare individuals who has a deep and lasting impact on the outlook and philosophy of his students. As one of those students he guided to the terminal degree, I can take the liberty to paraphrase a well-known beer commercial. *Bud, this Doc's for you!*

ACKNOWLEDGMENTS

I want to thank Dr. J. Mark Erickson, old friend and former colleague, for his prodding me to sit down and formalize a few thoughts that had been gathering dust for too long a time. His patience and counsel sustained me through many a midnight oil session. Bob Truman of ResTech Houston, colleague and friend, encouraged me to utilize company resources in preparation for this paper. Judy, my wife, put up with my absence for too many weekend nights and days, and bore her role as geological widow without complaint, and with much love.

PURPOSE OF STUDY

The tabulate and rugose corals occurring in exposures of Ordovician-age argillaceous and carbonate sedimentary rocks in the vicinity of the Williston Basin have not previously been studied as a complete entity. Previous workers have dealt with a single species or with the rugosans (Elias, 1982), or have included the corals as parts of a larger fossil assemblage. This study is an outgrowth of an earlier work (Caramanica, 1974) that dealt with the tabulates and rugosans collected from exposures of the Red River, Stony Mountain, and Stonewall Formations of southern Manitoba and the Bighorn Formation in northern Wyoming (Figure 1).

The topics of this study are:

1. Description of the stratigraphic framework of the Ordovician rocks studied.

2. Description of the colonial tabulates and rugosans occurring in the type areas of the Red River, Stony Mountain, Stonewall, and Bighorn Formations.

3. Determination of interelationships among genera and species of corals.

4. Determination of the degree of evolutionary advancement of the Ordovician corals studied.

5. Determination of paleoecologic relationships between corals and the substrates they lived on.

The Ordovician corals and sedimentary rocks were studied in two regions -- southern Manitoba and the Bighorn Mountains of northern Wyoming, as well as from two conventionally-cored sections of a test well in the extreme eastern part of North Dakota (Figure 1). Geographic descriptions of study localities are given in Appendix A.

In southern Manitoba, the Red River, Stony Mountain, and Stonewall Formations are exposed at their type and allied localities. The combination of

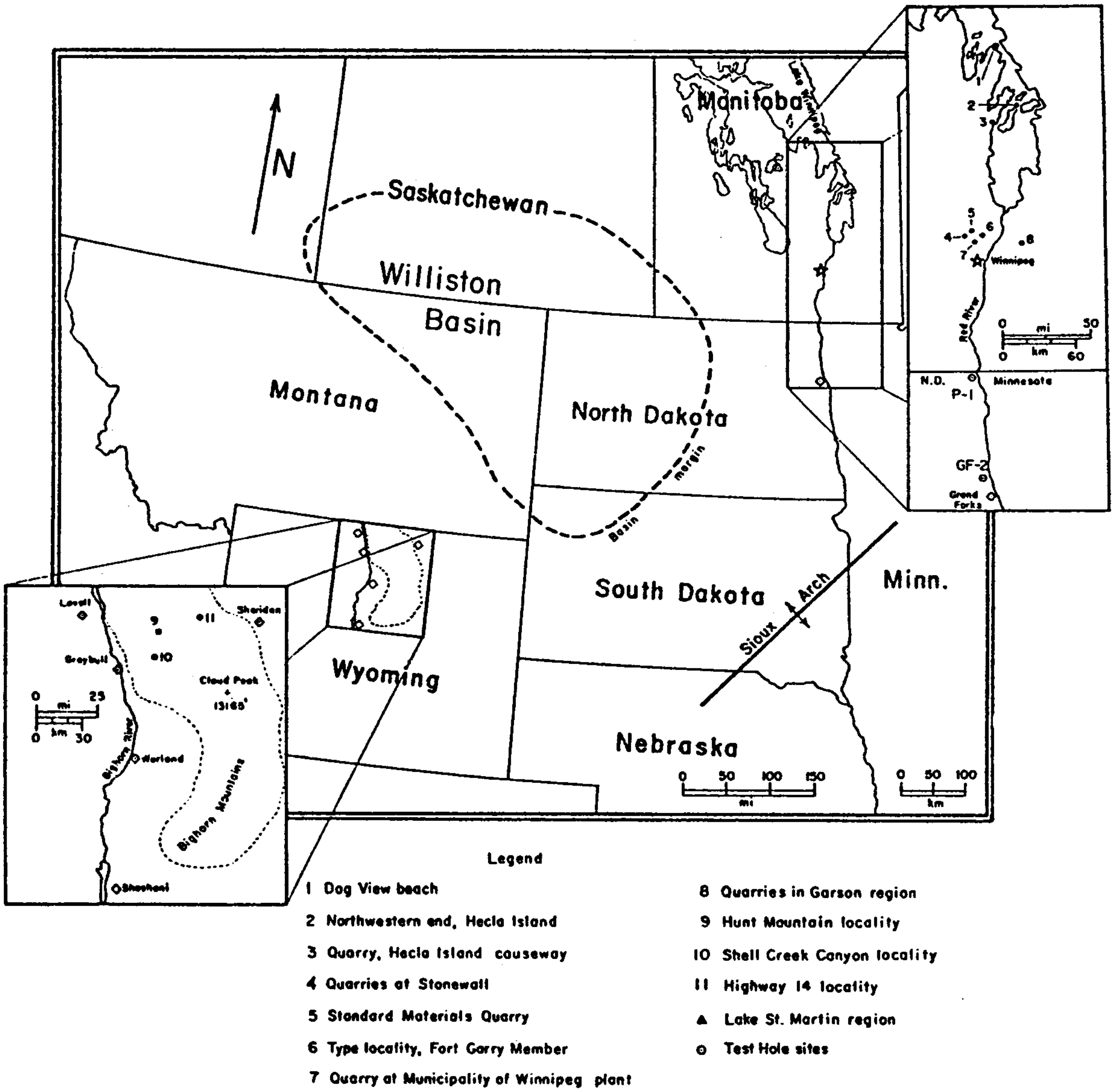


Figure 1-Index map showing areas studied, numbered localities, and Sioux Arch. Margin of Williston Basin from Porter and Fuller (1959).

little topographic relief, low dip angles (one degree or less) and Pleistocene glaciation have resulted in poor exposures. The only exposures of these formations are in quarries in the vicinity of Winnipeg, and along the western shore of Lake Winnipeg and on the islands in the lake. No complete stratigraphic succession of the three formations is exposed and most exposures are only a few tens of feet of a single formation.

In the northern portion of the Bighorn Mountains in Wyoming (Figure 1) the Bighorn Formation is completely exposed on the eastern and western flanks of the range as nearly horizontal and steeply-dipping strata. Between Manitoba and Wyoming, the Williston Basin contains, in the subsurface, the physical equivalents of the Ordovician units exposed along the basin periphery. Cores from wells in the basin that are in the collection of the North Dakota Geological Survey were examined, and the cores from Test Holes P-1 and GF-2 were described in order to determine lithology and fossil content. The southern Manitoba and northern Wyoming exposures were sampled to obtain suites of Ordovician tabulate and rugose corals and their enclosing sedimentary rocks.

Paleoecologic data on exposures of small areas of bedding plane surfaces and the contained coral fauna of the Selkirk Member of the Red River were gathered from quarry exposures of the unit. This offered a unique opportunity to record the lateral placement of corals as they occurred on the Ordovician sea floor at given instants of geologic time.

Large numbers of corals from the Red River, Stony Mountain, and Stonewall Formations were collected for about 35 years by students and faculty of the Geology Department of the University of North Dakota. Stratigraphic control of the occurrences of these corals presented no problem due to the well-delineated and geographically-distinct intervals in the Winnipeg region. Those workers and I sought to obtain the greatest number and maximum variety of collectable corals. Systematic collection methods were unusable however, where scarcity, inaccesability, and extraction made collection difficult or impossible. Stratigraphic control was commonly accurate to one-tenth (1/10) foot (4 cm).

STRATIGRAPHY

Southern Manitoba

RED RIVER FORMATION.--Present interpretations of the stratigraphy of the Red River (McCabe and Barchyn, 1982) subdivide it into four members; the Dog Head (basal), Cat Head, Selkirk, and Fort Garry (uppermost; Figures 2, 3).

Dog Head Member.--The Dog Head Member conformably overlies the Winnipeg Formation and is exposed along the western shore of Lake Winnipeg in the region of the Narrows, and in the vicinity of and on Hecla Island. As exposed at Dog Head and south of there, the unit is a 20- to 30-foot (6.1 to 9.1 m) thick, cliff-forming, dolomitic, mottled limestone. Dowling (1900, p. 41F) had reported a maximum thickness of 70 feet (21.3 m) for the Dog Head in the northern part of the western shore of Lake Winnipeg, McCabe and Bannatyne (1970, p. 15) reported a total thickness of 83 feet (23 m) for the unit in a test hole in the Lake St. Martin, Manitoba area, that bottomed in the underlying Winnipeg Formation. McCabe and Barchyn (1982) reported that the unit was 30 to 45 meters (98 to 148 ft) thick in southwestern Manitoba.

Cat Head Member.--The "Cat Head Limestone" of Dowling (1900, p. 42F) was described by him as "...cream-coloured dolomitic limestones of a general even colour and texture and rather fine grained in which are found nodules of chert of varying sizes." The contact with the underlying Dog Head has not been observed in exposures of the unit and McCabe and Bannatyne (1970) did not discuss the character of the contact. Dowling (1900, p. 42F) indicated the thickness of the Cat Head in the type area to be 68 feet (20.8 m), McCabe and Bannatyne (1970) cited a thickness of 50 feet (15.3 m) in the Lake St. Martin test hole, and McCabe and Barchyn (1982) reported a thickness of 20 meters (65 ft) in southwestern Manitoba. In a quarry near Riverton, Manitoba, the exposure consists of 11 feet (3.5 m) of thick- to massive-bedded, mottled, microcrystalline dolostone with a saccharoidal texture and dolomitized crinoid ossicles. Rare macrofossils in the quarry exposure are preserved as external molds and no more than a few, unidentifiable solitary corals were noted. No sedimentary structures other than thick and massive beds occur. The uniform saccharoidal texture of the dolomite reflects late or epigenetic dolomitization, indicating that the pre-dolomitization lithology was probably a fossiliferous, burrowed, limestone similar to the undolomitized Dog Head Member.

Selkirk Member.--The Selkirk Member was reported by McCabe and Bannatyne (1970 p. 15) to be 75 feet (22.9 m) thick in the Lake St. Martin area, where it was described as a nearly pure limestone interbedded with dolomitic limestone and calcareous dolostone (their work, pp. 75-76). In southwestern Manitoba, McCabe and Barchyn (1982, p. 23) described the unit as 20 to 55 meters (65 to 180 ft) of burrow-mottled, dolomitic limestone, highly fossiliferous in part. In the Garson, Manitoba region, 20.8 feet (6.4 m) of the Selkirk is exposed, and the lithology is uniform throughout the Gillis Quarries Ltd. quarry exposure. It is a very pale orange, earthy-appearing, fossiliferous, mottled, dolomitic limestone with abundant stylolitic zones. The mottling is an aureole of a pale yellowish brown, saccharoidal dolomite around endobenthonic burrows. Similar mottling occurs in the Dog Head, but in that unit, burrows are not preserved or were never as well developed as in the Selkirk. In southern Manitoba, the unit is characterized by a higher clay content than is the Dog Head, which explains its earthy appearance.

Fort Garry Member.--The Fort Garry is the uppermost unit in the Red River Formation. The type section is a 14-foot (4.3 m) exposure in the Mulder Brothers Construction Co., Ltd., quarry No. 12, located six miles (9.6 km) east of the town of Stony Mountain (Appendix A). In the Lake St. Martin area, McCabe and Bannatyne (1970) reported that the unit is up to 96 feet (29.3 m) thick, whereas in southwestern Manitoba, the unit was eight to 35 meters (26 to 115 ft) thick (McCabe and Barchyn, 1982, p. 23). Dowling (1900, p. 89F) described the section from a well drilled through the Stony Mountain at what was then Mr. Gunn's quarry (now the abandoned quarry of the Municipality of Winnipeg) as:

> The well referred to above was drilled in the quarry, beginning 15 feet 11 inches [4.8 m] below the top of the rock in the above section, and was carried down through eighty six feet [26.2 m] through soft, chiefly reddish limestone, probably clayey [the Gunn Member of the Stony Mountain Formation] to a band of hard limestone [probably the Fort Garry Member] from which a supply of water was obtained.

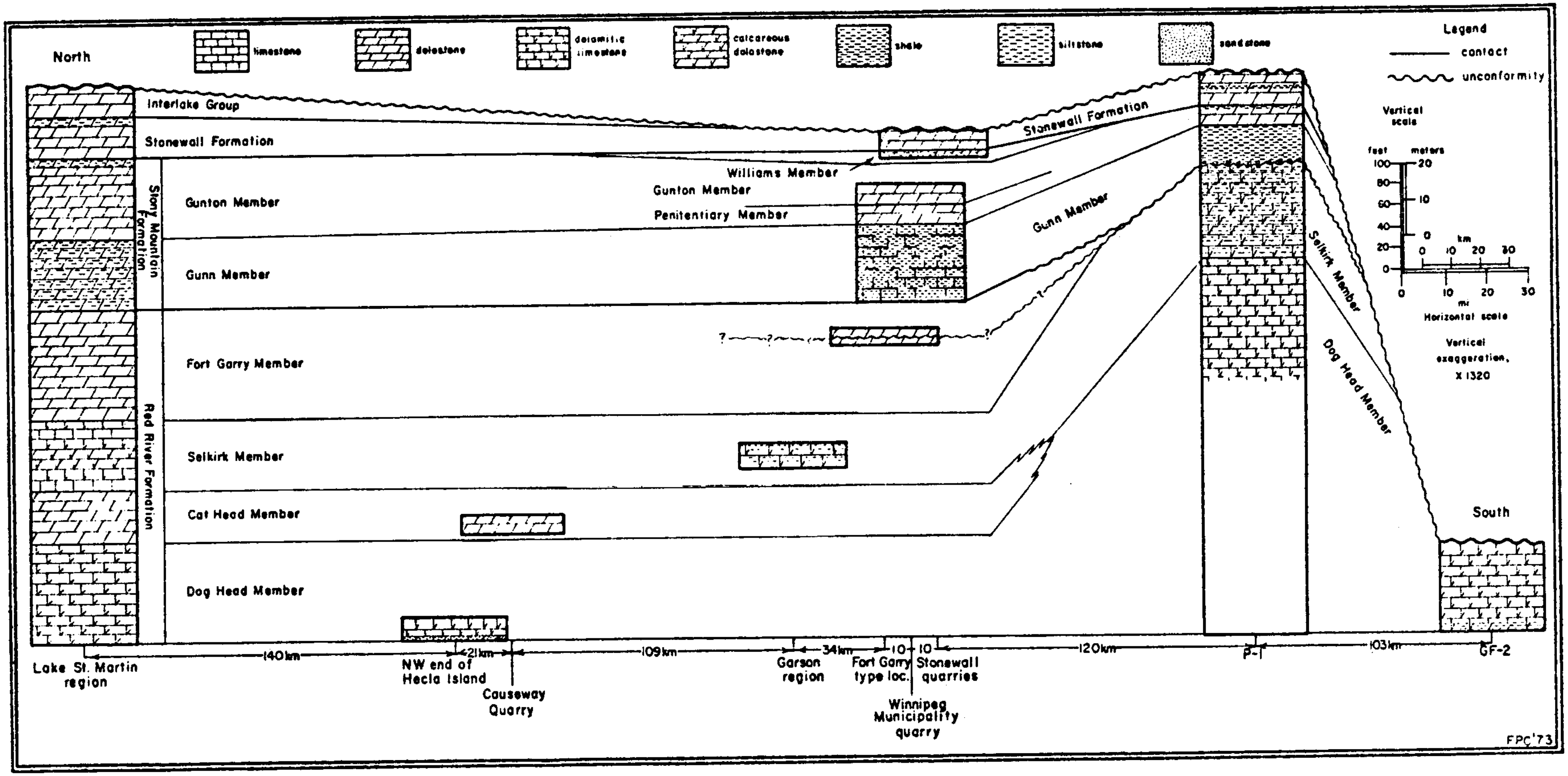


Figure 2-North-south cross section of exposures and cores of the Red River-Stonewall interval in southern Manitoba and eastern North Dakota. Datum is top of Winnipeg Formation. Data on Lake St. Martin region from McCabe and Bannatyne (1970).

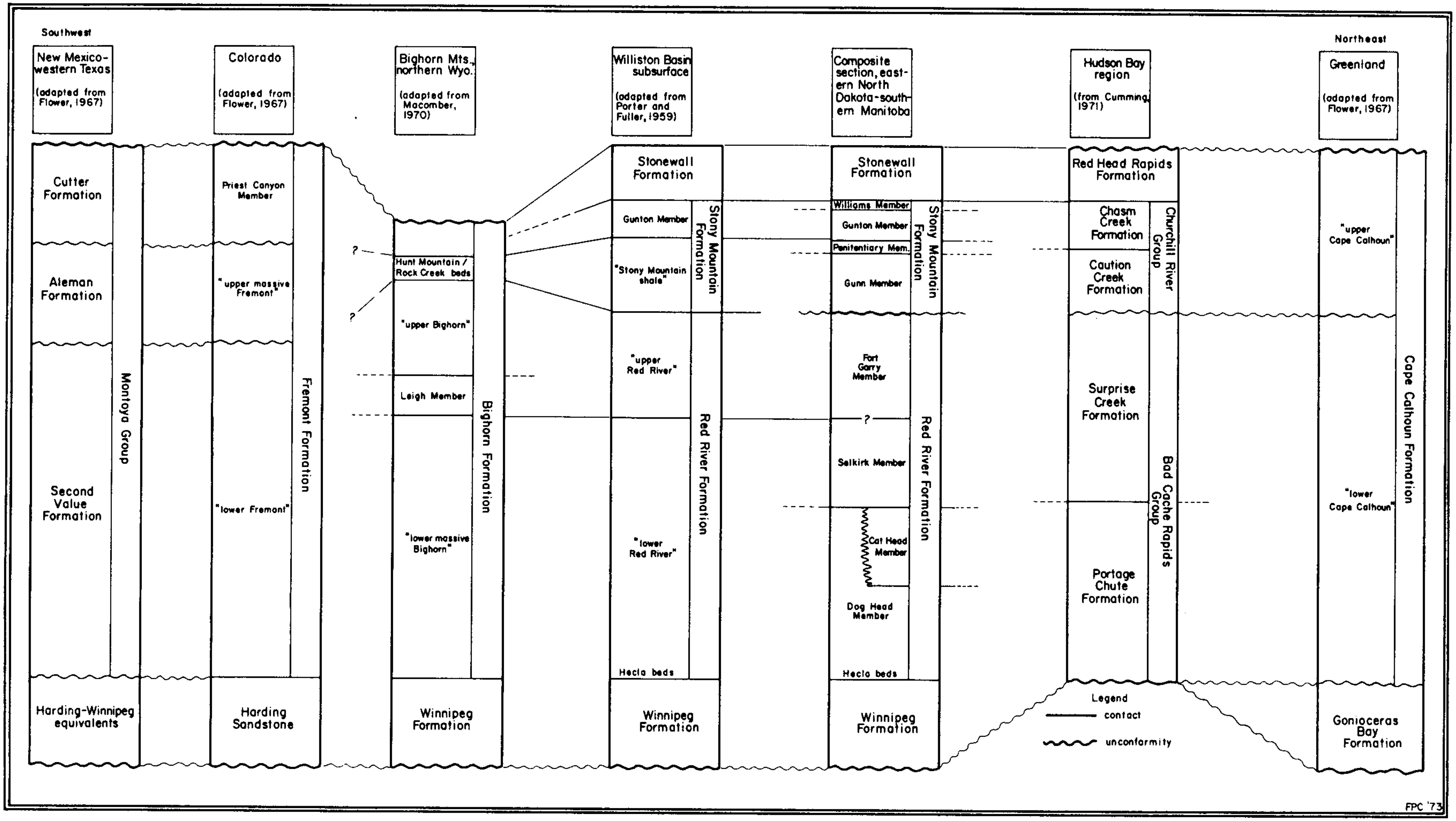


Figure 3-Nomenclature and relative positions of lithostratigraphic units in the middle and upper portions of the Ordovician System in a belt from New Mexico to Greenland. No thickness scale is implied, but thicknesses are approximately proportional within each column. The Hunt Mountain/Rock Creek beds and the Gunn Member of the Stony Mountain Formation are considered to be correlative.

Dowling's description and his accompanying illustration (p. 91F) show an abrupt lithologic break between the Fort Garry and the overlying Gunn Member.

The four rock types in the type section of the Fort Garry are:

1. Mottled, very thickly-bedded dolostone with poorly-preserved fossils,

2. Thinly-bedded lithographic dolostone,

3. Pale, reddish-brown, lutaceous dolostone with imbricate dolomite clasts,

4. Red and green clays.

The boundaries between all four rock types are commonly diastemic and no transitional zones were noted among the different lithologies. Fossils are rare and occur only in the mottled dolostone portion of the unit. Clay-bounded diastems (some with small-scale scour surfaces) and the micritic dolostone breccia suggest that the Fort Garry-Gunn contact is unconformable, as had been suggested by Dowling's (1900) description.

STONY MOUNTAIN FORMATION.--The Stony Mountain is currently divided into four members (Figures 2, 3; Cowan, 1971; McCabe and Barchyn, 1982); the Gunn (lowermost), Penitentiary, Gunton, and Williams (uppermost).

Gunn Member.--At the type locality, Dowling (1900, p. 91F) logged a total thickness of 74 feet (22.6 m) for the Gunn Member, and McCabe and Bannatyne (1970, p. 6) reported a thickness of 54 feet (16.5 m) for the unit in the Lake St. Martin region. In southwestern Manitoba, McCabe and Barchyn (1980, p. 23) described the Gunn as absent to 20 meters (66 ft) thick, grading laterally northward into lithologies corresponding to those of the overlying Penitentiary Member (Figures 2, 3). At the type locality (Appendix A), the Gunn consists of bioturbated, fossiliferous interbeds of pale, pink calcareous shale and pinkish-grey, argillaceous bioclastic limestone. The argillaceous portions have been reworked by infaunal burrowers, and the entire unit is very fossiliferous, with all the carbonate at the type exposure having been derived from the skeketal material of marine invertebrates that consist predominantly of articulate brachiopods and small, solitary rugose corals.

Much of the distinctive lithologic character and color of the shale and shaly limestones of the unit are due to the burrowing action of endobenthonic organisms, probably polychaete annelids, whose burrowing activity produced a sufficient change in the permeability of the sediments so that different concentrations of iron oxides in varying oxidation states accentuated the outline of the burrows, as can be observed in outcrop. Thin section microscopy shows concentrations of finely-divided hematite along the perimeter of each burrow, whereas the unburrowed matrix exhibits the same type of finely-divided hematite, but in lesser quantities, resulting in the matrix having a paler, more greyish aspect.

The top of the Gunn in the type area is defined in this study within a one foot (0.3 m)-thick transition zone wherein the preservation of the fossils changed from calcitic typical of the Gunn to the molds characterizing the Penitentiary.

Penitentiary Member.--In the type area (Appendix A), the Penitenitary conformably overlies the Gunn and is 15 feet (4.6 m) thick (Okulitch, 1943, p. 61). The unit is yellowish grey on fresh surfaces, and weathers to a greyish-orange, argillaceous, microcrystalline dolostone with a saccharoidal texture. The lower eight feet (2.4 m) at the Stony Mountain exposure contains abundant interior and exterior molds of fossils that replicate minor skeletal details. The fauna is the same as that of the underlying Gunn Member, composed predominantly of solitary corals and articulate brachiopods, commonly with the valves articulated. The upper portion of the unit is sparsely fossiliferous, and is characterized by small zones of pale red dolostone with a burrowed pattern made visible by concentrations of iron oxide that parallel bedding planes. Biogenic reworking is seen in the yellowish-grey portions of the dolostone, but is different than in the reddish zones. In the reddish-colored zones, the burrows are densely packed, the sediment appears to have been extensively reworked, and all burrows tend to parallel bedding planes. Within the yellowish-grey zones, burrows are less dense, the sediment appears to have been less extensively reworked, and burrows tend to be more subparallel to bedding planes. McCabe and Bannatyne (1970) reported no occurrence of the Penitentiary Member in the Lake St. Martin region, whereas in southwestern Manitoba, McCabe and Barchyn (1982, p. 23) indicated that the unit was present and varied from six to 25 meters (20 to 82 ft) thick.

Gunton Member.--The Gunton Member of the Stony Mountain Formation is named for a quarry exposure approximately 12 miles (19 km) north of Stony Mountain. Okulitch (1943, p. 60) originally described it as being 15 to 19 feet (4.6 to 5.8 m) thick with an overlying unit he termed the Birse Member. Baille (1952) included the 15 to 17 feet (4.6 to 5.2 m) of the Birse in the Gunton, making it a total of 27 feet (8.2 m) in the type section. McCabe and Bannatyne (1970, p. 16) described the unit in the Lake St. Matin area as being 80 feet (24.4 m) thick, and in southwestern Manitoba, McCabe and Barchyn (1982, p. 23) reported it is 12 to 20 meters (39 to 66 ft) thick.

The Gunton in the Stony Mountain region is a massive, very pale-orange, mottled, microcrystalline or micritic dolostone, interspersed with layers of burrowed, greyish-pink to pale-red, argillaceous dolostone. Fossils are poorly preserved, replaced by dolomite, silicified, or are preserved as molds. The columnar stromatoporoid *Beatricia* sp. is the most prominently preserved organism. The mottling throughout the unit is a secondary mineralization feature initiated by the burrowing action of infaunal organisms, and burrows in the argillaceous portions of the unit, like those in the argillaceous portions of the Gunn and Penitentiary, are densely packed and oriented parallel to bedding planes. Several bedding plane surfaces in the dolomitic portions of the Gunton at Stony Mountain show radiating hairline fractures reminiscent of dessication processes, which may represent thin stromatolitic or algal structures.

The contact of the Gunton with the underlying Penitentiary in the type area is conformable, with the change in lithology between the two members occurring over a short stratigraphic interval.

Williams Member.--The uppermost unit in the Stony Mountain, the Williams Member was named by Cowan (1971) from a type section in the Williams quarry a short distance north of the town of Stonewall (Appendix A). In this quarry, 6.5 feet (2 m) of the unit are exposed and consist of very pale orange to pale red, thin-bedded, argillaceous dolostone, with scattered, angular, silt-size quartz grains. No fossils were noted, and one bed in the type exposure shows low-angle, planar, cross bedding accentuated by concentrations of iron oxide pigment. Cowan (1971, p. 238) indicated that the Williams thins to the north and pinches out in the Interlake region (that region between Lakes Manitoba and Winnipeg). McCabe and Barchyn (1982, p. 23) described five meters (16 ft) of "argillaceous sandy silty dolomite, commonly medium greyish red" Williams in southwestern Manitoba.

STONEWALL FORMATION.--The lower, Ordovician portion of the Stonewall at the type locality in the Williams quarry consists of 18 feet (5.5 m) of very pale-orange, to pale yellowish-brown, thin- to thick-bedded, mottled, finely-crystalline to very finely-crystalline dolostone with dolomitized fossils. The basal portion of the unit is light greenish-grey, arenaceous, very finely-crystalline dolostone. An increase in argillaceous content produced a pale-red, "nodular", (Baille 1952, p. 55) finely-crystalline dolostone with burrows significantly more abundant than in the less argillaceous portions of the unit. McCabe and Bannatyne (1970) reported the unit in the Lake St. Martin area, and McCabe and Barchyn (1982, p. 23) described five meters (16 ft) of Ordovician-Silurian Stonewall from southwestern Manitoba.

Eastern North Dakota

In order to compare the Ordovician rocks of southern Manitoba with those in the subsurface of eastern North Dakota, two conventional well cores were selected from a total of eight collected from test holes drilled by the North Dakota Geolgocial Survey. Wells P-1 and GF-2 (Figures 1, 2; Appendix A) were drilled near the west bank of the Red River of the North and were cored through the Ordovician section. Anderson and Haraldson (1968) originally described the cores. The core from GF-2 contained the Winnipeg Formation and the Dog Head Member of the Red River whereas the core from P-1 contained section from the Dog Head up through the Stonewall.

WINNIPEG FORMATION.--In the GF-2 core eight feet (2.4 m) was cored, and unlike the exposures along Lake Winnipeg further north, the rock is a massive, mottled, argillaceous limestone or calcareous mudstone, grading upsection from light brownish-grey with greyish-red to purple mottles and greenish-grey clay inclusions, to a pinkish-grey color at the top of the section.

RED RIVER FORMATION.--The Red River section in the P-1 core is 197 feet (50 m) thick and does not contain the Red River-Winnipeg contact.

Dog Head Member.--The contact of the Dog Head with the underlying Winnipeg is characterized in the P-1 core by an upsection decrease in argillaceous content, grading into the mottled, dolomitic limestone of the Dog Head. The lithology of the unit in the cored interval (105 ft; 32 m) is very similar to that observed in fresh exposures along the western shore of Lake Winnipeg, in the type area -- a massive, mottled, yellowish- to light olive-grey, dolomitic limestone with burrows accentuated by mottling.

Cat Head Member.--The Cat Head does not occur in the P-1 core (Figure 2), indicating that the member pinches out north of the Canadian border.

Selkirk Member.--The uppermost 92 feet (27 m) of the Red River occurs as lithologies identifiable as the Selkirk Member in the P-1 core, and is very similar to exposures of the unit in the quarries at Garson, Manitoba. There is a 25 foot (7.6 m)-thick interval, the top of which is 27 feet (7.9 m) below the top of the Selkirk, that is identical to the exposed Selkirk at Garson, and contains some of the characteristic fossils such as *Receptaculites oweni, Armenoceras richardsoni,* and *Grewingkia robusta.*

Fort Garry Member.--The stratigraphic position of the Fort Garry in the P-1 core is represented by a one foot (0.3 m)-thick interval consisting of a yellowish-grey limestone with micrite dolostone clasts ranging in size from 0.5 to 20 mm. This is the "breccia" of Anderson and Haraldson (1968, p. 19) and it indicates that the Fort Garry was either eroded or not deposited in the vicinity of the P-1 well (Figure 1). The presence of the dolostone clasts, the absence of the Fort Garry, and the apparent conformable bedding plane contact observed between the Red River and the Stony Mountain Formations correspond to a paraconformity (Dunbar and Rodgers, 1958, p. 119).

STONY MOUNTAIN FORMATION.--The Stony Mountain is 56 feet (17 m) thick in the P-1 core and exhibits a paraconformable contact at the base and has a conformable contact with the overlying Stonewall. Lithologies attributable to the Penitentiary Member are not present, and the Gunton-type lithologies are more argillaceous than in the southern Manitoba type area.

Gunn Member.--The Gunn is 44 feet (13.4 m) thick in the core and is lithologically identical to the unit in the type area. Ten feet (3 m) below the top of the Gunn thin layers of greenish-grey clay are present, but contain no fossils or other bioclastic carbonates.

Gunton Member.--Twelve feet (3.7 m) of lithologies similar to the Gunton were observed in the core. The lower 8.5 feet (2.6 m) of the unit is pinkish-grey, punky, argillaceous dolostone with scattered fossil molds. The uppermost 2.5 feet (0.75 m) of the unit is a yellowish-grey, microcrystalline, argillaceous dolostone with small inclusions of greyish-green clay.

STONEWALL FORMATION.--The Stonewall is 31 feet (9.1 m) thick, thicker than the type section. Unlike the type section, there are no signs of mottling in the P-1 core. Fifteen feet (4.6 m) above the base of the unit, there are several laminae (0.5 mm) of greyish, blue-green clay, which may be the "t" horizon of Porter and Fuller (1959, p. 160), which Brindle (1960, p. 19) suggested may represent the Ordovician-Silurian systemic boundary.

Southern Manitoba to Eastern North Dakota

Figure 2 shows the regional changes in the Red River, Stony Mountain and Stonewall Formations from the Lake St. Martin region, to the type areas in the Lake Winnipeg-Winnipeg region, southward to the eastern portion of North Dakota (Figure 1):

1. The Red River Formation thickens southward.

2. The Dog Head is continuous throughout and thickens markedly to the south.

3. The Cat Head loses definition between the exposure near Hecla Island and northeastern North Dakota.

4. The Selkirk is continuous from the Lake St. Martin region southward to northeastern North Dakota, but does not contain the dolomitic mottling at the northern end, and instead contains microcrystalline, dolomitic limestone and calcareous dolomite (McCabe and Bannatyne, 1970, p. 16).

5. The Fort Garry pinches out southward.

6. The Gunn is dolomitic in the Lake St. Martin area (McCabe and Bannatyne, 1970, p. 16) and becomes more limey toward the type area and more argillaceous to the south.

7. The Penitentiary loses definition northward and southward from the type area.

8. The Gunton becomes more argillaceous southward from the type area.

9. The Williams may be represented in the Lake St. Martin area by the argillaceous interval at the top of the Gunton and may be partially represented in the argillaceous character of the uppermost portion of the Stony Mountain in the P-1 core.

Northern Wyoming

UPPER PORTION OF THE BIGHORN FORMATION.--The Ordovician carbonate section exposed in the Bighorn Mountains in northern Wyoming (Figure 1) is divided into a lower massive portion ("lower Bighorn"), a central thin-bedded portion -- the Leigh Member, and a massive dolostone referred to as "upper Bighorn" by Macomber (1970). He informally termed part of this upper Bighorn the "Hunt Mountain beds", although the faunas suggest they are correlative to the Stony Mountain Formation.

Forty-two feet (13 m) of the upper Bighorn directly underlying the Hunt Mountain beds occur at the Hunt Mountain locality (Appendix A) as medium- to thickly-bedded, very pale orange, finely crystalline dolostone with chert nodules. Few fossils occur and no corals were present. The contact with the overlying Hunt Mountain is marked by a thin bed of shale, an upward change from a dolostone to an argillaceous limestone and an increase in fossil content.

HUNT MOUNTAIN BEDS.--Correlative to the Stony Mountain Formation of southern Manitoba, the Hunt Mountain beds of Macomber (1970), because of their faunal and lithologic similarity to the Gunn Member of the Stony Mountain at the Manitoba type section, are considered to be a time-correlative lithostratigraphic unit. At the Hunt Mountain locality, the unit consists of 16 feet (4.9 m) of thin-bedded, greyish-orange, argillaceous, bioclastic limestone interbedded with thin beds of burrowed, calcareous, silty shale of the same color. The unit is fossiliferous, and solitary corals are small. No colonial rugosans were noted, but several species of *Paleofavosites* occur.

UPPER ORDOVICIAN UNDIVIDED.--The transition between the Hunt Mountain and the overlying strata is marked by a significant reduction in argillaceous content in the basal portion of the overlying strata. The total thickness of the strata overlying the Hunt Mountain beds is 57 feet (18 m). The basal 13 feet (4 m) are exposed, and the remaining 44 feet (13.5 m) are covered by soil and vegetation. The lower 28 feet (8.5 m) of this portion are thin-bedded, very pale orange, fossiliferous limestone ranging in texture from biomicritic to coarse crystalline. The base of the interval is argillaceous, but the argillaceous content decreases rapidly upsection. *Calapoecia ungava* Cox, *Paleofavosites* spp., *Palaeophyllum pasense* Stearn, a large *Lobocorallium trilobatum* (Whiteaves) and *Cyathophylloides hollandi* n. sp., were collected.

From 28 to 57 feet (8.5 to 18 m) above the base of the unit, the lithology changes to a thin-bedded, greyish orange, medium crystalline dolostone with abundant pore spaces (five percent of the total rock volume) formed by the molds of fragmental skeletal material. The dolostone is secondary, composed of euhedral dolomite rhombs, and is burrowed, with the dolomite in the region of the burrows more finely textured than the dolomitic rock matrix. A large, cateniform, rugose corallum was collected from this interval, *Palaeophyllum sinclairi* n. sp., represents the most advanced colonial rugosan encountered in the study. Corals of the Hunt Mountain beds are generally relatively abundant, small, solitary rugosans, as was observed in the Gunn Member of the Stony Mountain in southern Manitoba, and colonial forms are usually very small. The reduction in argillaceous content in the rocks overlying the Hunt Mountain is accompanied by an increase in colonial corals and the near absence of solitary types.

"ARCTIC" CORAL FAUNAS

In the past, the term "arctic" had been used to denote the macrofauna occurring in the Red River Formation and its lateral equivalents. The term was usually used for the large, massive, colonial corals, receptaculitids, gastropods and cephalopods of these units. The term is misleading since it has Holocene climatic implications that do not reflect Ordovician paleoclimate and paleogeography. It was coined due to the presence of large fossils in the region of northwestern Greenland and Baffin Island that were once thought to have migrated from the "Arctic Islands" region (Nelson, 1959a, p. 45) southward toward New Mexico. The "arctic" fossil assemblage ranges in geographic extent from New Mexico to Greenland in a northwest-trending belt of Ordovician carbonates physically equivalent to the Red River Formation.

Flower (1946, p. 120) used "boreal" for the faunal elements that invaded the Cincinnati, Ohio region during Trentonian time because they came from northern waters. Conversely "austral" referred to those invading the Red River area from the south. Flower (1946) and Nelson (1959a) were the first to refer to the faunas in these rocks as reflecting tropical conditions. Flower suggested (1946, p. 126) that the fossils such as those in the Red River were tropical due to their large size and their occurrence in the New Mexico-Greeland belt and that the "austral" fossils were more typical of temperate climates. Nelson suggested that the faunas delineated a tropical climatic zone on the basis of their elongate distribution along the New Mexico-Greenland belt. In the 1960s and 1970s, use of the term "arctic" had been restricted to the Red River faunas and their correlatives (Nelson, 1963, p. 21; Cuming, 1971, p. 194; Caramanica, 1974).

Barnes and Fahreaus (1975) coined the term Red River-Stony Mountain Province for the occurrence of Ordovician units equivalent to the two formations that extend from western Texas and New Mexico to northern Greenland to the Maritime Provinces (Elias, 1981). They proposed that the Red River-Stony Mountain Province was characterized by waters with higher than normal temperatures and salinities, and the solitary rugose corals of the province were characterized by Caramanica (1974, p. 56) as having developed a lateral angulation on the cardinal side of *Grewingkia* and *Dieracorallium* in the Red River, whereas the solitary corals in the Stony Mountain are predominantly angulate and have ancestral forms in the Red River. Elias (1982) noted that they are characterized as having unusual external form such as triangulate and trilobate cross sections.

Coral faunas are well developed in the Selkirk Member of the Red River Formation and the colonial forms of both the orders Tabulata and Rugosa are characterized by massive-hemispherical, cerioid, and cateniform coralla. Most colonial coralla are large, up to one meter diameter, and are lamellar, composed of successive layers of skeletal material interspersed with carbonate sediment. Only one rugosan colonial coral, *Palaeophyllum argus*, was not massive. Solitary corals are in distinct minority in the Red River, both in terms of numbers of species and numbers of individual coralla. Only representatives of one genus, *Grewingkia*, are large. The other solitary coral genera are represented by small individuals. As was mentioned above, a characteristic of solitary corals in the Red River is the development of the lateral angulation on the cardinal side of the corallum of two genera, and all solitary corals are closely related or show fairly direct descendence from the genus *Streptelasma*.

The coral fauna of the Stony Mountain Formation differs from the Red River fauna in that colonial genera are not as abundant. Most of the tabulates are favositids, and no descendancy from the Red River tabulates is apparent. The solitary rugosans on the other hand, are predominantly angulate, and have ancestral forms in the Red River, since the genera *Streptelasma, Bighornia,* and *Dieracorallium* are common to both the Red River and Stony Mountain faunas.

Generic Content

Of the 20 coral genera encountered in the original study (Caramanica, 1974), 14 (70%) of them occur in the Red River and the rest occur in the Stony Mountain Formation (Table 1). In northern Wyoming, only three genera were documented from the lower massive portion of the Bighorn Formation. The Hunt Mountain beds in the "upper" Bighorn contain eight genera, the most diverse found in the formation. The lowermost 28 feet (8.5 m) of Ordovician strata overlying the Hunt Mountain beds contain five genera and the overlying interval yielded only one genus (Table 1).

The coral faunas, when broken down to generic taxa, are predominantly tabulate colonial. The fauna of the Gunn Member of the Stony Mountain shows a generic shift toward solitary, rugose corals, *Streptelasma*, or genera descendant from it. The fauna of the Penitentiary Member is basically the same as the underlying Gunn, but not all the rugose genera present in the Gunn persisted into the depositional environment characterized by the Penitentiary.

The coral fauna in the lower part of the Bighorn Formation is not completely represented in, but it shows a definite relationship to, the fauna of the Red River. The Hunt Mountain beds contain the same rugose genera as does the Gunn Member of the Stony Mountain, but part of the tabulate genera in the beds are the same as those in the Red River. The basal 28 feet (8.5 m) of the Ordovician carbonate strata overlying the Hunt Mountain beds have genera that have affinities with the coral faunas of both the Gunn and Red River. *Lobocorallium* and *Paleofavosites* occur in both the Hunt Mountain beds and the Gunn, but *Calapoecia* is found in the Selkirk Member of the Red River and the Gunton Member of the Stony Mountain.

Distribution in Southern Manitoba

Coral species are listed with units in which they occur. Within the Red River Formation, the updating of the species listing for the Dog Head Member is based on the premise that the species listed by Dowling (1900, p. 49F) are the same as those that occur in the Selkirk Member, since I did not examine Dowling's specimens.

Calapoecia anticostiensis Billings

Catenipora robusta (Wilson)

Palaeophyllum argus Sinclair

Streptelasma sp.

Grewingkia sp.

Grewingkia robusta (Whiteaves)

[?]Protrochiscolithus magnus (Whiteaves)

[?]Coccoseris astomata Flower

It is uncertain as to whether Dowling (1900, p. 72F) was referring to *P. magnus* or *C. astomata*, since they are difficult to distinguish from one another without thin section study.

No previous worker has cited corals from the Cat Head Member of the Red River and no readily identifiable corals, other than a fragmental external mold of a small solitary coral, were found in the exposure of the Cat Head in the vicinity of Hecla Island (Appendix A).

The Selkirk Member of the Red River contains the "arctic" fauna of earlier workers and is well developed with respect to species diversity, being the most diverse of any in the study. It consists of 14 species of predominantly large, lamellar or encrusting, cerioid and canteniform colonial corals and at least five species of solitary corals. Of particular note is the absence of *Paleofavosites*. Dowling (1900, pp. 79F, 81F) and Baille (1952, p. 28) listed *Paleofavosites prolificus* for the Selkirk, but thin-section microscopy and microskeletal interpretation of the colonial tabulate genera show the genus to be absent. *Trabeculites* and *Nyctopora* are similar to *Paleofavosites* with respect to corallum habit and cerioid, polygonal corallites, but their corallite wall microstructures are significantly different from that of *Paleofavosites*. The two genera, therefore, can be easily confused with *Paleofavosites*, both in the field and in laboratory study.

TABLE 1

Distribution of coral genera in post-Winnipeg strata in northern Wyoming and southern Manitoba
Question marks indicate listings of Dowling (1900) for the Dog Head and Cat Head Members

GENERA	Red River Fm.				Stony Mountain Fm.				Stonewall Fm.	Bighorn Fm.			
Order Tabulata	Dog Head	Cat Head	Selkirk	Fort Garry	Gunn	Penitentiary	Gunton	Williams		Lower Massive	Hunt Mt. Beds	0-26' above beds	26-57' above beds
Trabeculites			X										
Nyctopora			X										
Manipora			X								X		
Calapoecia	?		X	X			?					X	
Protarea					X	?							
Coccoseris			X								X		
Protrochiscolithus	?		?										
Paleofavosites				X	X	X			X		X	X	
Angopora							X		X		X		
Favosites					X								
Catenipora	X	?	X	X						X			
Order Rugosa													
Streptelasma	X		X		X	X					X		
Palaeophyllum			X						X			X	X
Grewingkia	X									X			
Lobocorallium					X	X					X	X	
Dieracorallium			X		X						X		
Bighornia			X		X						X		
Crenulites			X							X			
Cyathophylloides												X	
Tryplasma									X				
Order Tabulata %	60	100	54	100	43	50	100		66	33	50	66	0
Order Rugosa %	40	0	46	0	57	50	0		34	67	50	34	100
Colonial Genera %	60	100	69	100	42	50	100		100	33	50	66	100
Solitary Genera %	40	0	31	0	58	50	0		0	67	50	34	0

Two species of *Calapoecia* occur in the Selkirk. One, *C. arctica*, is a species originally described from the Arctic region. *Coccoseris astomata* is relatively abundant and, like *Protrochiscolithus magnus*, has been previously misidentified in the field as an encrusting stromatoporoid. *Coccoseris* cannot be easily distinguished from *Protrochiscolithus* in the field. Thin-section microscopy is the only reliable method of separating the two genera.

Of the colonial Rugosa, *Crenulites* is the only cerioid genus present, and according to Flower (1961, p. 84), is "gradational" into *Favistina* Flower (=*Favistella* Dana). *Palaeophyllum* is the only phacelloid colonial genus found in the Selkirk.

Of the solitary coral species in the Selkirk, only *Streptelasma poulseni* is represented by small coralla with circular transverse sections. *Grewingkia robusta* is the largest of the solitary corals and is the most numerous. It is characterized by circular transverse sections or by a pronounced angulation in the cardinal region of the corallum. *Grewingkia goniophylloides* is very closely related to, or is gradational with the cardinal-angulate types of *G. robusta*. *Dieracorallium* sp. is characterized by a keel-like angulation in the cardinal region, and appears to be ancestral to *D. manitobense* in the Gunn Member of the Stony Mountain. *Bighornia* sp. has the lowest stratigraphic occurrence of the genus in the Ordovician system and appears to be a transitional form between *Streptelasma* sp. and *Bighornia* in the Gunn. The following lists the coral species identified from the Selkirk, including those of Elias (1982).

Trabeculites maculatus Flower

T. manitobensis n. sp.

Nyctopora fissisepta n. sp.

Calapoecia anticostiensis Billings

C. arctica Troedsson

Coccoseris astomata Flower

Protrochiscolithus magnus (Whiteaves)

Manipora garsonensis n. sp.

M. amicarum Sinclair

Catenipora robusta (Wilson)

C. rubra Sinclair and Bolton

Streptelasma poulseni Cox

Palaeophyllum argus Sinclair

Grewingkia robusta (Whiteaves)

G. goniophylloides (Teichert)

Dieracorallium sp.

Bighornia sp.

Helicelasma randi Elias

Crenulites rigidus Flower

C. duncanae Flower

Tabulate species comprise approximately 60 percent of the total species present, but colonial species, both tabulate and rugose make up almost 75 percent of the total.

Corals in the type section of the Fort Garry Member of the Red River (Appendix A) are completely dolomitized and fragmental, reflecting fragmentation and pre-burial reworking in an intertidal or infratidal-nearshore environment, due to their close association with what may be intertidal and supratidal sediments a few feet downsection. Three species were noted in the member:

Calapoecia sp. cf. *C. anticostiensis* Billings

Paleofavosites sp. A

Catenipora sp.

Of particular note here is the occurrence of *Paleofavosites*, the lowest documented occurrence of the genus in the Ordovician rocks in the Williston Basin region. This occurrence is of importance in determining the age of the coral faunas studied. The absence of any solitary corals observed in the type section of the Fort Garry may reflect these factors: (1) No solitary corals may have been able to survive in the infratidal region within which the colonial corals were found; or (2) The solitary corals living in association with the colonial corals were not transported to the burial site of the colonial coralla found. The colonial forms occur as subrounded fragments with a lesser density and greater potential for bottom transport than the denser, more streamlined, conical, solitary corals (Elias 1982b, p. 1592).

The Gunn Member is the most fossiliferous unit in the Stony Mountain Formation and contains a fauna that is markedly different from those in the underlying Red River. The Gunn or "typical" Stony Mountain coral fauna is second only to that in the Selkirk Member with respect to the number of species and number of individuals. The Stony Mountain fauna is characterized by relatively few genera of tabulate (4) and rugose (4) corals. Seven tabulate and five rugose species occur. Asterisks indicate species described by Leith (1952) but not found in this study. The following species are those listed by previous workers and are included in this study.

Protarea sp. cf. *P. cutleri* Leith

**Praginella arborescens* Leith

Paleofavosites sp. cf. *P. kuellmeri* Flower

P. prolificus (Billings)

Paleofavosites sp. cf. *P. prolificus* (Billings)

P. okulitchi Stearn

Favosites manitobensis n. sp.

Streptelasma kelpinae n. sp.

Lobocorallium trilobatum (Whiteaves)

Dieracorallium manitobense Nelson

Bighornia sp.

B. patella (Wilson)

Helicelasma selectum (Billings)

On the whole, the tabulate species do not reflect a direct descendance from any species of genera in the Red River corals. *Protarea* sp. cf. *P. cutleri* and *Praginella arborescens* however, appear to be related to *Coccoseris* and *Protrochiscolithus* of the Red River coral fauna. *Paleofavosites*, directly derived from *Foerstephyllum* (Flower, 1961, p. 70), has no direct ancestor in that fauna.

Favosites manitobensis n. sp., is unusual in being the second recorded occurrence of the genus in rocks of the Ordovician System in the Williston Basin and its peripheral areas, or within the Texas-New Mexico-Greenland belt of Ordovician rocks. No solitary corals however, have their ancestral stocks present in the underlying Selkirk Member. *Streptelasma kelpinae* is derived from a simple species of *Streptelasma*, possibly similar to the *Streptelasma* sp. occurring in the Dog Head Member of the Red River. *Lobocorallium trilobatum* is a descendant of *Grewingkia goniophylloides* of the Red River fauna, and *Bighornia* sp. and *B. patella* were apparently descendants from a species of *Bighornia* sp. from the Selkirk.

The basal seven feet (2 m) of the Penitentiary Member of the Stony Mountain Formation contain the following:

Paleofavosites prolificus (Billings)

Streptelasma kelpinae n. sp.

Lobocorallium trilobatum (Whiteaves).

These three species survived up to the time of sedimentation of the Penitentiary, but the other coral species seen in the underlying Gunn Member were not observed. At stratigraphic levels greater than seven feet (2 m) above the base of the Penitentiary, the corals are absent.

The coral fauna of the Gunton Member of the Stony Mountain differs markedly from that of the underlying members. No solitary corals were observed, but two molds of *Calapoecia* sp. and *Catenipora* sp., and the favositid *Angopora* sp. were seen.

No fossils were reported by Smith (1963) in the uppermost unit in the Stony Mountain -- the Williams Member, nor were any observed during the study.

The uppermost 14.9 feet (4.5 m) of the type section of the Stonewall Formation contains a reestablished coral fauna similar to that of the Gunton Member of the Stony Mountain:

Paleofavosites prolificus (Billings)

Paleofavosites sp. A cf. *P. prolificus* (Billings)

P. okulitchi Stearn

Paleofavosites sp. cf. *P. capax*

Paleofavosites sp. B

Angopora manitobensis Stearn

Tryplasma gracilis (Whiteaves)

No species of solitary coral were observed, and the fauna is predominantly favositid. The favositid genera *Paleofavosites* and *Angopora* are also present in the Gunton, with the Stonewall forms probably descendant of the Gunton species. All coralla collected at the Stonewall type locality are fragmental, and, like those in the Fort Garry Member, were very likely reworked and transported prior to burial. The lack of solitary coralla may have been due to the resistance of the conical corallum to transport noted previously.

Distribution in Northern Wyoming

In the northern Wyoming portion of the study, the few species collected from the Bighorn Dolomite occurred within the basal 133 feet (41 m) of the lower massive portion of the unit (Appendix A):

Catenipora robusta (Wilson)

**Grewingkia robusta* (Whiteaves)

Grewingkia goniophylloides (Teichert)

Crenulites rigidus Flower

C. duncanae Flower

* Listed by Duncan (1956)

The occurrence of *G. robusta* and *G. goniophylloides* in Wyoming represents the southwestern-most range of the species.

The coral fauna of the Hunt Mountain beds of the Bighorn Formation (Appendix A) contains species that are also present in the Gunn Member of the Stony Mountain in southern Manitoba:

Coccoseris sp.

Paleofavosites kuellmeri Flower

**Paleofavosites okulitchi* Stearn

Paleofavosites sp. cf. *P. okulitchi* Stearn

Angopora wyomingensis n. sp.

Manipora bighornensis n. sp.

***Streptelasma kelpinae* n. sp.

S. sheridanensis n. sp.

***Lobocorallium trilobatum* (Whiteaves)

**Dieracorallium manitobense* Nelson

***Bighornia patella* (Wilson)

B. parva Duncan

B. bottei Nelson

* Reported by Ross (1957) on the eastern side of the Bighorn Mountains.

** Species also occurring in the Gunn Member in southern Manitoba.

The inclusion of the five species also present in the Gunn indicates faunal communication around or across the Williston Basin to northern Wyoming. In addition, four of these species, *P. okulitchi, L. trilobatum, D. manitobense,* and *B. patella* were reported by Nelson (1963) from the Caution Creek and Chasm Creek Formations of the Churchill Group in the Hudson Bay region. In addition, *L. trilobatum* was reported from northern Greenland by Troedsson (1929). The coral fauna in the Hunt Mountain beds represents a mixture of species from the sub-Arctic and southern Canada, new species with unknown ranges, and a species from the Montoya Group of New Mexico (Flower 1961). This fauna contains a mixture of corals from both ends of the Texas-New Mexico-Greenland belt of Ordovician carbonate rocks, and shows a predominance, in terms of many individuals representing each species, of solitary coral. Each colonial species, on the other hand, was represented by a single observed specimen.

The thin-bedded limestones in the lowermost 28 feet (8.5 m) of the limestone overlying the Hunt Mountain beds show an influx of advanced (in the evolutionary sense) species of colonial rugosans, apparent holdovers from the colonial fauna in the Hunt Mountain:

Calapoecia ungava Cox

Paleofavosites mccullochae Flower

Paleofavosites sp. cf. *P. prayi* Flower

Palaeophyllum pasense Stearn

Lobocorallium trilobatum (Whiteaves)

Cyathophylloides hollandi n. sp.

Calapoecia ungava is a descendant of the *C. arctica-C. anticostiensis* lineage in the Red River and associated faunas. *Paleofavosites* sp. cf. *P. prayi* and *P. mccullochae* are species originally described from the Montoya Group of New Mexico (Flower, 1961) and *Palaeophyllum pasense* was originally described by Stearn (1956) from the Stonewall Formation in southern Manitoba. This gives evidence that the strata may be as young as Stonewall age, but this is based on only one shared species.

Lobocorallium trilobatum is a holdover from the

Hunt Mountain fauna, and *Cyathophylloides hollandi* is probably derived from species of *Cyathophylloides* described by Flower from the Montoya Group.

The scarcity of solitary corals -- *L. trilobatum* is the only one present, may be due to two factors: (1) In this partially-covered exposure (Appendix A) solitary coralla are not as prominent and as large as colonial coralla, or (2) Solitary species were not extensively developed in the post-Hunt Mountain sediments.

The thinly-bedded dolostone portion (28-57 feet; 8.5-17.5 m) above the Hunt Mountain beds had only one observable species, *Palaeophyllum sinclairi*, very similar to *P. pasense*. Since the stratigraphic interval 13 to 57 feet (4 to 17.5 m.) above the Hunt Mountain is partially covered, some inaccuracy in reporting fossil occurrences must be expected, and it is very likely that the fauna is more extensive than herein reported.

Table 2 shows the stratigraphic occurrence for the coral species in the study. Few species occur in more than one member, but four long-ranging species are: *Calapoecia anticostiensis*, *Catenipora robusta*, *Palaeophyllum argus*, and *Grewingkia robusta*. All four range from the Dog Head to the Selkirk members of the Red River Formation in southern Manitoba. *Grewingkia goniophylloides*, *Crenulites rigidus*, and *C. duncanae* are in the basal strata of the Bighorn Dolomite and do not occur in the Red River any lower than the Selkirk Member. This is evidence that: (1) species migrated in from the Texas-New Mexico portion of the Red River-Stony Mountain faunal province, or (2) these species were not able to survive the environmental conditions during deposition of the Dog Head Member of the Red River Formation.

GEOGRAPHIC DISTRIBUTION OF SPECIES

The coral fauna of the Red River Formation, typified by that in the Selkirk Member, is a mixture of three kinds of species- those from the southwestern end of the Red River-Stony Mountain Province, those from the northeastern end (the Greenland, Baffin Island region), and indigenous species not reported from either. Table 3 shows the geographic distribution of the species studied. Most of the Red River species are widely distributed. *Trabeculites maculatus*, *Manipora amicarum*, *Crenulites rigidus*, and *C. duncanae* all range from the Texas-New Mexico region to southern Manitoba or the Hudson Bay region. *Calapoecia anticostiensis*, *C. arctica*, *Catenipora robusta*, *C. rubra*, *Grewingkia robusta*, and *G. goniophylloides* all range from Greenland and/or Baffin Island southwestward to southern Manitoba or northern Wyoming.

The Stony Mountain coral fauna, typified by that in the Gunn Member, the basal portion of the Penitentiary Member, and the Hunt Mountain beds, also contains species that are fairly widespread. *Calapoecia ungava*, *Paleofavosites prolificus*, *P. okulitchi*, *Lobocorallium trilobatum*, *Dieracorallium manitobense*, *Bighornia patella*, and are species that range from the Hudson Bay region southwestward to southern Manitoba or northern Wyoming. *Paleofavosites kuellmeri* and *P. mccullochae* are the only species that range from the Texas-New Mexico region northeastward to northern Wyoming. On the whole, the Stony Mountain species are more restricted in geographic range than were the Red River species. The only exception is *L. trilobatum*, which ranges from Texas-New Mexico to Greenland. Most of the species are restricted to the northern Wyoming-Hudson Bay region.

The small solitary corals, such as *Streptelasma*, *D. manitobense*, *B. patella*, and *B. bottei* are absent from the Texas-New Mexico and Greenland-Baffin Island areas. Hill (1959) described and listed several species of corals from the Montoya Group of Texas-New Mexico. Only one poorly-preserved *Streptelasma* was described and it was not from a physical equivalent of the Stony Mountain Formation. Although it is unlikely, it is possible they were overlooked in the field. Troedsson (1929) stated that several of the collections from Baffin Island and Greenland were made during exploration expeditions and that (p. 164) "...all the collections referred to have been collected, like the Cape Calhoun fauna, without any detailed stratigraphic examination of the succession of the strata." Under such conditions, it is possible that small solitary corals were not observed.

The Stonewall coral fauna appears to show an even more restricted geographic distribution. The only species having considerable distribution are *Paleofavosites prolificus* and *P. okulitchi*, both of which also occur in the Stony Mountain fauna. All other Stonewall species or their presumed equivalents in the strata above the Hunt Mountain beds in northern Wyoming, with the exception of *Palaeophyllum pasense*, are apparently restricted to the southern Manitoba region.

Nelson (1963) noted no Stonewall corals other than *Paleofavosites prolificus* and *P. pasense* in the Hudson Bay region, but one should not disregard the possibility that the apparent restriction of geographic range of the Stonewall forms may be due to poor preservation. Small or fragile coralla such as *Angopora manitobensis* or *Tryplasma gracilis* may not have been preserved outside the southern Manitoba outcrop region of the Stonewall. This especially holds true for the partially-covered portion of the "upper Bighorn" in northern Wyoming where small forms could have been overlooked.

TABLE 2

Stratigraphic ranges of coral species in the Ordovician System in southern Manitoba, the Williston Basin (*), and northern Wyoming. Colonial species (o), solitary species (").

SPECIES	Red River Fm.				Stony Mountain Fm.				Stone-wall Fm.	Bighorn Fm.			
Order Tabulata	Dog Head	Cat Head	Sel-kirk	Fort Garry	Gunn	Peni-ten-tiary	Gunton	Will-iams		Lower Mass-ive	Hunt Mt. Beds	0-26' above beds	26-57' above beds
Trabeculites maculatus			- - - - - o										
T. manitobensis			- - - - - o										
Nyctopora fissisepta			- - - - - o										
Calapoecia anticostiensis	- - - - -	- - -	- - - - - o										
Calapoecia sp. cf. C. anticostiensis				- - - - - o									
C. arctica			- - - - - o										
C. ungava												- - - - -	o
Protarea sp. cf. P cutleri					- - - - -	o							
Coccoseris astomata	- - ? - -	- - ? - -	- - - - - o										
Coccoseris sp.											- - - - -	o	
Protrochiscolithus magnus	- - ? - -	- - ? - -	- - - - - o										
Paleofavosites kuellmeri											- - - - -	o	
Paleofavosites sp. cf. P. kuellmeri				* - ? - -	- - - - -	o							
P. mccullochae												- - - - -	o
Paleofavosites sp. cf. P. prayi												- - - - -	o
P. prolificus				* - ? - -	- - - - -		- - - - -	o					
Paleofavosites sp. A cf. P. prolificus								- - - - - o					
Paleofavosites sp. B cf. p. prolificus					- - - - -	o							
P. okulitchi					- - - - -	- - -	- - -	- - -	- - - - - o				

TABLE 2 - CONTINUED

SPECIES Order Tabulata	Dog Head	Cat Head	Sel-kirk	Fort Garry	Gunn	Peni-ten-tiary	Gunton	Will-iams	Stone-wall Fm.	Lower Mass-ive	Hunt Mt. Beds	0-26' above beds	26-52' above beds
Paleofavosites sp. cf. P. capax									- - - - - o				
Paleofavosites sp. A				- - - - - -	o								
Paleofavosites sp. B									- - - - - o				
Angopora manitobensis									- - - - - o				
A. wyomingensis											- - - - - o		
? Angopora sp.							- - - - - o						
Favosites manitobensis					- - - - - o								
Manipora garsonensis			- - - - - o										
M. amicarum			- - - - - o										
M. bighornensis											- - - - - o		
Catenipora robusta	- - - - - -	- - -	- - - - - o							- - - - - o			
C. rubra			- - - - - o										

Order Rugosa	Dog Head	Cat Head	Sel-kirk	Fort Garry	Gunn	Peni-ten-tiary	Gunton	Will-iams	Stone-wall Fm.	Lower Mass-ive	Hunt Mt. Beds	0-26' above beds	26-52' above beds
Streptelasma poulseni			- - - - - "										
S. kelpinae					- - - - - "						- - - - - "		
S. sheridanensis											- - - - - "		
Streptelasma sp.	- - - - - "												
Palaeophyllum argus	- - -	- - -	- - - - - o										
P. pasense									- - - - - o			- - - - - o	
P. sinclairi													- - - - - o
Grewingkia robusta	- - - - - -	- - -	- - - - - "							- - - - - "			
G. goniophylloides			- - - - - "							- - - - - "			
Grewingkia sp.	- - - - - "												
Lobocorallium trilobatum					- - - - - -	- - "					- - - - - -	- - - "	
Dieracorallium manitobense				* - - - - -	- - - - - "						- - - - - "		
Dieracorallium sp.			- - - - - "										

TABLE 2 - Continued

SPECIES Order Rugosa	Dog Head	Cat Head	Sel-kirk	Fort Garry	Gunn	Peni-ten-tiary	Gunton	Will-iams	Stone-wall Fm.	Lower Mass-ive	Hunt Mt. Beds	0-26' above beds	26-52' above beds
Bighornia patella					- - - - - "								
B. parva											- - - - - "		
B. bottei											- - - - - "		
Crenulites rigidus			- - - - - o							- - - - - o			
C. duncanae			- - - - - o							- - - - - o			
Cyathophylloides hollandi												- - - - - o	
Tryplasma gracilis									- - - - - o				

TABLE 3

Geographic distribution of Red River, Stony Mountain, and Stonewall coral species from New Mexico to Greenland, Red River species (*), Stony Mountain species (o), Stonewall Species ("), Fort Garry (+).

SPECIES	NEW MEXICO	NORTHERN WYOMING	SOUTHERN MANITOBA	HUDSON BAY	BAFFIN IS. ARCTIC IS.	GREEN-LAND
Trabeculites maculatus	*	*	*			
T. manitobensis			*			
Nyctopora fissisepta			*			
Calapoecia anticostiensis			*	*	*	*
Calapoecia sp. cf. *C. anticostiensis*			+			
C. arctica			*	*	*	*
C. ungava		o	o	o	o	
Protarea sp. cf. *P. cutleri*			o			
Coccoseris astomata	*	*	*			
Coccoseris sp.			o			
Protrochiscolithus magnus			*			
Paleofavosites kuellmeri	o	o				
Paleofavosites sp. cf. *P. kuellmeri*			o			
P. mccullochae	o	o				
Paleofavosites sp. cf. *P. prayi*	"	"?				
P. prolificus			o"			
Paleofavosites sp. A cf. *P. prolificus*			"			
Paleofavosites sp. B cf. *P. prolificus*			o			
P. okulitchi		o"	o"			
Paleofavosites sp. cf. *P. okulitchi*		+				
Paleofavosites sp. cf. *P. capax*			"			
Paleofavosites sp. A			+			
Paleofavosites sp. B			"			
Angopora manitobensis			"			

TABLE 3 - Continued

SPECIES	NEW MEXICO	NORTHERN WYOMING	SOUTHERN MANITOBA	HUDSON BAY	BAFFIN IS. ARCTIC IS.	GREEN-LAND
Angopora wyomingensis		o				
Angopora sp.			o			
Favosites manitobensis			o			
Manipora garsonensis			*			
M. amicarum	*	*	*	*		
M. bighornensis		o				
Catenipora robusta		*	*	*	*	*
C. rubra			*	*	*	
Catenipora sp.			+			
Streptelasma sp.			*			
S. kelpinae		o	o			
S. poulseni			*	*	*	
S. sheridanensis		o				
Palaeophyllum argus			*			
P. pasense		"	"			
P. sinclairi		"				
Grewingkia sp.			*			
G. robusta		*	*	*	*	*
G. goniophylloides		*	*	*	*	
Lobocorallium trilobatum		*	*	*	*	o
Dieracorallium sp.			*			
D. manitobense		o	o	o		
Bighornia sp. A			*			
Bighornia sp. B			o			
B. patella			o	o		
B. parva		o				
B. bottei		o	o	o		
Crenulites rigidus	*	*	*			
C. duncanae	*	*	*			
Cyathophylloides hollandi		"				
Tryplasma gracilis			"			

In summary, successive Ordovician coral faunas appear to have had an increasingly restricted geographic range until, during Stonewall time, many of the species appear to have been relatively localized.

PALEOECOLOGY

Corallum Type and Substrate

The carbonates of the Red River Formation in sourthern Manitoba and the beds overlying the Hunt Mountain Beds in the upper portion of the Bighorn Dolomite in northern Wyoming contain a primarily colonial coral fauna (Table 2). The Fort Garry Member of the Red River, the Gunton Member of the Stony Mountain, and the Stonewall Formation also contain coral faunas that are primarily colonial. The only exceptions are the two species of solitary corals in the Stonewall reported by Stearn (1956, p. 15) in the Flin Flon, Manitoba area. Colonial coralla in the dolomitic Fort Garry Member of the Red River, the Gunton Member of the Stony Mountain, and Stonewall in their type areas were all observed to be fragmental and appear to have undergone transport and reworking.

The absence of solitary corals in these units may be due, in part, to the resistance of these coralla to transport as was discussed by Elias (1982b, p. 1593) wherein he stated that the non-circular corals were resistant to rolling by currents. This writer observed that most of the solitary coralla have a higher skeletal mass per unit volume of corallum than do the colonial forms. This is due to stereoplasm deposits on septa and walls of the solitary forms, whereas the colonial corals, especially the cerioid forms have relatively low mass per unit volume due to relatively low volumes of stereoplasm. Moreover, relatively few solitary coral species may have lived in these predominantly carbonate depositional environments.

Units characterized by argillaceous lithologies, particularly the Gunn Member in southern Manitoba, and its correlative, the Hunt Mountain beds in northern Wyoming, have a higher number of solitary species and individuals in each (Table 2). In this type of lithology, the colonial species are represented by no more than one observed corallum, whereas the solitary species are represented by hundreds of individuals in each outcrop. A reason for the predominance of solitary individuals in environments of terrigenous deposition is very likely a greater tolerance of the solitary forms for these clastics. The possession of relatively deep calices by most of the solitary forms may have enabled individuals to avoid settling clastic particles by withdrawal of the polyp into the calyx, or to clean themselves off by periodic retraction and extension of the body column.

The colonial corals were not so fortunate. The interconnection between polyps by coenosarc, or by the peripheral, basal edges of adjacent polyps prevented them from shaking off or avoiding settling terrigenous clastic material. The material may have accumulated on the ectodermal polyp surface between adjacent body columns. The presumed mutualistic zooxanthellae or chloranthellae may have been covered, to a degree sufficient to cause a decrease in photosynthesis. The drop in photosynthesis may have caused a buildup of respiratory CO_2 and other waste products (Goreau, 1959).

The reduction of algal CO_2 uptake may have been more than body wall diffusion could accomodate, resulting in a buildup of metabolic toxins and death of the colony. The death of the colony may have been hastened by the reduced production of photosynthetic O_2 as well as carbohydrate output, and the reduction in uptake of metabolic CO_2.

The high number of small solitary corals in the argillaceous carbonates was likely a response of these solitary forms utilizing free energy in the form of food not being taken up by now-noncompetetive, rare, colonial forms. The cerioid colonial corals, due to their close-packed arrangement of polyps over the corallum surface, were more efficient gatherers of food than were the solitary corals. They could capture much of the available food out of the water that passed over the polyps. The reduction of numbers of coral colonies in an argillaceous depositional environment would have taken a significant amount of energy-absorbing biomass out of the Ordovician marine ecosystem. Such a removal would have enabled the less-efficient solitary corals to develop to the maximum permitted by environmental conditions, including a less-depleted food supply.

Conversely, the lack of incoming terrigenous clastics may have enabled the more efficient colonial corals to utilize nearly all the food available in the ecosystem. In conditions of autochthonous carbonate sedimentation in the Red River-Stony Mountain faunal realm, the shallow water was well lighted, enabling the mutualistic algae to function efficiently. Such an efficient mutualistic microsystem resulted in optimum conditions for the colonies. The colonial forms spent less energy secreting skeletal tissue on a unit volume and individual polyp basis, had coenosarc between the polyp body columns for additional photosynthesis area, and swept up food more efficiently due to the total surface area of the colony. As a result, the solitary corals may not have been able to compete as effectively.

The Search for a Suitable Substrate

Colonial corals in the Selkirk are characterized by four morpho-types:

1. Large shield- or mound-shaped, cerioid coralla, rarely up to one meter diameter, composed of successive layers of generations often separated from one another by sediment on the peripheral areas.

2. Large, cateniform coralla of *Catenipora*, which commonly exceed one meter in diameter.

3. Rare, phacelloid coralla such as *Palaeophyllum argus*, and

4. Small, encrusting, cerioid coralla of *Calapoecia, Coccoseris*, and *Protrochiscolithus* commonly assuming the same shape as the underlying substrate.

Layers of sediment between successive layers of the cerioid coralla indicate that periodic influxes of carbonate sediment overlapped peripheral portions of the distal corallum surface, and killed the affected polyps. Surviving polyps closer to the center of the corallum then peripherally expanded out over the offending sediment and reestablished a growth layer at the site of the dead polyps. This is most commonly observed in coralla of *Crenulites* which attain sizes larger than other cerioid genera. Strong bottom currents or wave action stirred up the unconsolidated carbonate sediment to such a degree that the colonies were completely overwhelmed or partially wiped out by smothering of some of the polyps. Strong currents or wave activity are indicated by some coralla being completely overturned and large nautiloid shells being abraded to such a degree that only the resistant siphuncle remains. This is commonly the only way that such nautiloid genera such as *Armenoceras, Narthecoceras*, and *Vaginoceras* are preserved.

Shield- or mound-shaped coralla are hydrodynamically stable and resistant to overturning since a minimum of surface area per unit diameter is exposed to moving water. Very low, shield-shaped coralla have a surface area hardly exceeding that of the area of a circle of similar diameter. However, because of the low skeletal mass per unit volume of colony, and the low volume of the colony per unit of surface area, accelerated bottom scour of the sediments may have been sufficient to undermine a given corallum, allowing moving water to impinge upon the large area of the light colony and easily overturn it once the streamlined aspect of the corallum was lost. The point of origin of several of these large, cerioid coralla was commonly a small fragment of calcareous skeketal material upon which the planktonic larval form of the polyp settled. The unconsolidated carbonate sediment was an unsuitable substrate, and the location of the colony was determined by the location of the suitable skeletal fragment.

The encrusting corals solved the substrate problem differently. Genera such as *Calapoecia, Coccoseris*, and *Protrochiscolithus* utilized entire skeletal structures such as a nautiloid shell, solitary coral, or stromatoporoid coenosteum for a substrate wherein the entire exposed area served as an attachment surface. In the latter two genera, this resulted in a corallum whose shape replicated that of the substrate to which it was attached. Few of the colonies of the encrusting coral species and the lamellar stromatoporoids were overturned because they are small and heavy with a flat base and little exposed surface area. All three genera in the Selkirk Member were intolerant of direct contact with the sediment and as a result, their size is limited by that of the substrate they were attached to. Several coralla of these genera were collected from the Selkirk Member and show use of the same substrate by succeeding generations of colonial corals.

One such specimen (UND13728.) has six generations of corals:

1. *Coccoseris astomata* at the origin encrusted by

2. *Nyctopora* sp. encrusted by

3. *C. astomata*, which is encrusted in turn by

4. *Calapoecia arctica*, which is encrusted by

5. *C. astomata*, covered by

6. Stromatoporoid capped at the distal surface by

7. *C. astomata*.

These seven succeeding generations of coelenterates cover each other, demonstrating that available substrate, at least for them, was severely limited. It is clear that the relationship between succeeding colonies was not parasitic, rather it was a case of each colony encrusting on one that was already dead. A planktonic larva of a polyp would probably not have been able to settle on the surface of a living colony. Nematocysts in the ectodermal layer of the living tissue would have probably killed it and utilized it for food. Modern anthozoan larvae resist metamorphosis to a polyp until a proper, clean substrate is found. A larva might drift until it was out of range of habitation of the species and die, or found a suitable substrate under the correct environmental conditions. Thus the behaviour of modern anthozoans gives insight into the proper colony-substrate relationship: a living colony on an already dead host.

Coral Distribution over the Sea Floor

Two bedding plane exposures of the Selkirk Member of the Red River Formation at locality A889 (Appendix A) afforded a unique opportunity to map the areal distribution of the sessile benthonic organisms. The exposures were clean of overburden and contained the organisms as they were situated on the sea floor prior to burial. Figure 4a shows a bedding plane surface approximately three feet (0.9 m) below the top of the exposed Selkirk section, whereas Figure 4b represents a bedding plane surface 4.9 feet (1.5 m) below the top. The organisms preserved on the surfaces include receptaculitids, stromatoporoids, and corals. On the upper bedding surface (Figure 4a), receptaculitids comprise 61 percent of the total of 87 individuals. Stromatoporoids are 25 percent of the total, and corals represent only 14 percent of the organisms. On the lower surface (Figure 4b), receptaculitids comprise 81 percent of the total, stromatoporoids are 10 percent, and corals are only 9 percent.

Neither figure defines a clear pattern of organism distribution. Small areas such as these show only gross features such as the predominance of the receptaculitids. On both bedding surfaces, the areas of coelenterate concentration do not exclude the receptaculitids, nor do the coelenterates reflect control by the abundant receptaculitids. Both surfaces show varying concentrations of organisms. In Figure 4b, the number of solitary corals such as *Grewingkia* differ from those on the overlying surface (Figure 4a). It is not clear whether these corals are *in situ* or have undergone transport. The unfragmented colonial coelenterates did not appear to have been overturned or moved from their original positions.

CORAL EVOLUTION

Flower (1961) used corallum wall skeletal microstructural morphology to differentiate between genera of Ordovician colonial corals and was able to shed light on their evolution. He showed that the microstructure of the corallite wall is one of the most important generic characters and is the most important feature for determining how an Ordovician coral genus is related to other genera.

The Flower Model

The starting point of Flower's model of evolutionary interrelationships of Ordovician colonial corals (Figure 5) is the genus *Lichenaria* which Bassler (1950, p. 256) and Flower (1961, p. 25) considered to be a likely ancestor for the Paleozoic corals. *Lichenaria* has a characteristically fibrous wall with two layers of sclerenchymal fibers abutting along an axial plane-- the *Lichenaria*-type wall, which was the starting point for seven different lineages.

One lineage leads from *Lichenaria* to *Eofletcheria*, the second leads from *Lichenaria* to *Quepora* to *Catenipora* of the Halysitidae. This second lineage includes the separation of the *Lichenaria*-type wall into a single layer, the addition of a thin outer layer--a holotheca, and the arrangement of the corallites into cateniform ranks. This produced *Quepora*, a genus not found in the present study. The addition of septal spines and the separation of the single wall layer into a trabecular common wall resulted in *Catenipora*.

The main lineage involved the crenulation of the *Lichenaria*-type wall, the addition of septal spines and mural pores to produce *Saffordophyllum* which, according to the model, lies along this lineage and gave rise to *Manipora*, a cateniform version of *Saffordophyllum*, a branch off the main lineage.

The modification of the *Lichenaria*-type wall of *Saffordophyllum* to a wall with monacanthine trabeculae, plus the accompanying alteration of the axial planes to short planes or lines, resulted in a cerioid coral, *Trabeculites*, in a lineage characterized by the breakup of the planar wall into separate trabecular rods. This trend culminated in two subordinate lineages rising from *Nyctopora*, which possesed trabeculae that are more distinct than in its ancestor, *Trabeculites*.

From *Nyctopora*, the *Calapoecia* lineage attenuated an increasing separation of trabeculae, whereas the *Coccoseris* lineage arising from *Nyctopora* developed a closely-packed arrangement of trabeculae.

Along the main lineage, the evolution of *Foerstephyllum* from *Saffordophyllum* was accompanied by the corallite wall developing an axial plate in the position of the former axial plane. In this wall type, which occurs in all the cerioid rugosans and is termed the "rugosan" wall, the inner ends of the schlerenchymal fibers abut the flanks of the axial plate.

From *Foerstephyllum*, two main evolutionary branches lead away. One accentuates the development of mural pores and the reduction of septal ridges in *Foerstephyllum* to separate spines. This gave rise to *Paleofavosites*, in which the mural pores are concentrated in the corners of the walls, and spines are present or absent. Continued development of this branch is marked by a shift of the mural pore positions from the corners to the centers of the corallite walls. In *Favosites manitobensis* n. sp. from the Gunn Member of the Stony Mountain Formation, the rugosan-type corallite wall develops trabeculae that appear as diffuse expansions of the axial plate.

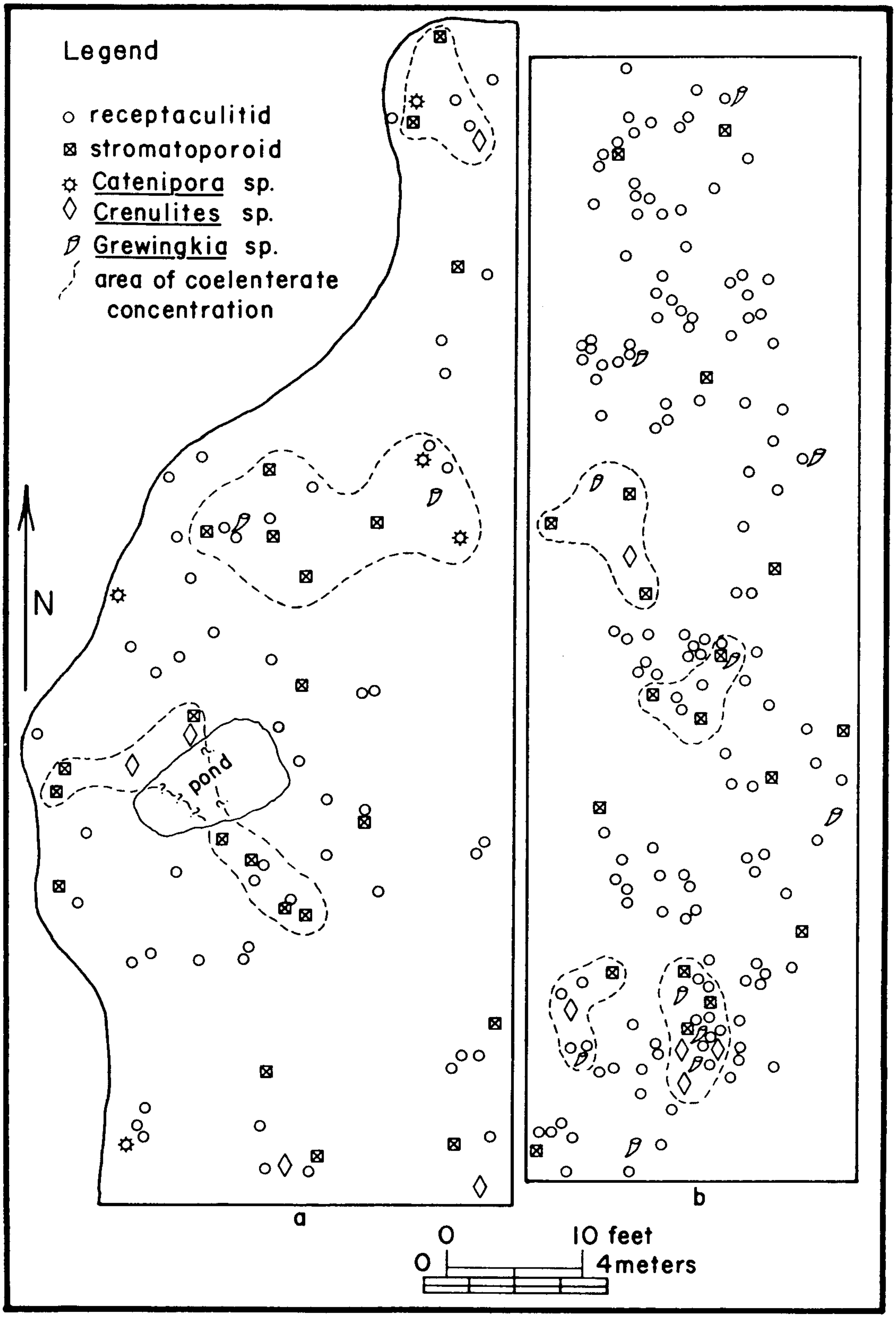


Figure 4-Distribution of sessile benthonic organisms on bedding plane surfaces in the Selkirk Member of the Red River Formation (Appendix A, locality A889). A. Three feet (0.9 m) below the top of exposed section. B. 4.9 feet (1.5 m) below top of exposed section. Concentration areas include sclerosponges as well as corals.

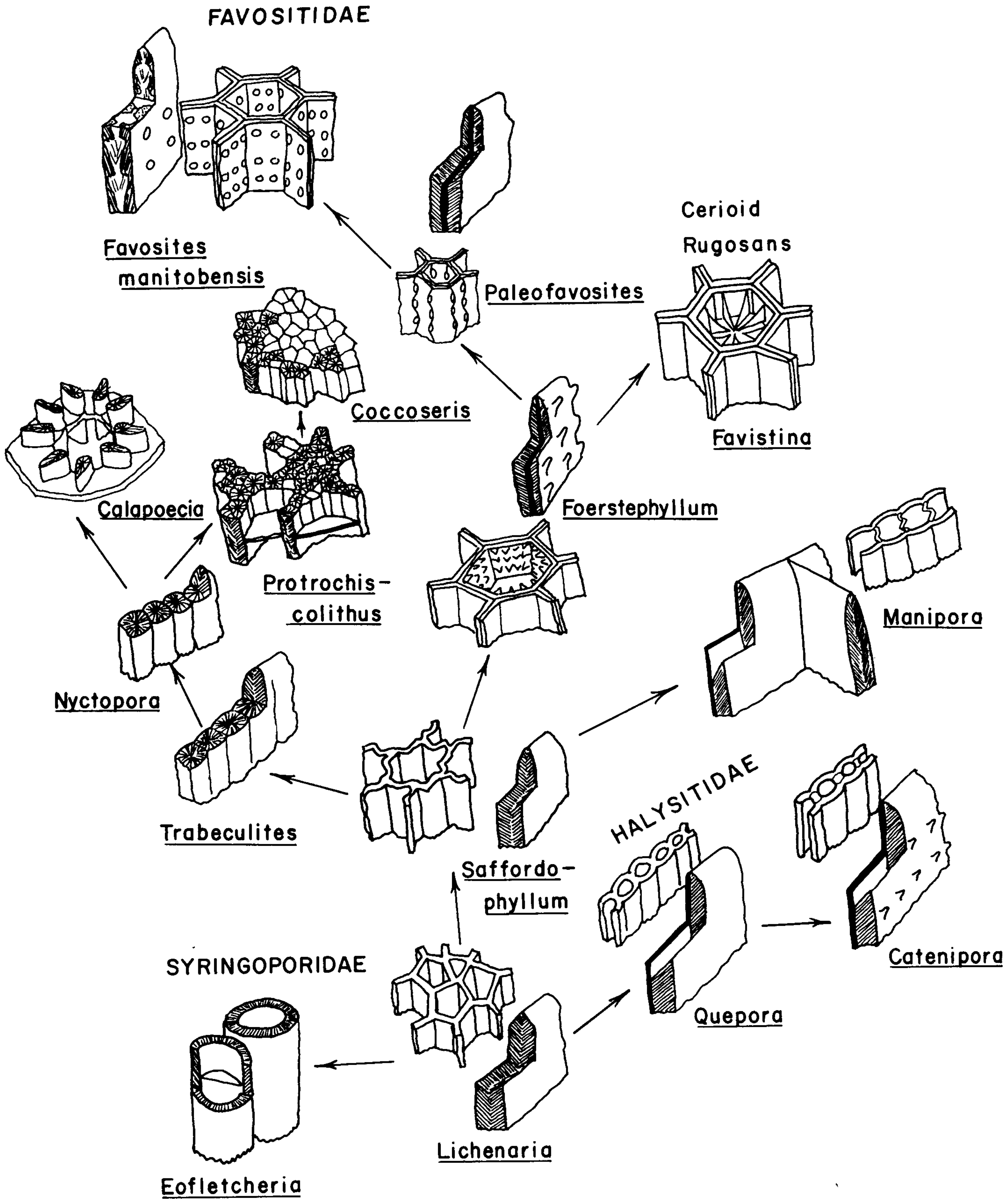


Figure 5-Evolutionary relationships between genera of Ordovician colonial corals (Flower, 1961)--the Flower Model.

The second branch from *Foerstephyllum* led to the cerioid Rugosa. The rugosan wall is retained and the development of septa from the spines of *Foerstephyllum* characterizes the cerioid genera related to *Favistina*.

The rugosans *Crenulites* and *Cyathophylloides* are similar to *Favistina*, but they differ in the number, extension, and differentiation of septa and in the type of tabulae. The rugosan wall consists of three elements, wherein lateral separation of the corallites produces characteristics typical of *Palaeophyllum*. The axial plate of the rugosan wall splits (Flower, 1961) and becomes an epitheca around each corallite (Figure 6). This parallels, and is analogous to, the development of a holotheca and wall fiber layer that occurred in the lineage of the Halysitidae from *Lichenaria*. The halysitid lineage differs in that the outer wall layer may have developed within the lineage itself, as there is no ancestral plate homologue in *Lichenaria*.

Streptelasma, according to the Flower model, results from a decrease in budding and the development of a conical rather than a cylindrical corallite (Flower, 1961, p. 35). Figure 6 illustrates an extension of the model into some of the Ordovician solitary corals. The solitary genera related to the ancestral streptelasmid genus, possibly *Streptelasma*, differ from that genus primarily by accentuation or distortion of features occurring in *Streptelasma*. *Grewingkia* and its descendant *Lobocorallium*, have more septa, a differing axial structure, and a change in corallum shape. *Bighornia* developed a corallum curvature in the opposite direction from that of *Streptelasma*, a flattened shape due to increases in corallum width along the alar septa, and an axial structure different from *Streptelasma* in that the counter septum is accentuated. *Dieracorallium* was modified from *Streptelasma* by the development of a prominent angulation in the region of the cardinal septum, a prominent fossula, and unmerged septa abuting at the corallum axis.

In the Flower model and its modification, those genera characterized by a *Lichenaria*-type wall or one of its derivatives are herein classed as "primitive" whereas those with the rugosan wall or modifications of it are "advanced".

The Flower Model in Septal Structure

Adaptation of the wall microstructure model of Flower and the extension of that model to the develop ment of septal microstructure shows a pattern which parallels that of the corallite wall (Figure 7). For purposes of illustration, only a few representative species are shown. There is no direct lineage implied in this version of the model. Rather, the species shown represent the type of septa contained within a general trend of increasingly complex septal spines, ridges, and septa in the Ordovician tabulates and rugosans.

The simplest type of septum or septal spine consists of a series of fibers diverging from a central line or plane. In primitive coral genera such as *Trabeculites* and *Nyctopora*, the septa consist of longitudinal ridges composed of fibers divergent about a central plane. As Flower (1961, p. 35) had pointed out, these often were little more than extensions of the wall schlerenchymal layer. The next, more-advanced septal structures commonly show a faint delineation between the septal material and the wall schlerenchyme, showing that the septa are structural entities distinct from the wall. This is illustrated by the septal ridges of *Paleofavosites okulitchi* (Figure 7).

The colonial rugosans represent another advancement in septal structure. *Crenulites rigidus* contains two septal types, major and minor. The major types are commonly distinct from the wall and they take on the appearance of the rugosan wall wherein two fibrous layers are separated by a septal axial plate similar in appearance to the plate in that wall type. It is not possible to tell whether or not the septal axial plate is a homologue of the wall plate. Minor septa, on the other hand, are simple extensions of the wall schlerenchyme in this species.

Palaeophyllum sinclairi, *Streptelasma poulseni*, and *Grewingkia robusta* show their septa to be distinct from the corallite wall. No axial plate appears to be present in these species, but the central planes of the septa appear to be occupied by a diffuse zone of translucent material. The fibers in the septa diverge laterally from the central plane. Longitudinal sections through septa of these species show no clear-cut tendency for grouping of these fibers into any recognizable structure. *Streptelasma kelpinae* shows a tendency for septal fibers to be grouped into fascicles, or bundles, producing primitive trabeculae. Both nontrabeculate and trabeculate septal microstructures occur within the genus *Streptelasma*.

Bighornia possesses the best-developed trabeculate septa. In *Bighornia* sp., the central translucent region of the septa is laterally expanded. Longitudinal sections through the septa show well-developed trabecular structures.

Relative Phylogenetic Position

The coral fauna in the Selkirk Member of the Red River Formation contains a large number of primitive coral genera: *Trabeculites*, *Nyctopora*, *Manipora*, and *Catenipora* do not possess the rugosan wall. Their walls were derived from the *Lichenaria*-type of wall

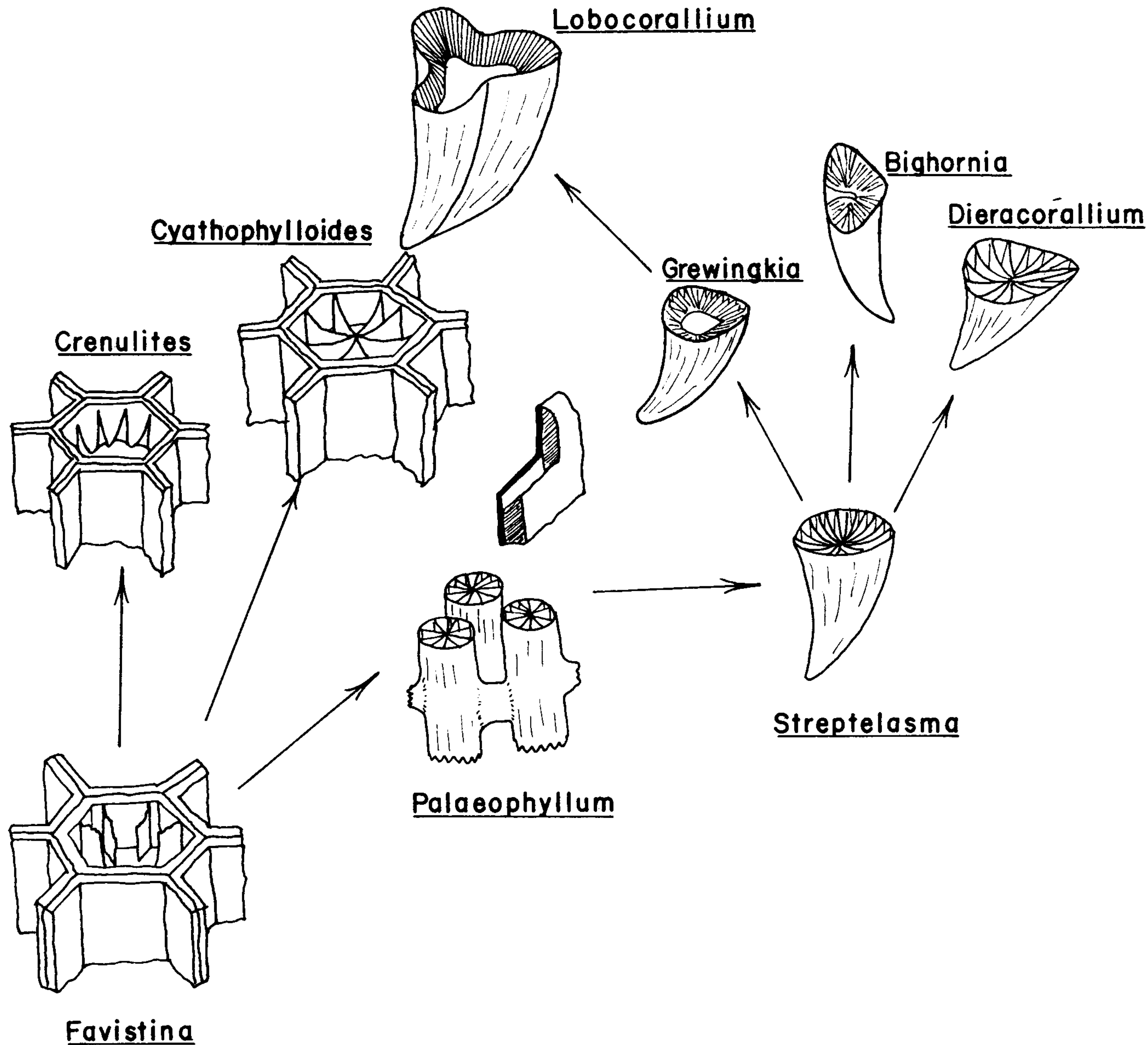


Figure 6-Extension of the Flower Model (Flower, 1961) in the Order Rugosa to the solitary corals. Solitary corals oriented with cardinal sides to the right.

microstructure and did not attain the characteristics typical of the rugosan wall (Figure 5). Septal microstructures in these genera are not advanced beyond the stages represented by *Trabeculites maculatus* and *Paleofavosites okulitchi* (Figure 7).

Protrochiscolithus and *Coccoseris* in the Selkirk fauna are more advanced than *Nyctopora*, due to the replacement of longitudinal structures such as septa, walls, and columellae by closely-packed, polygonal trabeculae. *Calapoecia* represents the continued breakup of the *Lichenaria*-type wall in which separation is more pronounced than in *Nyctopora*. Based on wall structure and a septal structure similar to that of *T. maculatus* (Figure 7), *Protrochiscolithus*, *Coccoseris*, and *Calapoecia* present a "mid range" evolutionary level, because these genera are characterized by a more advanced wall structure than that in the primitive genera noted above.

The only colonial cerioid genus in the Selkirk fauna that can be considered to be beyond the primitive

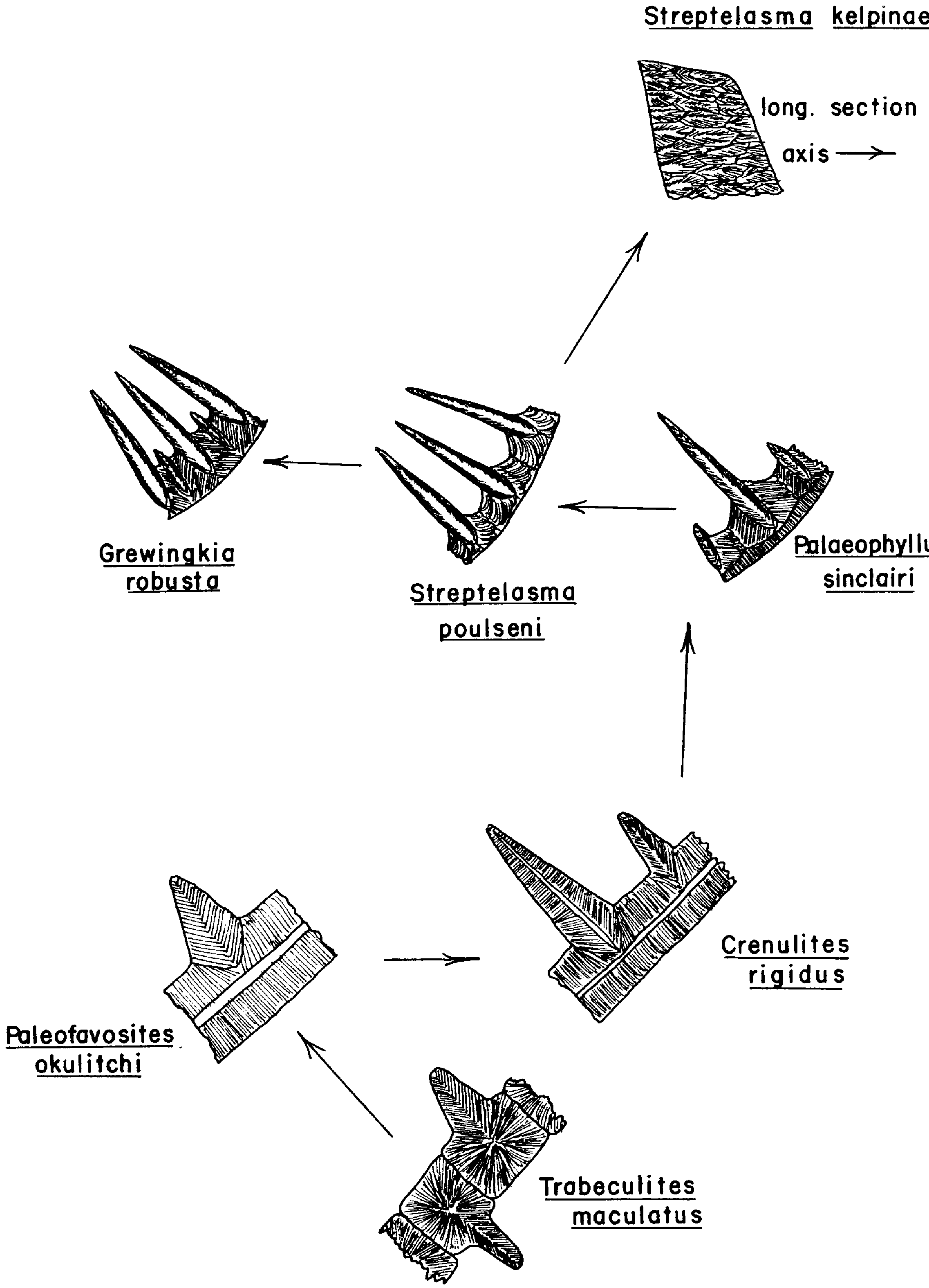


Figure 7-Gradation of septal microstructure from spinose to trabecular types in Ordovician corals. Arrows show progression with time from simple to complex septal structures. No evolutionary relationships are implied except for the rugosan species of *Palaeophyllum*, *Streptelasma*, *Grewingkia*, and *Bighornia*.

stage is *Crenulites*. It has the rugosan wall, but has septa that are nontrabeculate and has an axial plate-like septal structure (Figure 7). It appears to represent a mid range in septal development and advancement. The solitary corals *Streptelasma poulseni* and *Grewingkia* spp. are advanced in terms of position within the Flower model, but their septal development had not advanced to the trabeculate stage (Figures 6-8).

Figure 8 illustrates the evolutionary position of Ordovician coral taxa in this study based on wall and septal microstructures. Most of the corals in the Red River Formation are primitive or mid range, whereas those in the Stony Mountain Formation and the Hunt Mountain beds and Upper Bighorn are advanced. *Paleofavosites* and *Favosites* have the rugosan wall or a trabecular modification of it. The solitary corals of the post-Red River units are also advanced, as all of them are characterized by trabeculate septa.

Ordovician Corals as Correlation Indices

Previous discussion noted the sensitivity of the corals to depositional facies, indicating the corals should be primarily considered as facies fossils. This alone should be sufficient to reject them as widespread tools for correlation, because few species and genera are shared between the Middle and Late Ordovician type areas and the areas dealt with in this study. Several are useful for correlation within the Red River-Stony Mountain Province due to their wide geographic distribution within it (Table 3). The distribution of these facies fossils appears to have been the result of widespread uniform environmental conditions paralleling the Ordovician equatorial zone (Smith, et al., 1973).

***Paleofavosites* as Age Indicator**.--An important genus in attempting to use corals as age indicators is *Paleofavosites*. According to Leleshus (1971, table 2) the genus occurred during Late Ordovician time in all of the paleozoogeographic provinces covering North America, the Soviet Arctic, Siberia, central Asia, and northern Europe. According to him (his table 1) *Paleofavosites* did not occur in any of the provinces during Middle Ordovician time. No citations of the occurrence of *Paleofavosites* were given by Bassler (1950) from type areas of Middle and Late Ordovician rocks, complicating the problem of dating the onset of *Paleofavosites*.

Strata of Richmondian age in northern Michigan, southern Ontario, and Antocosti Island all contain the genus, but no strata older than these have documented occurrences of the genus. Based on Bassler's work (1950), the genus does not appear to be in rocks older than Richmondian age in the eastern United States and eastern Canada. This invalidates the conclusion of Twenhofel et al. (1954, Chart 2) who correlated the entire Ordovician section of southern Manitoba and northern Wyoming with the Richmondian- and Gamachian-age strata on Anticosti Island. *Paleofavosites* occurs throughout the entire Ordovician section on the island (Twenhofel, 1928, p. 85). In Twenhofel et al. (1954, p. 282) it was stated that the Red River fauna is very closely correlative with the English Head Formation on the island. A comparison of the Red River coral genera and species in this study with his list of corals for the unit (1928, pp. 63-65) shows one genus--*Streptelasma* and species *Calapoecia anticostiensis* in common. On the basis of *Paleofavosites*, all of the Red River Formation except the Fort Garry Member is pre-Richmondian if Twenhofel's citations of the genus and Richmondian-Gamachian strata are adhered to.

The complete absence of the genus from the Red River below the Fort Garry indicates that the pre-Fort Garry portion is older than the *Paleofavosites*-containing Ordovician rocks to which Bolton (1972) assigned a Richmondian age.

Flower (1961, p. 73) described *Paleofavosites sparsus* from the Second Value Formation of New Mexico, a unit probably correlative with the Red River. He did state however, that the species had several characters also occurring in *Foerstephyllum*. He was of the opinion that it may have been *Foerstephyllum* rather than *P. sparsus*. The species appears to be a transition between the two genera, hence its presence in pre-Richmondian strata. Flower's opinion (1961) suggested that the Second Value Formation may not have been where *Paleofavosites* evolved from *Foerstephyllum*. Hence it appears that *Paleofavosites* did not become established until the Richmondian, by which time *Paleofavosites* such as seen in the Fort Garry Member of the Red River Formation had evolved.

Time and Skeletal Microstructures.--Comparison of the skeletal microstructures of the coral faunas in the Red River and Stony Mountain Formations shows a marked distinction in the degree of evoluntionary advancement of the faunas. The paraconformity between the two formations observed in cores from the test wells in eastern North Dakota and the diastemic nature of the Fort Garry Member in southern Manitoba represent the passage of a considerable interval of geologic time. The exact amount of time represented by the disastems and the paraconformity is not known, but the coral faunas above and below are significantly different.

Colonial corals in the Red River Formation, particularly those in the Selkirk Member are characterized by the primitive, *Lichenaria*-type corallite wall (as

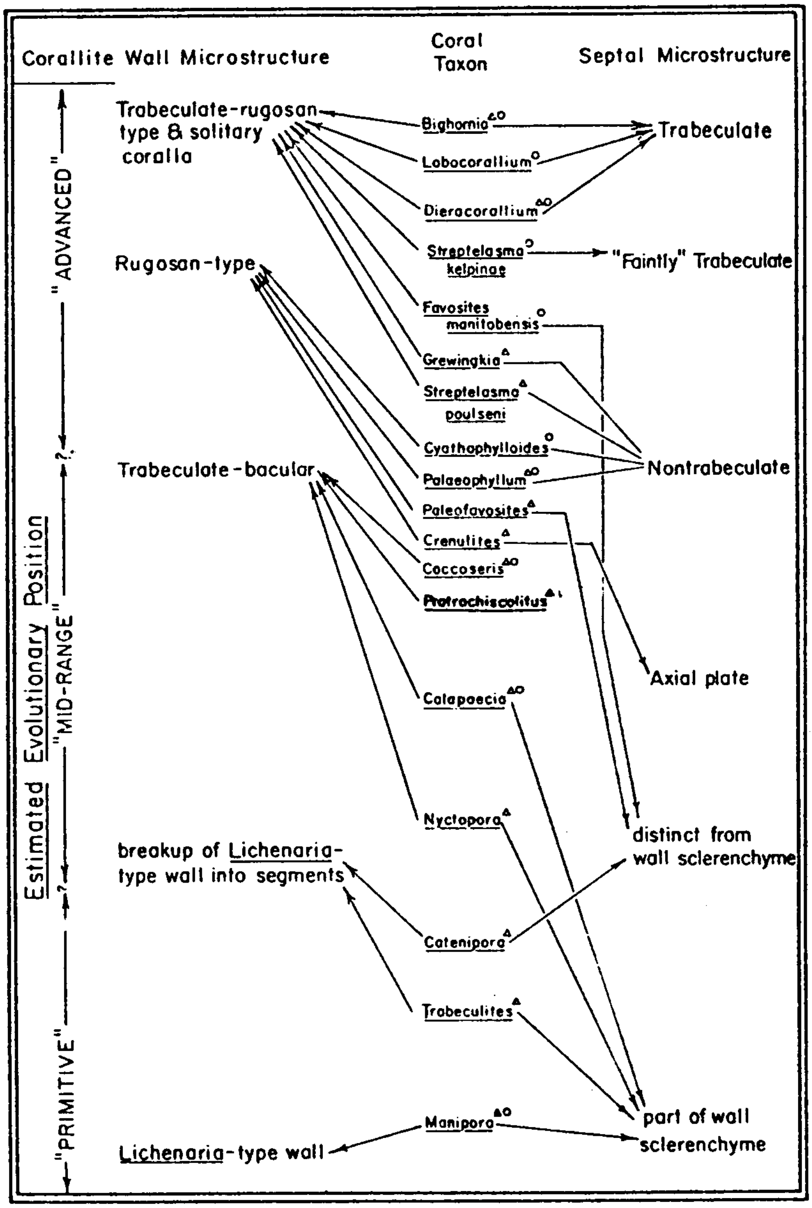


Figure 8-Evolutionary positions of coral genera and species studied. Red River and correlative faunas ( ); Stony Mountain, Stonewall, and correlative faunas (0).

in *Manipora*) or the wall type in which individual trabeculae are present -- as in *Trabeculites, Nyctopora*, and others. Those in the Gunn Member of the Stony Mountain Formation are characterized by the more advanced rugosan wall of *Paleofavosites* and *Favosites*.

Septal microstructure in the solitary corals above and below the paraconformity and the Fort Garry show the same contrast seen in the wall structures. Septal structures in the solitary corals of the Red River (*Streptelasma* and *Grewingkia*) are nontrabeculate. Thin sections through representatives of these genera show no strong evidence of septal trabeculae. All the solitary corals above the paraconformity and the Fort Garry (*Streptelasma, Lobocorallium, Dieracorallium,* and *Bighornia*) are distinctly trabeculate. *Streptelasma* is unique because species on the lower and upper side of the erosional gap are nontrabeculate and trabeculate, respectively.

The quality of septal trabeculation arises within *Streptelasma* (and probably other solitary coral genera) during the span of time represented by the Fort Garry and the paraconformity. This allows separation of the corals of the Red River from those of the Stony Mountain. The progression from nontrabeculate to trabeculate septa is part of a larger trend within all Paleozoic solitary rugosans, where with passing time, septal microstructures became increasingly complex. Kato (1963, p. 588) commented that Silurian rugosans were characterized by more complex "multitrabecular" microstructures than were the Ordovician "unitrabecular" or "nontrabecular" forms.

The interval of time represented by the paraconformity and the Fort Garry is also critical in that it was the time that *Paleofavosites* appeared in the Red River-Stony Mountain Province, and may have also been the time that the genus became distributed outside the region.

PALEONTOLOGY

Order **TABULATA**

Family **SYRINGOPHYLLIDAE**

Subfamily **BILLINGSARIINAE**

Genus ***Trabeculites*** Flower, 1961

Trabeculites manitobensis n. sp.

Figure 9; Plate 1, Figures 1-4

Species Diagnosis.--Corallite walls of trabeculae swollen at center, narrow at lateral margins, forming wall with swollen and constricted portions; septal spines short, 16-25 per corallite, averaging 22, tabulae predominantly complete, crenulate near corallite margin, often upturned at corallite wall, oriented normal to corallite axis, varying in curvature from concave, through planar, to convex; incomplete tabulae occurring in zones parallel to upper surface of corallum, oblique to corallite axis, varying in curvature from concave to convex, tabular spines uncommon, occurring most frequently on oncomplete tabulae; tabular spacing nearly uniform.

Description of material.--The corallites in the massive, cerioid holotype corallum (UND 13561.) are polygonal to sub-polygonal in cross section and are oriented parallel to each other, opening normal to the nearly-planar corallum surface in mature portions of the corallum. The holotype is fragmental, with observed maximum corallum height of 55 mm and an estimated width of at least 90 mm. Lateral margins of the corallum show that lateral corallum expansion occurs by the lateral budding of peripheral polyps, and simultaneous secretion of new corallites over the sediment surface.

Corallite cross section varies from polygonal to

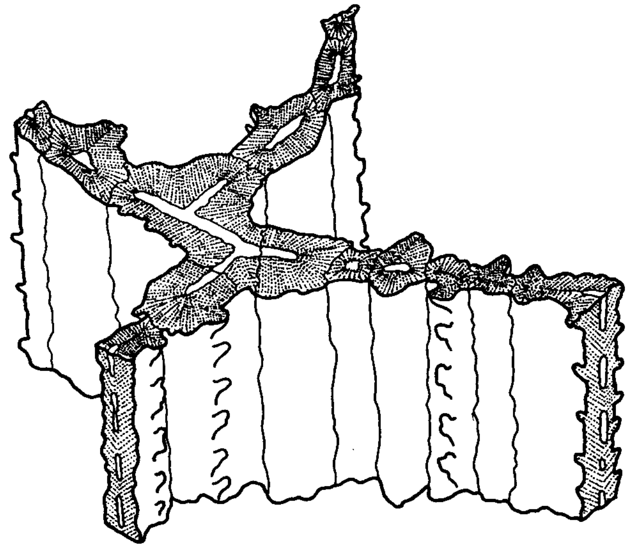


Figure 9-Corallite wall of *Trabeculites manitobensis* n. sp. Fibrous structure of walls and septa shown by patterned stippling. Axial plates and rods shown by clear areas within walls. Approximately X16.

subpolygonal. This variance was controlled by corallite wall thickness at the junctions of three or more adjacent corallites. Thick walls of these junctions result in a rounding of corallite lumina, whereas thin walls result in sharply-defined, polygonal lumina. The corallite wall is composed of longitudinally-directed, parallel, monacanthine trabeculae composed of calcite fibers arranged in cone fashion about a rod or a narrow, thick, axial plate at the center of each trabecula. The resulting conical sets of upwardly-inclined fibers with their bases at the axial plate or rod of each wall trabecula have their apices directed toward the corallum base (Figure 9). Most trabeculae in the holotype are markedly thicker at the trabecular center than at the lateral margins. Measured swollen wall trabeculae in the holotype show that the mean width of the trabecular margin is 0.62 times the width of the trabecular center (Table 4). Fiber orientation in transverse section shows a radial pattern of divergence from both the trabecular axial plates and rods. This forms indistinct but observable inter-trabecular boundaries by the abutting of the peripheral ends of one trabecular set against those of adjacent trabeculae (Figure 9).

Septal spines occur as axial projections of elongate trabecular fibers from the corallite wall. In transverse section, spines show sets of fibers in two orientations (Figure 9) with a central line of divergence marking the septal midline. Septa per corallite range from 16 to 25 and mural pores are absent.

Tabulae show no zonation of spacing, and complete and incomplete forms occur. Complete forms are mostly oriented normal to the corallite axis, and are most commonly planar, or planar with upturned margins. Concave forms are less common, and convex forms are rare. Incomplete tabulae are predominantly oriented oblique to the corallite axis. Convex curvature of these forms is predominant, with concave types being less common. Complete and incomplete tabulae are in zones parallel to the upper corallum surface. The marginal edges of tabulae show a crenulate or undulatory aspect close to the line of attachment to the corallite wall. Short, triangular tabular spines are rare, but are most common on incomplete tabulae. Since complete and incomplete tabulae are segregated into separate zones parelleling the corallum growth surface, tabular spine occurrence is also zoned. Some of these spines rarely show a very faint pattern of calcite fibers arranged in a manner similar to those in the corallite walls.

Type.--Holotype. UND 13561.

Occurrence.--Quarry exposures in the immediate vicinity of Garson, Manitoba, Canada (Appendix A, locality A884).

Etymology.--The species *Trabeculites manitobensis* is named for the province of Manitoba, Canada, from which it was collected.

Discussion.--The corallum described above is assigned to *Trabeculites* due to its possession of features shared by the species *T. kiethae* and *T. maculatus*. *Trabeculites manitobensis* n. sp. shares similar corallite diameters with *T. maculatus*.

Comparison of *T. manitobensis* with three species of *Trabeculites* described by Flower (1961, p. 61-62) results in the designation of a new species named for its occurrence in the southern portion of the province of Manitoba. This designation is based on: (1) trabecular counts per corallite comparable to those in *T. kiethae*, (2) expanded trabeculae wider at their centers than at their margins--similar to those of *T. kiethae*, (3) crenulate tabular peripheral margins similar to *T. kiethae* (Flower, 1961, p. 61, plate 26, figure 7) and (4) corallite diameters comparable to those of *T. maculatus*.

Comparison of wall outline and thickness, trabecular width at center and margin, septal counts, septal length, tabulae type, and tabular spine development of *T. manitobensis* with *T. maculatus* shows the following: *Trabeculites maculatus* has a nearly straight corallite wall, with trabeculae having nearly the same width at the margin and center, whereas the holotype of *T. manitobensis* has a wall with undulatory thicknesses, a result of wall trabeculae being thicker at the center than at the margin.

Septa in *T. maculatus* are fewer and longer than those in *T. manitobensis*. Those in the former species number from 12 to 17 per corallite (hypotype UND 13560.) with an average of 16, whereas in the latter there are 16 to 25 with an average in the holotype of 22. Septa in the former range from 0.14 to 0.48 mm length with an average of 0.28 mm, whereas in the holotype of *T. manitobensis* they range from 0.04 to 0.22 mm length with an average of 0.1 mm. (Table 4).

Tabulae in *T. maculatus* are complete, and segregated into zones of narrow- and widley-spaced types, whereas those in the holotype of *T. manitobensis* are both complete and incomplete, showing no tendency for grouping into zones. Tabular spines on the UND hypotype of *T. maculatus* are relatively abundant, especially on closely-spaced tabulae, whereas the holotype of *T. manitobensis* has tabular spines occurring very infrequently, usually only on incomplete tabulae.

Flower (1961) described the holotype of *T. kiethae* from the Second Value Formation of the Montoya Group, western Texas. *T. maculatus* occurs in Ordovician strata of late Red River or early Richmond age on Akpatok Island in the Canadian Arctic. The holotype of *T. manitobensis* appears to be intermediate between the two other species of *Trabeculites*, both in terms of morphology and geographic location. All occur in Ordovician strata containing faunas similar to the Red River Formation, or in the Red River itself.

Genus *Nyctopora* Nicholson, 1879

Nyctopora fissisepta n. sp.

Figure 10; Plate 1, Figures 5-7; Plate 2, Figure 1

Species Diagnosis.--Lamellar, cerioid coralla with parallel, prismatic corallites normal to the distal corallum surface; diameter range 1.0 to 1.8 mm; corallite wall 0.08 to 0.18 mm thick; septa developed in two orders; major septa long, extending nearly to corallite axis, axial ends often bifurcated near distal tabular surface, with denticulate margins inclined upward; minor septa approximately half as long as major forms. Tabulae all complete; slightly concave to planar, to slightly convex; tabulae oriented normal to corallite axes.

Description of Material.--The holotype corallum (UND 13703.) is a fragment of a larger corallum estimated to be at least 20 cm in diameter. The maximum diameter of the fragment is 7.0 cm and it is 1.5 cm in maximum thickness. The corallum is lamellar with all contained corallites parallel to each other and normal to the distal corallum surface. The corallites are

TABLE 4

Biometrics of holotype of
Trabeculites manitobensis n. sp.

SPECIMEN	HOLOTYPE UND 13561
Corallum form	Massive, cerioid
Corallum width	90 mm. +
Corallum height	55 mm.
Corallite diameter	1.6-2.45 mm. mean=2.0 mm. n=88
Trabeculae per corallite	20-24 mean=22 n=22
Trabecular width at margin	0.1-0.32 mm. mean=0.18 mm. n=131
Trabecular width at center	0.13-0.43 mm. mean=0.29 mm. n=131
Margin width / Center width	0.33-1.0 mean=0.62 n=131
Septa per corallite	16-25 mean=22 n=131
Septal spine length	0.04-0.22 mm. mean=0.1 mm. n=208 mean extension into corallite lumen=0.1 radii
Septal spine spacing (longitudinal)	0.1-0.42 mm. mean=0.19 mm. n=132
Septal spine orientation	34-90 degrees mean=68 deg. n=137
Tabular spacing	0.06-1.06 mm. mean=0.32 mm. n=169

TABLE 5

Biometrics of holotype of
Nyctopora fissisepta n. sp.

SPECIMEN	HOLOTYPE UND 13703
Corallite diameter	0.0-1.8 mm. mean=1.36 mm. n=136
Wall thickness	0.08-0.18 mm. mean=0.12 mm. n=90
Septal spine orientation	26-78 deg. mean=53 deg. n=172
Major septal length (L)	0.14-0.5 mm. mean=0.37 mm. n=80
Major septal extension	0.23-0.71 rad. mean=0.52 rad. n=80 corallite radii=rad.
Minor septal length (l)	0.06-0.22 mm. mean=0.14 mm. n=78
L/l	0.17-0.86 mean=0.37 n=78
Tabular spacing	0.2-0.8 mm. mean=0.46 mm. n=88

cerioid, subpolygonal in transverse profile, rectangular to hexagonal, and 1.0 to 1.8 mm diameter (mean diameter 1.36 mm). The corallite wall exhibits no amalgamation of layering. Wall structure is that of parallel, longitudinal bundles of monacanthine, trabecular rods with constituent fibers set in a series of cone-like patterns. Trabecular fibers are inclined upward from the trabecular center (Figure 10). Longitudinal sections through trabeculae show a vertical series of chevron-like fiber patterns. Rare wall perforations, possibly mural pores, occur in transverse rows between septa and above the distal surfaces of tabulae. Sixteen septal rows occur in each corallite, eight major and eight minor septa. Mean maximum extension of major forms into the lumen is 0.52 times the mean corallite radius, whereas mean minor septal length is 0.37 times that of the major septa (Table 5).

Septal development varies from a minimum wherein both the major and minor forms are of equal length to a maximum where major forms extend more than halfway to the corallite axis. The length of the minor septa remains relatively constant in both developmental stages. Major septal development is variable along the length of a corallite, and from corallite to corallite, and is best developed in regions of the corallum where the tabulae are closely spaced. The major septa at their intersection with the distal tabular surface are often bifurcated at their axial margins (Figure 10), and vary from longitudinal rows of upwardly-inclined, axially-projecting individual spines to blade-like structures with spinose margins.

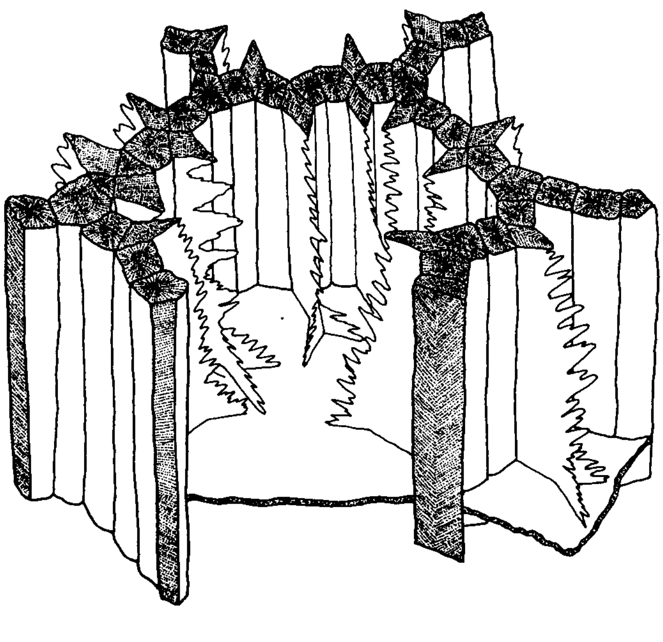


Figure 10-Cut away of a corallite of *Nyctopora fissisepta* n. sp. Fibrous wall and septal structure shown by patterned stippling. Approximately X20.

Tabulae are complete and vary in curvature from slightly concave, through planar, to slightly convex. Tabular spacing is zoned, and varies from 0.2 to 0.8 mm, and parallels the corallum growth surface.

Type.--Holotype, UND No. 13703.

Occurrence.--The holotype corallum was collected from the Selkirk Member of the Red River Formation at the Garson Quarry on the eastern edge of the town of Garson, Manitoba (Appendix A, locality A897).

Etymology.--The presence of axially-bifurcating major septa has not been previously recorded in the genus *Nyctopora*. *Nyctopora fissisepta* n. sp. is named for this septal quality.

Discussion.--Septal spines viewed in tangential sections of corallites appear as series of longitudinal rows of truncated, obliquely-oriented spine tips. The development of individual spines or acanthine septal blades was controlled by the width and degree of merging of obliquely-oriented, fibrous, trabeculae which, in turn, may have been affected by the variations of longitudinal growth rates of the corallites. Growth rates are reflected by tabular spacing, and rapid rates of growth resulted in longitudinally-separated, short septal spines and widely-spaced tabulae. Slower growth rates, reflected by closely-spaced tabulae, resulted in the merging of longitudinally-adjacent septal spines to form a septal blade with denticulate axial ends.

Transverse sections of the holotype, when examined under crossed nicols, showed extensive replacement of the original skeletal material, obliterating much of the fibrous microstructure. Sufficient remnants of the original structure were observed and Figure 10 illustrates the probable skeletal structure. Septal spines appear as skeletal units not in direct fibrous continuity with the monacanthine wall trabeculae. This is based on observations of very faint, poorly-preserved skeletal features and may not be truly representative of the original septal-trabecular relationships.

The only other species of *Nyctopora* with structures at the axial ends of the septa was described by Bassler (1950, p. 263): *Nyctopora* (*?Billingsaria*) *parvituba* (Troedsson) which has eight major septa which extend more than halfway to the corallite axis, and terminate in a thick, rounded structure. *Nyctopora fissisepta* n. sp. may be related to *N.* (*?B.*) *parvituba*, due to both species having structures on the axial septal margins, but *N. fissisepta* differs from the other species by its bifurcate septal margins.

Genus *Manipora* Sinclair, 1955

Manipora garsonensis n. sp.

Figure 11; Plate 2, Figures 2-4

Species Diagnosis.--Small, tabular corallum with nearly all corallites inclined outwardly from point of corallum origin; cateniform ranks short, small lacunae with profile varying from elongate, through kidney shaped, to triangular; approximately half of all corallites located in cateniform ranks; corallites large, approximately 2.3 mm mean diameter, nearly equidimensional in mostly uniserial ranks; polygonal in agglutinative patches, approximately 2.4 mm mean diameter, subrectangular to moniliform outline in convex, lateral walls in ranks; common walls between corallites undulatory, oriented normal to rank direction; septa isolated to undulatory common walls, terminating axially in spines, one to two per wall segment; tabulae commonly complete, incomplete forms rare, orientation predominantly horizontal, curvature varying from slightly concave through planar, to slightly convex, slightly thickened.

Description of Material.--The small cateniform and cerioid holotype (UND 13766.) is approximately four to five times as long and wide, as it is high (Table 6). Corallites at the corallum periphery are inclined outward from the colony point of origin, whereas only those at the corallum center are oriented vertically. Inclined corallites are predominantly oblique to the corallum growth surface, and perpendicular corallites are normal to it. Cateniform ranks are predominantly uniserial, with a mean length of 9.5 mm, enclosing small lacunae averaging 13 mm long by 5 mm wide, which vary in outline from elongate, through kidney-shaped, to triangular. Corallites in the cateniform ranks are large, with a mean length of 2.3 mm, and mean width of 2.4 mm, with a nearly equidimensional form, subrectangular to moniliform in outline with convex lateral walls. Marginal width of the cateniform corallites averages 0.8 times the mean width at their center. Cerioid corallites average 2.4 mm diameter, and are polygonal with hexagonal and pentagonal forms predominating, and comprise 44 percent of all corallites in the holotype. The lateral corallite wall enclosing the lateral portions of the corallum has a mean thickness of 0.12 times the cateniform corallite diameter, retaining a relatively uniform thickness along the lateral surface of the corallite. The two-layered lateral corallite wall has a dark outer layer of coarse, blunt, prismatic crystals oriented parallel to the fibers in the inner wall layer (Figure 11).

Fibers in the inner layer are inclined upward toward the corallite center and are normal to the external surface of the lateral wall when it is viewed in transverse section. The common wall is oriented normal to the direction of the cateniform rank, and its mean width is 0.14 of its length (Table 6). This wall shows an undulatory habit when viewed in transverse section, and commonly has a septum positioned on the convex side of the fold (Figure 11). Longitudinal sections of the common wall show chevron-like orientation of two fiber sets, each set diverging upward and outward from the axial plane formed by the promixal ends of abutting sets of fibers.

Transverse sections of the common wall show fibers oriented normal to the common wall surface and axial plane. Lateral margins of the wall are embedded within the fibrous inner layer of the lateral wall, resulting in a sharp structural boundary between the two wall types separating contrasting sets of oriented fibers (Figure 11). Fiber orientation angles differ between the lateral and common corallite wall.

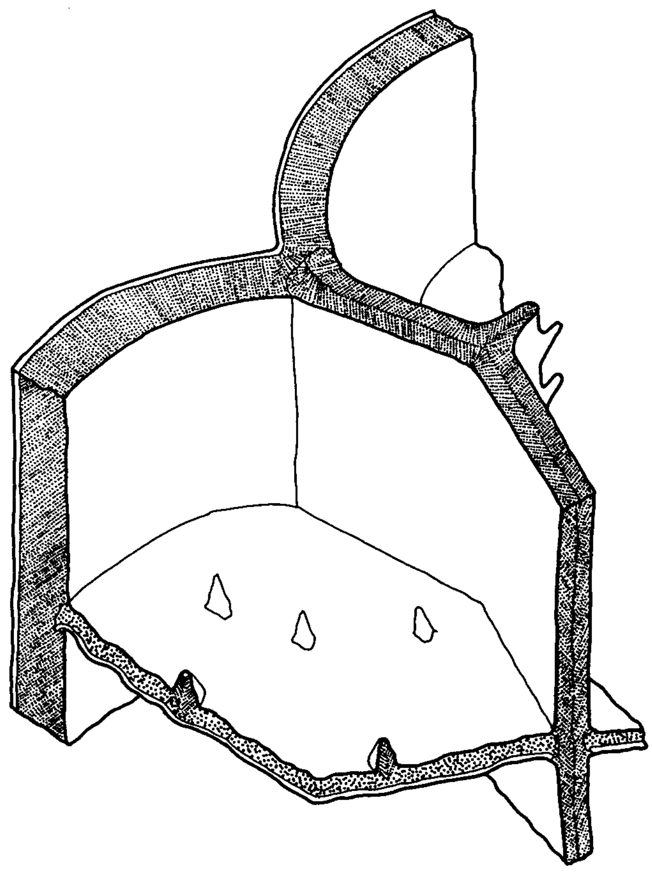


Figure 11-Portions of the lateral and common walls and tabulae of *Manipora garsonensis* n. sp. Fibrous structure of walls, septa, and tabular spines shown by patterned stippling. Tabular stereoplasm shown by patternless stippling. Tabulae and holotheca shown by clear areas. Approximately X12.

TABLE 6

Biometrics of Manipora garsonensis n. sp., and Manipora bighornensis n. sp.

SPECIES	*M. garsonensis*	*M. bighornensis*
SPECIMEN	**HOLOTYPE UND 13766**	**HOLOTYPE UND 13768**
Corallum width, length	120x90	fragmental
Corallum height	25 mm.	fragmental
Cateniform rank length	5-15 mm. mean=9.5 n=28	
Lacuna width	3-8 mm. mean=4.9 mm. n=11	
Lacuna length	8-23 mm. mean=13 mm. n=11	
Lacuna width/length	0.19-0.66 mean=0.4 n=11	
Corallite length in cateniform rank	1.9-2.8 mm. mean=2.3 mm. n=44	
Corallite width in cateniform rank	2.05-2.7 mm. mean=2.36 n=35	
Corallite width/length in cateniform rank	0.85-1.2 mean=1.0 n=35	
Corallite diameter in cerioid portion	2.0-2.65 mm. mean=2.44 mm. n=17	1.45-2.3 mm. mean=1.79 mm. n=47
Cateniform corallite width at lateral margin (wm)	1.6-2.3 mm. mean=1.9 mm. n=34	
Cateniform corallite width at center (wc)	2.05-2.7 mm. mean=2.36 mm. n=34	
wm/wc	0.66-0.93 mean=2.36 n=34	
Common wall length (perpendicular to rank direction)	1.2 to 1.84 mm. mean=1.57 mm. n=25	

TABLE 6
Continued

SPECIES	*M. garsonensis*	*M. bighornensis*
SPECIMEN	HOLOTYPE UND 13766	HOLOTYPE UND 13768
Common wall width (parallel to rank direction	0.18-0.35 mm. mean=0.23 mm. n=25	0.06-0.2 mm. mean=0.16 mm. n=24
Fiber orientation in lateral corallite walls	50-78 deg. mean=63 deg. n=27	53-77 deg. mean=66 deg. n=4
Fiber orientation in common corallite walls	32-66 deg. mean=46 deg. n=54	41-68 deg. mean=54 deg. n=30
Longitudinal septal spine spacing	0.24-0.58 mm. mean=0.45 mm. n=12	
Septal spines per intertabular space	1 to 2	
Septal spine length	0.1-0.3 mm. mean=0.17 n=25	
Tabular thickness	0.04-0.18 mm. mean=0.07 mm. n=106	0.04-0.08 mm. mean=0.05 mm. n=29
Tabular spacing	0.25-0.92 mm. mean=0.63 mm. n=106	0.3-1.1 mm. mean=0.66 mm. n=29

Fibers in the common wall have a mean orientation of 63 degrees from the corallite axis, whereas those in the lateral wall have a mean orientation of 46 degrees. Mural pores are rare, and appear to be restricted to cerioid corallites within the agglutinative corallite patches.

Septa are not present in the inner surface of the lateral corallite wall. Only an occasional cone-shaped protrusion, laterally continuous with the fibrous inner layer, is present. Septa with spines on their axial margins occur only on the common wall between corallites. The number of septa per corallite is controlled by whether the corallite is in a rank or in a patch. The location determines the number of polygonal sides formed by the common walls, single common wall sides have one or two septa per wall. The cateniform corallites therefore, have one to four septa per corallite, and the cerioid forms have more, up tonine in a pentagonal corallite. Mean longitudinal spine spacing is 0.45 mm, with one or two spines present in each intertabular space (Table 6), and mean spine length is 0.07 times the mean cerioid corallite diameter.

Tabulae are predominantly complete, and incomplete types are rare. Orientation is predominantly normal to the corallite axes, with tabular curvature varying from slightly concave, through predominantly planar, to slightly convex. Tabular thickness varies from 0.04 to 0.15 mm, with a mean of 0.07 mm. No clear structural delineation between the tabula and the thickening stereoplasm was seen, nor can structural features of either one be readily observed. The thickened tabular plate appears to be granular under high magnification. Broad tabular spines embedded in the distal portion of the tabular material (Figure 11) appear to have a microstructure unlike that of the tabulae. Very faint lineations on the surface of and within the spines indicate a fibrous microstructure, similar to that of the common corallite wall. Tabular placement within corallites is continuous, occurring at similar levels within adjacent corallites.

Type.--Holotype, UND 13766.

Occurrence.--The holotype of *Manipora garsonensis* came from a bedding-plane exposure of the Selkirk Member of the Red River Formation 0.3 meters (0.9 ft) below the top of the exposed section east of Garson, Manitoba, (Appendix A, locality A899).

Etymology.--The species is named for the village of Garson, Manitoba, near the quarry from which the holotype was collected.

Discussion.--The combination of large corallites and common corallite walls normal to the cateniform rank direction preclude the assignment of the holotype to a previously-described species of *Manipora*. *Manipora trapezoidalis* Flower is the only species having corallites of sufficient diameter, but the occurrence of the common corallite wall oblique to the rank direction in this species prevents assignment of the holotype to it. The diagnostic species characters within provide no corresponding match for those seen in the holotype. As a result, a new species *Manipora garsonensis* is designated.

Agglutinative patches in the holotype occur most frequently as short, alternate biserial groupings of cerioid corallites formed by the merging of four or more uniserial, (cateniform) ranks. No agglutinative patch more than two corallites in width was present in the holotype.

Long, narrow common corallite walls within the cerioid and cateniform portions of the corallum contain fibers in chevron-like sets (Figure 11). No structurally- or crystallographically-distinct axial plate, characteristic of more advanced coral genera is present. Mean fiber orientation in the lateral and common corallite walls shows an interesting contrast. Lateral wall fibers are oriented at a mean of 63 degrees, whereas those in the common wall are oriented at a mean of 46 degrees from the corallite axis. This difference in orientation between sets of wall fiber types reflects a significant variation in type and mode of skeletal deposition of the two wall types, peculiar to the cateniform genera *Catenipora* and *Manipora*.

Common walls of both genera were deposited by interpolypid calicoblast layers underlying the interconnecting tissue. In *Manipora*, no discrete centers of wall deposition were present, and sites of common wall construction were distributed uniformly along the length of the layer. In *Catenipora*, common wall construction took place at discrete sites within the calicoblast layer, resulting in a common wall composed of one or more trabeculae, as can be observed in *C. rubra* and *C. robusta*.

Differences in common wall microstructure between the two genera lend support to Sinclair's (1955, p. 97) statement of affinity of *Manipora* to *Saffordophyllum*. Both these genera have similar common walls, which are crenulate in transverse section, and are non-trabecular with no axial plate.

Tabulae in the holotype of *M. garsonensis* are of variable thickness (Table 6), and no striking contrast occurs between the tabular plate and the overlying stereoplasm. Only a thin, clear layer was observed between the tabular plate and the overlying tabular stereoplasm. The overlying layer of stereoplasm is essentially structureless as is the clear layer, possibly due to recrystallization. The former microstructure of tabulae and stereome is shown by the presence of secondary needles and prisms of calcite, on the upper and lower tabular surfaces, oriented with their long axes normal to the tabular surface. Orientation of the needles and prisms may be due to secondary crystallization in crystallographic continuity with the original skeletal fibers.

Spines embedded in the tabular stereoplasm occur at discrete, continuous levels within adjacent corallites. Very faint lineations within some spines hint that spine microstructure is divergent, with spines radiating from a central axis (Figure 11). This structure contrasts with the vertical fibers of the tabulae and resembles the microstructure of the septal spines.

Tabulae thickened by stereome do not appear to be related to occurrences of the tabular spines. The spines are on tabulae with and without stereome. Thickened tabulae are not related to tabular spacing, but are present where tabulae are both closely and widely spaced. Tabular spacing did not seem to exericse any control over the placement of tabular spines, since they are present throughout the range of tabular spacing. Therefore it appears that rates of upward growth of the corallum did not control spine placement, nor did it control the volume of stereome deposited on the tabulae.

Manipora bighornensis n. sp.

Plate 2, Figures 5, 6; Plate 3, Figures 1, 2

Diagnosis.--Small corallum composed of interconnected patches of cerioid corallites, with interconnection by narrow extension of cerioid patches with corallites in biserial or triserial arrangement; no cateniform corallites; corallites predominantly polygonal, mean diameter 1.8 mm, none to 14 septal ridges per corallite where developed; tabulae complete, normal to corallite axes, predominantly planar; no zonation of tabular spacing.

Description of Material.--The small, fragmental holotype has a higher degree of amalgamation than that of cateniform species of *Manipora*. Corallites are arranged in agglutinative patches interconnected by patches of corallites in biserial or triserial arrangement. All corallites are cerioid, with those on the corallum periphery bounded on their peripheral side by a lateral wall continuous around patches of cerioid corallites. Corallites average 1.8 mm diameter, range from 1.4 to 2.3 mm, and have a polygonal cross section. Those corallites on the corallum periphery commonly have their polygonal outline modified by a convex lateral wall.

The common wall between corallites is transversely crenulate, with septal spines projecting from convex crenulate surfaces into the corallite lumen. The common wall has two sets of fibers, each sloping toward the wall's axial plane where the fibers in one set abut against those in the other. Mean common wall thickness is 0.16 mm, with a mean fiber orientation of 54 degrees to the corallite axis (Table 6). Terminal ends of the common walls are embedded in the schlerenchymal layer of the lateral wall bordering the exterior of the corallum on all but the growth surface. The lateral wall averages 0.17 mm thickness with a mean fiber orientation of 66 degrees from the plane of the wall. No holothecal layer is present.

Septal spines are poorly developed and occur sporadically on the convex portion of the crenulations in the wall, forming a longitudinal series of low septal ridges. Two or three crenulations commonly occur on each segment of the common wall. The number of ridges per corallite is controlled by the number of sides on the polygonal corallite. Tabulae are complete, transverse to the corallite axes, and are predominantly planar. There is no clear-cut segregation of tabulae into zones of closely- and widely-spaced forms. Tabular spacing ranges from 0.3 to 1.1 mm with a mean of 0.7 mm.

The corallum exterior is covered by an encrusting corallum composed of fibrous, monacanthine trabecular rods oriented normal to the surface of the host holotype. The encrusting form has no well-preserved distal surface, but seems to be of the genus *Coccoseris* Eichwald.

Type.--Holotype UND 13768.

Occurrence.--The small, fragmental holotype occurred as a float specimen from the Hunt Mountain beds from locality A542 on the western flank of the Bighorn Mountains in northern Wyoming (Appendix A).

Etymology.--The species *M. bighornensis* is named for the Bighorn Mountains, from which the holotype corallum was collected.

Discussion.--The holotype presents a problem of generic placement. As summarized by Flower (1961, p. 45) the genus *Manipora* Sinclair is characterized by:

1. Cateniform ranks and cerioid patches,

2. Crenulate common walls with no axial plate set into the outer wall,

3. Septal ridges formed by longitudinal, convex, common wall flexures, and

4. Plane and transverse tabulae.

The holotype of *M. bighornensis* corresponds to the generic description of *Manipora* with the exception of the overall corallum form. No cateniform ranks occur, and any observed interconnection between cerioid patches was accomplished by elongate cerioid extensions of the patches. The holotype was placed in *Manipora* Sinclair since it has the internal features of the genus. It is regarded in this study as an example of a genus showing a genetic ability for the corallum to assume an increasingly-pure cerioid arrangement within strung-out agglutinative patches. The possible genetic response this colony of *Manipora* possessed may be the sole evolutionary advancement over the more cateniform species of *Manipora* occurring in the Red River Formation.

Lieth (1944, plate 42, figures 1, 2) illustrated a halysitoid coral later assigned to *Manipora amicarum* by Sinclair (1955). Lieth's illustrations show this species also has well-developed, aggluntinative patches of cerioid corallites interconnected by cateniform ranks in which corallites are arranged in uniserial, parallel biserial, and alternate biserial fashion. No such elongate ranks occur in the holotype of *M. bighornensis*, but this may be due to a lack of sufficient corallum material as well as due to genetic restriction of corallum form. The holotype occurred higher in the stratigraphic section and existed later in time than did the Red River species of *Manipora*, and may represent an evolutionary advancement over the earlier forms. This is based on *Manipora*-like characters superimposed on a corallum form in which all corallites are cerioid - indicating a greater degree of intercorallite and interpolyp continuity than in all earlier forms of the genus. Whether this greater degree of communication represents an evolutionary advancement and is a genetically-controlled trait, or represents an environmentally-influenced response within genetically-imposed limits of polymorphism cannot be determined. If genetic controls were responsible, the species represents an evolutionary advancement.

The possibility of environmental or other external controls affecting the corallum form is raised by the encrusting *Coccoseris* on the holotype exterior. Insufficient material is available to determine whether the encrusting form is an exocommensal or parasitic organism restricting lateral growth of the host corallum, or if it simply utilized an already dead colonial corallum for a substrate.

Comparison of the holotype with other species of *Manipora* shows that it is more similar to *M. amicarum* with respect to corallite diameter and wall thickness than to other species. One significant contrast to *M. amicarum*, other than corallum form, is the poor development of septal spines and the number of septal ridges per corallite. Spines in the holotype are indeterminable as to longitudinal spacing and spine length because of their rarity and the small amount of material available for study.

Despite the lack of greater amounts of material for study, the well-preserved portions in thin sections yield sufficient data for comparison to other species of *Manipora*. The unique corallum form and size, stratigraphic occurrence, and unique interior morphology warrant designation of a new species, *M. bighornensis*. Flower (1961, p. 45) stated that the genus is restricted to faunas that are equivalent in age to the Red River Formation, but the occurrence in the Hunt Mountain beds in Wyoming extends the age and stratigraphic range of the genus in North America.

Unique, too, is the occurrence of an encrusting form of *Coccoseris* Eichwald on the holotype. It was previously reported twice in Ordovician strata of North America; once by Flower (1961. p. 56) from the Second Value Formation of the Montoya Group, and once in this study from the Selkirk Member of the Red River Formation in southern Manitoba. This occurrence shows evidence of continuity of the genus between New Mexico and Wyoming, and Wyoming and southern Manitoba.

Family **FAVOSITIDAE**

Subfamily **FAVOSITINAE**

Genus ***Angopora*** Jones, 1936

Angopora wyomingensis n. sp.

Plate 3, Figures 3-5

Diagnosis.--Very small, depressed hemispherical corallum with very small, subpolygonal corallites radiating from central portion of corallum, orientation varying from perpendicular to 45 degrees to sediment surface; corallite walls moderately thick in relation to corallite diameter, thickest where tabulae closely spaced; mural pores only in corallite corners, walls crenulate in corallite corners; wall microstructures varying from rugosan to fan-like, trabecular extensions of the axial plate; septa lamellar where tabulae most closely packed, and absent where tabulae widely spaced, with spines as intermediate stages; twelve longitudinal rows of septal structures per corallite; tabulae complete and normal to corallite axis, with curvature varying from gently concave to convex, commonly pierced by or draped over septal spines; well-defined zones of very closely- and widely-spaced tabulae.

Description of Material.--The cerioid holotype corallum is very small and fragmental. Length is indeterminable. Corallum width appears to be no more than 20 mm, and height is 9 mm. Corallites are very small, approximately 1 mm mean diameter, with a range of 0.7 to 1.2 mm. Corallites are subpolygonal with straight to gently-curved walls, and angular to rounded corallite wall corners, respectively. Mural pores are 0.13 mm mean diameter, and are restricted to the corallite wall corners, and have a mean longitudinal spacing of 0.32 mm. (Table 7). Corallite walls near the mural pores are crenulate with a mean maximum crenulation amplitude of about 0.1 times the mean corallite diameter and a mean crenulation periodicity of about 0.6 mm. The wall varies from thick in corallite regions where tabulae are closely spaced to thin where they are widely spaced (Figure 12).

Septal structures vary from continuous septal lamellae formed by the longitudinally-merged septal spines, to individual spines. Maximum longitudinal packing of spines occurs in corallite regions where tabulae are most closely spaced. Twelve rows of spines and septa per corallite have a mean axial extension of about 0.7 times the corallite radius, whereas extension of the spines varies from 0.4 to 1.0 times the mean corallite radius. Septal structures in the regions of widely-spaced tabulae are separate, widely-spaced spines with approximately the same length as septa in the regions of closely-spaced tabulae.

Schlerenchymal fibers in the corallite wall are inclined upward and away from a uniformly-thin axial plate in regions of widely-spaced tabulae. In regions of closely-spaced tabulae, the layered aspect of the wall deteriorates to such an extent that the fibrous schleren-

TABLE 7

Biometrics of holotype of *Angopora wyomingensis* n. sp.

SPECIMEN	HOLOTYPE UND 13754
Corallum form	Fragmental, cerioid, flattened hemispherical
Corallum width	20 mm.
Corallum height	9 mm.
Corallite diameter	0.7-1.23 mm. mean=0.97 mm. n=34
Mural pore diameter	0.08-0.18 mm. mean=0.13 mm. n=12
Mural pore spacing	0.2-0.58 mm. mean=0.32 mm. n=7
Corallite wall thickness	0.06-0.18 mm. mean=0.12 mm. n=20
Crenulation length	0.44-0.75 mm. mean=0.57 mm. n=5
Crenulation amplitude	0.08-0.1 mm. mean=0.09 mm. (0.09 x corallite dia.)
Septal spines per corallite	12 n=3 corallites
Septal spine length	0.22-0.5 mm. mean=0.38 mm. n=11
Septal spine extension (rad.=corallite radius)	0.4-0.96 rad. mean=0.69 rad. n=11
Wall fiber orientation (with respect to corallite axis)	35-70 deg. mean=55 deg. n=14
Closely spaced tabulae	0.08-0.26 mm. mean=0.15 mm. n=28
Widely spaced tabulae n=14	0.26-1.0 mm. mean=0.45 mm.

TABLE 8

Biometrics of the holotype of *Favosites manitobensis* n. sp.

SPECIMEN	HOLOTYPE UND 13757
Corallum diameter	28 cm. (estimated)
Corallum height	7+ cm.
Corallite diameter	1.8-3.8 mm. mean=2.78 mm. n=17
Mural pore diameter in corner of corallite wall	0.12-0.2 mm. mean=0.15 mm. n=17
Mural pore columns per corallite wall	2 to 4
Mural pore spacing at central region of corallite wall	0.3-1.4 mm. mean=0.74 mm. n=41
Lateral spacing of mural pore columns	0.4-1.1 mm. mean=0.67 mm. n=22
Corallite wall thickness	0.16-0.3 mm. mean=0.22 mm. n=26
Minimum axial plate thickness	0.02 mm.
Wall fiber orientation (with respect to corallite axis)	27-76 deg. mean=52 deg. n=32
Septal ridges per corallite	9 to 20 mean=14 n=10
Closely spaced tabulae	0.2-1.22 mm. mean=0.59 mm. n=25
Widely spaced tabulae	0.35-1.2 mm. mean=0.86 n=38

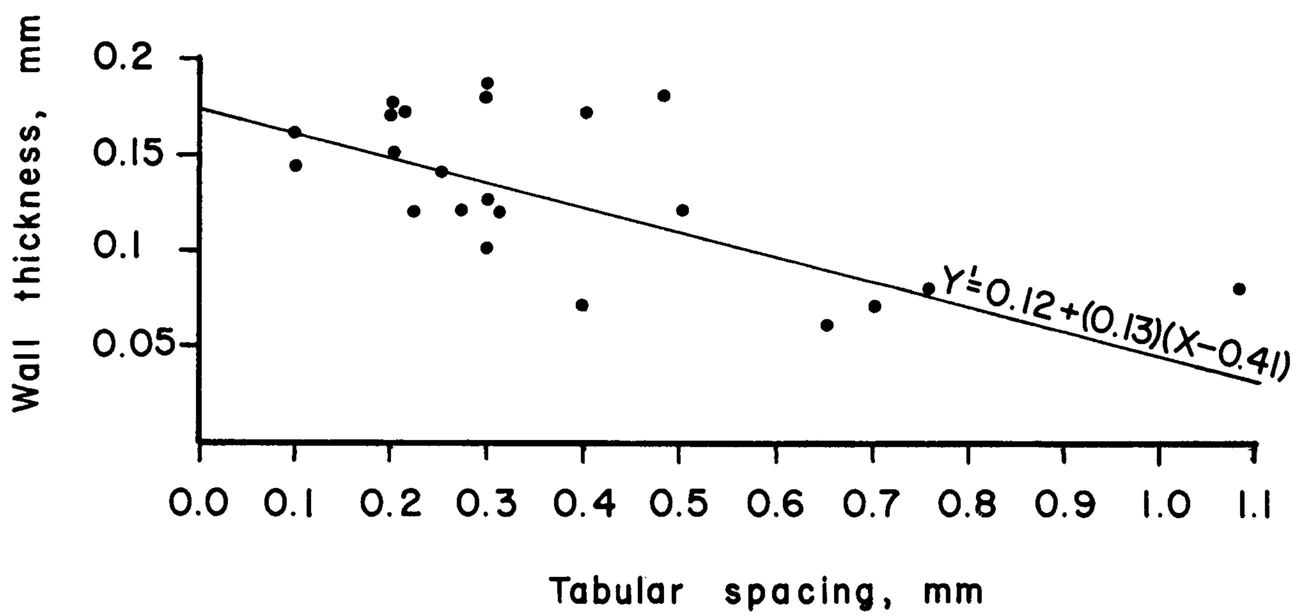


Figure 12-Scatter diagram and regression line for wall thickness plotted against tabular spacing for *Angopora wyomingensis* n. sp.

chyme appears to have been displaced longitudinally and laterally by fibrous, fan-like, trabecular extensions of the axial plate.

Tabulae are predominantly complete and normal to the corallite axes. Those in regions of well-developed septal spines are commonly pierced by or draped over these spinose projections. Tabulae are segregated into well-defined zones of closely-spaced tabulae with a spacing range of 0.08 to 0.26 mm, with a mean of 0.15 mm. Widely-spaced tabulae vary from 0.25 to 1.0 mm, with a mean of 0.45 mm. Tabulae in the former zone vary in curvature from concave, through planar, to gently convex, whereas those in the latter zone are planar or concave.

Type.--Holotype, UND 13754.

Occurrence.--The very small holotype came from the uppermost shale bed of the Hunt Mountain beds in the upper portion of the Bighorn Formation (Appendix A, locality A549), on the western side of the Bighorn Range.

Etymology.--The species is named for the state of Wyoming, U.S.A., from which it was collected.

Discussion.--The holotype resembles a very small corallite version of *Paleofavosites* with very long septal spines. Two generic assignments were considered: (1) *Angopora* Jones, resembles *Favosites* in that it has discontinuous lamellar septa that break up into spines (Jones, 1936, p. 18). (2) Assignment to *Paleofavosites* relies upon the occurrence of corner-mounted mural pores and a rugosan-type corallite wall. The species is placed in *Angopora* due to the presence of laterally-discontinuous septal lamellae in regions of closely-packed tabulae. Generic descriptions of *Paleofavosites* based on morphological descriptions (Hill, 1959; Flower, 1961) indicate that septa, when present, are discrete spines. Teichert (1937) and Stearn (1956) both described *Paleofavosites poulseni*, the species of *Paleofavosites* closest to *Angopora*, as having septa present as separate spines.

The presence of a three-layered, rugosan-type corallite wall in the holotypes resolves Flower's (1961, p. 71) uncertainty on the character of wall and septal microstructures in the genus *Angopora*. Stearn's (1956) description stated that the holotype and paratypes of *A. manitobensis* are dolomitized and no microstructural data were available, nor does Jones (1936) mention wall structure. The rugosan-type wall divorces *Angopora* from the *Saffordophyllum* lineage as was discussed by Flower (1961, p. 73) in which only a two-layered, *Lichenaria*-type wall with an axial plane occurs, instead of a structurally-distinct axial plate. Therefore, the *Angopora* lineage, exemplified by the wall microstructure of *A. wyomingensis* n. sp. appears to be most closely related to *Paleofavosites*.

In the holotype, the occurrence of lamellar septal structures occurs in corallum regions of closely-spaced tabulae, possibly reflecting regions where minimum rates of upward growth occurred. In these regions, lamellar septa may have resulted from the close, longitudinal packing of septal spines. Emplacement of each spine in a row, directly over the previous spine, produced a septal lamella.

Wall structures in the holotype are similar to those in *Favosites manitobensis* n. sp. (Figure 13) in which the axial plate layer has expanded laterally to displace the fibrous schlerenchymal layer within portions of the corallite wall. As is also observed in thin sections of *F. manitobensis* under crossed nicols, rotation of the microscope stage with the longitudinal wall thin sections of the holotype of *Angopora wyomingensis* n. sp. shows no distinct break in rotary extinction patterns. A narrow fan of extinction, reflecting a trabeculate wall structure, can be traced from the position of the axial plate to the position of the former schlerenchymal layer. There is no clear-cut textural break between the axial plate and its expanded lateral replacement of the schlerenchyme. Wall portions not showing displacement of the schlerenchymal layer continue to exhibit a sharp boundary between that layer and the axial plate.

The same question is posed for the holotype of *A. wyomingensis* n. sp. as is considered for *Favosites manitobensis* below. Does the expanded, fan-like fibrous structure represent a true lateral expansion of axial plate secretory centers to form trabecular bundles of fibers? The presence of a distinct textural boundary between the normal rugosan axial plate and schlerenchymal layers, and its lack within the trabeculate wall type with apparent crystallographic continuity across the wall edge indicates that the axial plate secretory centers did expand. The holotype of *A. wyomingensis* is one of two examples of colonial corals studied which has a rugosan wall exhibiting these particular structures. The isolated occurrence of the trabecular walls in this holotype and in no other corals from the same stratigraphic level and locality imply that it: (1) reflects a variable level of physiology wherein the entire wall is composed of a trabecular axial plate homologue, or (2) it may be a genetic character of this species.

This holotype appears to be from the lowest stratigraphic occurrence of the genus *Angopora*. Due to its stratigraphic restriction to a Gunn Member correlative, its separation from previously-described North American examples of the genus and its unique morphology, it is designated *A. wyomingensis* n. sp. It is similar to forms of *Angopora* found in the Gunton Member of the Stony Mountain Formation and the Stonewall Formation in southern Manitoba.

Genus ***Favosites*** Lamarck, 1816

Favosites manitobensis n. sp.

Figure 13; Plate 3, Figures 6-8; Plate 4, Figures 1-3

Diagnosis.--Large hemispherical corallum with corallites radiating from a center of corallum basal surface; moderately large, polygonal corallites approximately 2.8 mm mean diameter, attaining diameters of 3.8 mm; mural pores in corallite corners and walls, with two to four pore rows per wall; wall segments commonly slightly and transversely crenulate, with axial plate commonly expanded into fan-like trabecular structures; walls thin with variable number of septal ridges formed by wall crenulations, commonly capped with spines; tabulae all complete, normal to corallite axis, and crenulate with curvature varying from slightly concave, through plane, to slightly convex; tabular spacing zonation poorly defined.

Description of material.--The original cerioid corallum of which the holotype is a fragment, was large, estimated to be approximately 30 cm in diameter, with a height of more than 7 cm. The original corallum shape was hemispherical, with a nearly planar basal surface. Corallites radiate laterally and upwardly from the colony point of origin. Corallites are moderately large, ranging in diameter from 1.8 to 3.8 mm with a mean of 2.8 mm. In transverse section, corallites are polygonal with transversely crenulate walls and angular or rounded corallite wall corners.

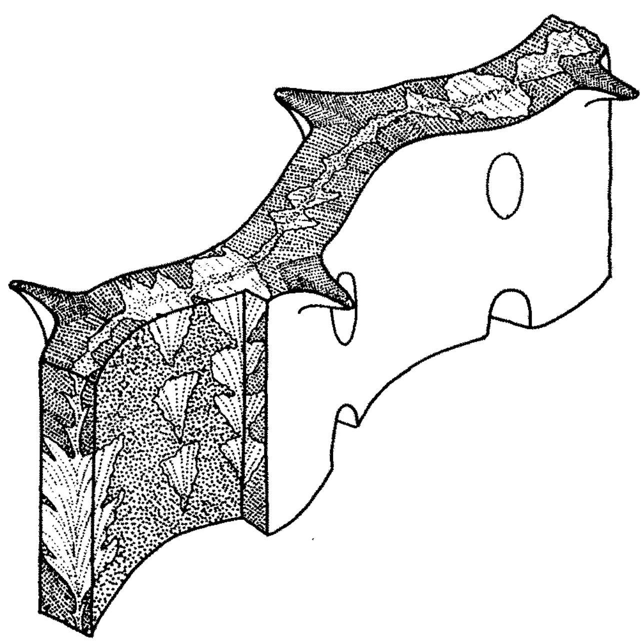


Figure 13-Portion of corallite wall of *Favosites manitobensis* n. sp. Part of wall removed to show interior adjacent to axial plate. Fibrous sclerenchyme shown by dense stippling. Spines are shown by lined, patterned stippling. Axial plate and trabeculae are shown by light, patterned stippling. Crenulation and wall thicknesses are exaggerated. Approximately X23.

Wall portions are not crenulate in the region of the corners. Circular mural pores are located in both the corners and on the walls. Those in the corners average 0.15 mm diameter and have a mean longitudinal spacing of 0.16 mm (Table 8). Pores in the walls have a mean diameter of 0.16 mm and occur in two or four longitudinal rows per corallite wall (Figure 14). The number of rows apparently were controlled by width of the corallite wall. Pore arrangements within the wall rows are biserial or in transverse rows in walls with two rows. Walls with three or four rows have all the pores arranged in transverse rows. Corallites on the basal surface of the corallum, close to the point of origin, have no pores on the basal corners and walls.

Corallite walls are commonly transversely crenulate, with the crenulation varying from absent to slight. This reflects development of a longitudinal wall ridge, with a row of septal spines along the convex portions. Nine to 20 ridges per corallite are present, with the highest counts occurring in the largest corallites. Walls vary from 0.16 to 0.3 mm in thickness, but thickness does not appear to be related to tabular spacing. An axial plate is sporadically developed, varying from a continuous, uniform structure of 0.02 mm minimum thickness to an expanded, finely-fibrous trabecula which occupies the entire thickness of the wall. The former developmental stage is flanked by fibrous schlerenchymal layers in the typical rugosan-type wall, with the schlerenchymal fibers oriented normal to the axial plate when seen in transverse section, and inclined upward and away from the plate in longitudinal section. The trabeculate stage occurs where the axial plate is expanded into a longitudinal series of fan-shaped fiber sets originating from the position of the axial plate. These fan-shaped sets completely displace the sclerenchymal layers of the rugosan-type wall (Figure 13).

Tabulae are all complete and normal to the corallite axis. Most are planar, or very slightly concave or convex. All appear to be crenulate at their periphery, and are grouped into poorly-defined zones of closely- and widely-spaced types which parallel the corallum growth surface.

Type.--Holotype, UND 13757.

Occurrence.--The holotype was collected from the contact of the Gunn and Penitentiary Members of the Stony Mountain Formation near Stony Mountain, Manitoba (Appendix A, locality A841).

Etymology.--The species *Favosites manitobensis* is named for the province of Manitoba, Canada from which the holotype was collected.

Discussion.--Mural pores in the corallite walls seem to be twice to four times as abundant as at the corallite wall corners. The form with which *F. manitobensis* might be most readily confused is *P. okulitchi*, from which the former differs by having the wall pores predominating, transversely-crenulate corallite walls with trabeculae, and crenulate tabular margins. *Paleofavosites okulitchi* has corallites of comparable diameter, but lacks the transversely-crenulate corallite walls. *P. okulitchi* has no more than two rows of pores in the walls.

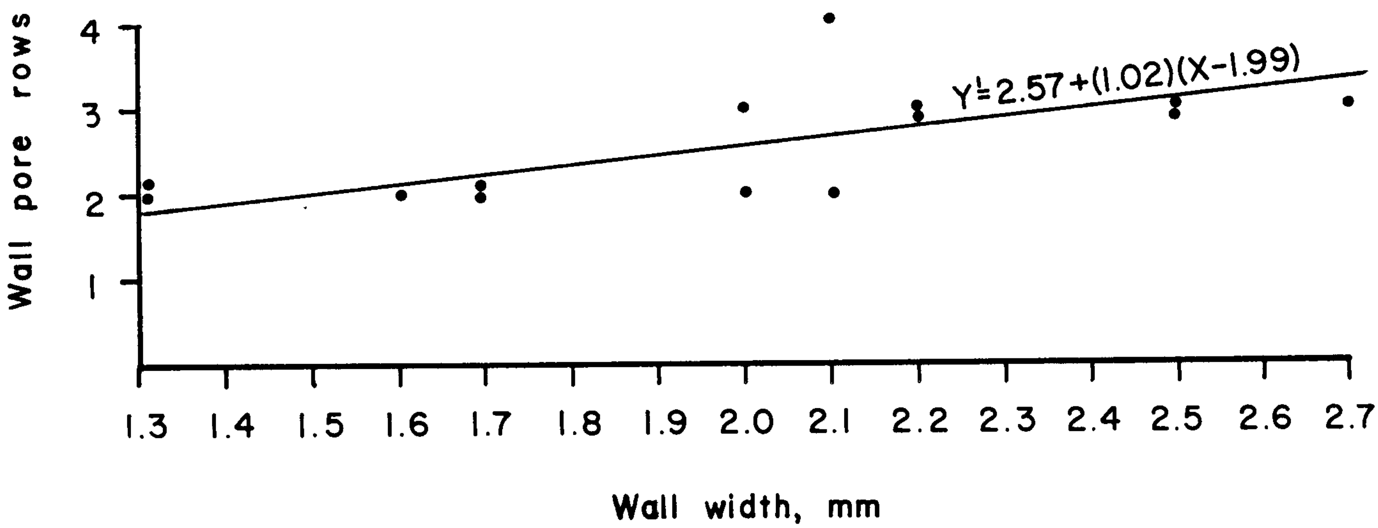


Figure 14-Scatter diagram and regression line for number of mural pore rows in the corallite walls plotted against wall width for *Favosites manitobensis* n. sp.

The number of pore rows per corallite wall was controlled by the width of the corallite wall (Figure 14), *i.e.*, more pore rows are present on wide walls than on narrow ones. Spacing between pore rows averages 0.74 mm (Table 8). Within the holotype, increasing corallite diameter led to an increasing number of pore rows, reflecting a greater capacity for interpolypoid communication at the calicinal level than *P. okulitchi*, which had similar size corallites. The colony's physiological processes required that a mural pore be formed to provide interpolyp communication at intervals around the perimeter of the corallite wall regardless of polyp and corallite diameter. This indicates increasing intercalicinal communication reflecting a higher metabolic rate or stage of evolution.

The trabeculate character of the axial plate or its homologue is a phenomenon not previously recorded in the favositid corals or in any Ordovician corals, other than *Favosites manitobensis* n. sp., and *Angopora wyomingensis* n. sp., both of which have the modified rugosan-type wall. Little, if any, differentiation can be made under crossed nicols between the axial plate and its trabeculate counterpart. Rotation of the longitudinal wall section under crossed nicols shows simultaneous rotary extinction of the thin axial plate along the corallite wall through approximately 50 degrees of stage rotation. This indicates that the axial plate is well preserved and is composed of calcite fibers with their c-axes oriented parallel or subparallel to the longitudinal wall direction (Figure 13). The apparent widening of the axial plate into a fan-like trabeculate structure which occupies the entire thickness of the wall section shows these fibers radiating out into these structures. Transverse sections of the axial plate under crossed nichols show no extinction as the stage is turned, indicating that the fiber c-axes are oriented in the axis direction of each fiber. This fan-like structure may be due to wall construction by secretory sites normally responsible for axial plate construction.

The axial plate between the fibrous sclerenchymal layers also exhibits the characteristic of rotary extinction, indicating the presence of fibrous material. Tracing of the axial plate upward to where it flares out to form the trabeculate structure shows very little contrast between the central portion of the wall and the flanking portions. The faint contrast appears to be due more to the divergence of uniformly-textured fibers than to contrasting fiber size.

The presence of original or replicated skeletal material appears to be consistent with the textural similarity within the trabecular structures. This indicates uniform crystal size and suggests that the fine, radiating fibers and the fibrous axial plate were secreted by the same or very similar depositional site(s), replacing those sites of sclerenchymal deposition flanking the site of axial plate construction. If this was the mechanism that functioned, no explanation accounts for its substitution for the more common rugosan-type wall. This trabeculate wall structure does not typify those Ordovician or later compound corallite walls. Swann's (1947) study of Devonian favositid wall structures revealed a rugosan-type wall. This showed that the trabeculate wall structure either (1) did not survive until Devonian time, or (2) it may be an aberrant form reflective of a pathological condition, a response to an environmental factor, or a short-lived genetic trait confined to *Angopora wyomingensis* and this species.

This species is a rare occurrence of a favositid with most of the pores in the walls, and represents the first report of *Favosites* in Ordovician strata in southern Manitoba. Nelson (1963, p. 54) described *F. wilsonae* from the Caution Creek Formation of the Hudson Bay region. He concluded that the species is closely related to *F. forbesi* Milne-Edwards and Haime, which occurs in latest Ordovician strata on Anticosti Island. The three species of *Favosites* represent the only occurrences of the genus in Ordovician rocks in North America. *Favosites manitobensis* n. sp. has larger corallites and more mural pore rows in the walls than does *F. wilsonae*, and Nelson (1963) did not discuss the character of the wall structure, so the trabeculate walls may not be present.

Bassler's (1950), Baille's (1952), and Stearn's (1956) faunal lists of the Stony Mountain Formation and overlying Ordovician strata did not contain any occurrences of *Favosites*. As a result, *F. manitobensis* appears to be a very uncommon or short-lived representative of the genus, since all *Favosites* in the Silurian Interlake Group have no pores located in the corners of the corallite walls (Stearn, 1956).

Order **RUGOSA**

Superfamily **ZAPHRENTICIAE**

Family **STREPTELASMATIDAE**

Subfamily **STREPTELASMATINAE**

Genus ***Streptelasma*** Hall, 1847

Streptelasma kelpinae n. sp.

Figure 16; Plate 4, Figures 4-11; Plate 5, Figure 1

Streptelasma rusticum (Billings), Whiteaves, 1895, Geol. Survey Canada, Palaeozoic Fossils, vol. 3, pt. 3, p. 113; Baille, 1952, Manitoba Dept. Mines and Mineral Resources, Pub. 51-6, p. 32; Proctor, 1957, M. Sc. Thesis, U. Manitoba, p. 15.

Streptelasma latusculum, Okulitch, 1943, Trans. Roy. Soc. Canada, vol. 37, sec. 4, p. 61, 62; Bassler, 1950, Geol. Soc. America, Mem. 90, p. 22.

Streptelasma aff. *S. latusculum* Okulitch, Duncan, 1956, U.S. Geol. Survey Bull. no. 21-F, p. 218, p. 21, figs, 1a, b; Duncan, 1957, Jour. Paleontology, vol. 31, no. 3, p. 613.

Streptelasma cf. *S. latusculum* Okulitch, Ross, 1957, U.S. Geol. Survey Bull. no. 1021-M, p. 474, pl. 37, figs. 4, 8.

Species diagnosis.--Small, curved, trochoid coralla with diameter of mature forms less than corallum length; corallum exterior nearly smooth or with transverse annuli; longitudinal furrows absent on well-preserved corallum exteriors; calyx depth up to 0.45 times the corallum length, with V-shaped calyx with smaller U-shaped central pit; up to 39 dilated major septa often filling corallum interior, weakly trabeculate, non-denticulate septa on distal margins, commonly forming counter-clockwise axial vortex, with lobate ends of major septa abutting to form columella; tabulae rare, restricted to septal interspaces between peripheral stereozone and columella.

Description of material.--Eighty-one specimens are assigned to *Streptelasma kelpinae*.

All coralla are small- to medium-length trochoid types with a circular, transverse profile. The cardinal side of all coralla is convex, whereas the counter side is concave as in most coralla of the genus *Streptelasma*. The corallum exterior is nearly smooth in well-preserved coralla. Only coarse growth annulations such as those on the exterior of hypotype UND 13697. modify a nearly featureless epithecal surface. No longitudinal septal furrows occur on well-preserved surfaces.

The individuals from the Gunn Member of the Stony Mountain Formation of southern Manitoba include three paratypes (UND 13622.-13624.), 66 individuals (UND 13696.) and one paratype from the Hunt Mountain beds of northern Wyoming. All of these show that the rate of increase of corallum diameter, as measured between the traces of the cardinal and counter septa, decreases with increasing corallum length (Figure 15). The four paratypes used (UND 13615., 13622-13624.) closely merge with the point scatter represented by the 66 individuals measured (UND 13696.). With increasing maturity and corallum length, the apical angle, which may be as high as 60 degrees near the apex, continually decreases with increasing corallum maturity.

The calicinal rims are most commonly oriented normal to the corallum axis. Neanic individuals however, commonly have inclined calicinal rims wherein the rim is inclined toward the counter side of the corallum. The longitudinal calicinal profile of a mature paratype (UND 13697.) and the holotype (UND 13699.) is characterized by the peripheral portion occupying the peripheral half of the calicinal radius, with a calicinal pit wall slope of 45 degrees to the corallum axis. At the axial border of the sloping pit wall, halfway between the calicinal rim and center, the wall parallels the corallum axis, deepening the calyx. The calicinal floor at the center is planar and normal to the axis, occupying the axial half of the calyx, with no columellar projection protruding from the floor.

Calicinal depth increases proportionately with increasing length, up to a maximum of 0.45 times the corallum length at 23 mm from the apex. Coralla longer than 23 mm are characterized by calicinal depths not exceeding 11 mm, and the proportional depths decrease as a function of increasing corallum length.

A maximum of 39 major septa occur, with a maximum rate of septal insertion of approximately 6 per millimeter within 2.5 mm of the apex for six paratypes (UND 13615., 13619., 13620., 13622.-13624.). From 2.5 to 7 mm from the apex, these six show a decreased insertion rate of two septa per millimeter of length. At greater than 20 mm from the apex, the insertion rate falls to zero, due to the increased prominence of the minor septa. These were inserted at distances from five to seven mm above the apex.

Within the corallum interior, the major septa are dilated and often completely fill in the neanic portions of the corallum. The ephebic portions however, usually contain major septa dilated to a lesser degree in the tabularium, but they are axially expanded in lobate fashion where they merge to form a columella. Major septa close to the calyx are usually dilated only at their peripheral margins, and completely or nearly fill the corallum interiors, and on their peripheries, stereozone is present.

The corallum wall consists of a septotheca formed by the laterally abutting ends of the septa. Therefore, a peripheral stereozone of fibrous stereoplasm occurs only in regions where the peripheral ends of adjacent septa are not in contract with each other. Minor septa are usually buried within the stereozone with only their axial ends protruding from it.

A prominent cardinal fossula commonly forms the

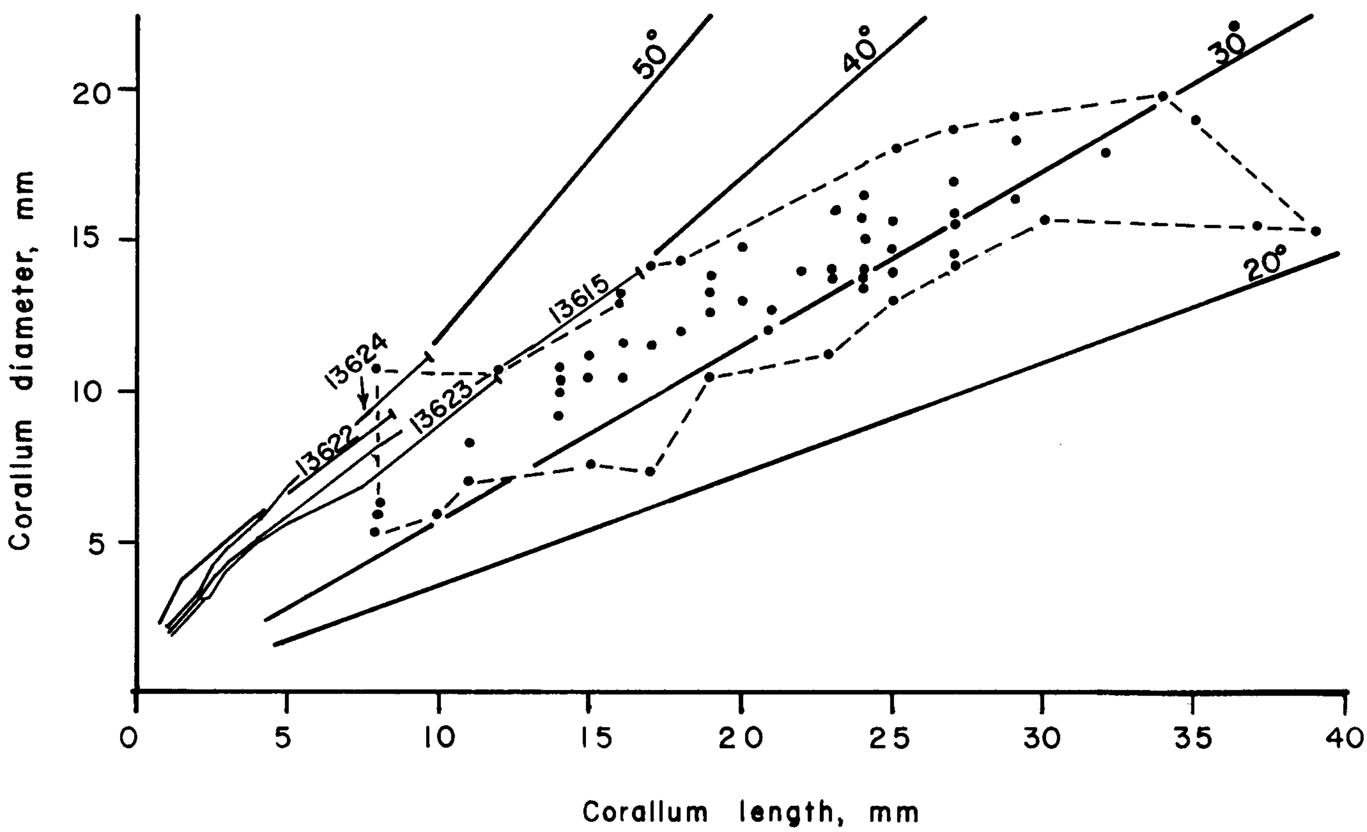


Figure 15-Line plots and scatter diagram of corallum diameter plotted against corallum length for *Streptelasma kelpinae* n. sp. (UND 13615., 13622., 13624., 13696.). Radiating lines represent corallum angles as a function of length.

only unoccupied space in the corallum interior unless interseptal spaces are present. The columella is composed of the merged, lobate, axial ends of major septa which, when viewed from the calyx, form an axial vortex composed of a counter-clockwise twisting of axial portions of the septa, as typified by paratype UND 13620. (Plate 4, Figure 5).

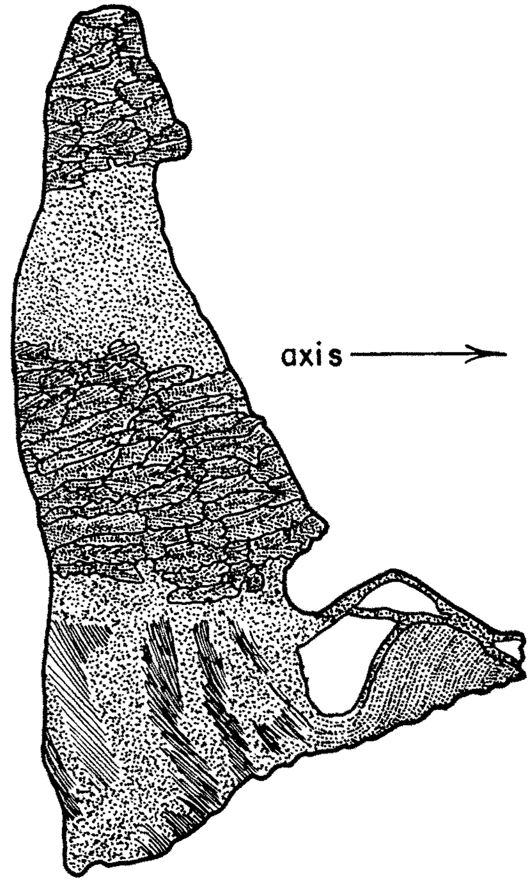
Septal microstructure is faintly trabeculate. A longitudinal section of one paratype (UND 13617.), cutting the plane of a septum, when viewed under crossed nicols shows diffuse, rectangular areas within which fan-like extinction patterns are produced by rotation of the microscope stage (Figure 16a). Each extinction pattern delineates the extent of a trabecula in the section through the plane of the septum. Transverse sections show a chevron-shaped fiber pattern, with the apices of the chevrons directed peripherally (Figure 16b). No well-defined layering within the transverse sections through the septa can be observed, other than a translucent area at the central plane of each septum, which is probably the axial region of the longitudinally-stacked, axially-oriented trabeculate. The trabecular structures are less well defined than those observed in *Bighornia*, *Dieracorallium*, and *Lobocorallium*, indicating that this poor definition may be reflective of the taxonomic position of *Streptelasma* in relation to the other genera.

Tabulae are rare in the sectioned paratypes, having been observed in only one (UND 13617.). In this one, the tabulae consist only of inclined, convex tabellar plates restricted to the interseptal region between the axial margin of the peripheral stereozone and the periphery of the columella. Spacing varies between 0.45 and 0.9 mm in four individuals.

Types and catalogued specimens.--Holotype, 13699.; paratypes, UND 13615., 13617.-13620., 13622.-13624., 13697., 13698., 13700.; catalogued specimens, UND 13616. (2 specimens), 13696. (69 specimens).

Occurrence.--*Streptelasma kelpinae* occurs at the following localities:

Zero to 3.4 meters (0 to 11 ft) below the top of the Gunn Member of the Stony Mountain Forma



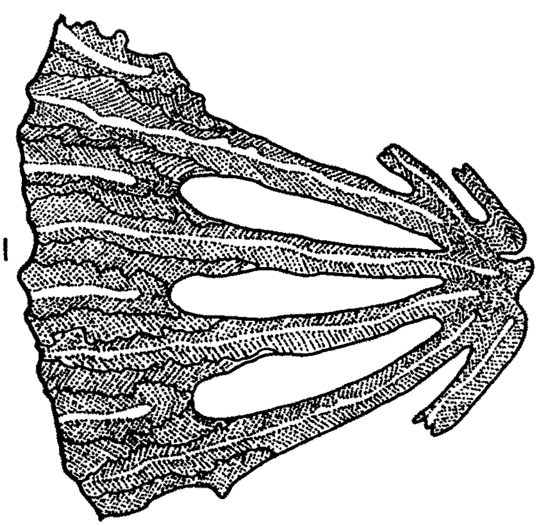


Figure 16-Paratypes of *Streptelasma kelpinae* n. sp. A. Calicinal rim of UND 13617. Longitudinal section cuts trabecular portion of minor septum (at top), and major septum (midway down section). Approximately X10. B. Portion of UND 13620., transverse section. Patterned stippling shows septal microstructure. Approximately X17.

tion in a quarry near Stony Mountain, Manitoba (Appendix A, locality A584).

Zero to 2.7 meters (0 to 9 ft) above the base of the Penitentiary Member of the Stony Mountain Formation at the same locality as above.

The Rock Creek beds in the upper portion of the Bighorn Formation on the south fork of Rock Creek, Johnson County, northern Wyoming, on the eastern flank of the Bighorn Mountains (Ross, 1957, p. 456).

The Hunt Mountain beds in the upper part of the Bighorn Formation in Shell Creek Canyon, four miles east of Shell, Bighorn County, Wyoming (Appendix A, locality A531).

At 0.12 and 1.6 m (0.4 and 5.2 ft) below the top of the Hunt Mountain beds east of the summit of Hunt Mountain, Sheridan County, Wyoming (Appendix A, localities A539, A549).

Etymology.--*Streptelasma kelpinae* is named for Shelly Kelpin, collector and daughter of the former superintendant of the Municipality of Winnipeg Aggregate plant near Stony Mountain, Manitoba.

Discussion.--The species was constructed for individuals of *Streptelasma* often previously assigned to *Streptelasma* aff. *latusculum* by Duncan (1956) and Ross (1957), and assigned to *Streptelasma latusculum* by Okulitch (1943). Twenhofel (1928, p. 112) described *S. latusculum* as follows:

> The corallum of this species is almost smooth; rugose annulations are present in a few examples; and in unworn specimens small annulae to the number of 3 to 4 to a mm band the shell. Septal ridges are present on a few species. The height and the diameter are nearly equal, with the diameter generally greater. The calyx has steep sides, the depth varies with age, but is generally from two-fifths to three-fifths the height of the corallum, proportionately greater in young specimens, and in individuals about 10 mm long the calyx extends to the apex. The septa are in two sets; the smaller are very inconspicuous and in some sets are merely rows of tubercles, the larger decrease in length to the edge of the calyx and bear distinct denticulations on their edges. These extend over the sides of the septa and outwards to the walls of the corallum as small keels about 1/2 mm apart. At their union with the wall the septa are somewhat thickened. The longer septa are 28 in number where the diameter is 13 mm, 23 where 8 mm. At the centre they twist together, uniting by twos and threes before so doing.

Bassler (1915, p. 1202) and Twenhofel (1928, p. 112) mentioned that Billings' (1865) original and subsequent descriptions of *S. latusculum* was based on material from Silurian strata of the Gun River and Jupiter Formations of Anticosti Island, Quebec.

Streptelasma latusculum, as described by Twenhofel (1928), is characterized by corallum diameters equal to or greater than height, a steep-sided calyx with depths of 2/5 to 3/5 of the corallum length, tuberculate minor septa and denticulate major septa. *Streptelasma kelpinae*, on the other hand, differs markedly from the above characters. Corallum diameters of this species do not exceed, and are always less than corallum lengths in specimens exceeding 10 mm length (Figure 15). The longitudinal calyx profile of the species has a U-shaped central area leading distally into a V-shaped portion whose distal portion terminates as the calicinal rim. The resulting profile appears as a small U with a larger V sitting atop it. No mention of such a profile was made by Twenhofel (1928) for *S. latusculum*. Lambe (1901, plate 6, figure 9) however, illustrated Billings' holotype for the species, which showed a calicinal profile not unlike that of *S. kelpinae*.

Septal denticulation is the most important diagnostic feature between the two species. Lambe's (1901) illustration, mentioned above, showed discernable septal denticulation on individuals of *S. latusculum*. The individuals and types representing *S. kelpinae* are not denticulate on their distal septal margins. This reflects the differing development of septal trabeculae between the two species. The denticulate, Silurian, *S. latusculum* reflects a greater degree of trabecular development than do the non-denticulate septal margins typical of *S. kelpinae*, whose trabeculae are poorly differentiated. This differing development of septal trabeculae may be reflective of differing evolutionary (and chronological) positions.

The closely-appressed, poorly-defined trabeculae of *S. kelpinae* are not longitudinally continuous (with respect to the trabecular axis), but appear to be very short, terminating within the central portion of the septum (Figure 16a). Immediately abutting the terminated end of a given trabecula, another trabecula continues toward the corallum axis. Thus it appears that *S. kelpinae* represents a very primitive form of trabecular development; axial trabecular continuity has not been established and appreciable differentiation between laterally-adjacent trabeculae had not occurred. This lack of lateral trabecular differentiation explains the lack of denticulate septal margins and constitutes one of the primary reasons for separating *S. kelpinae* from the denticulate *S. latusculum*. It has been suggested (Laub, 1990) that this and the succeeding species are assignable to the Silurian genus *Dinophyllum*. They may, indeed, be Ordovician precursors of that genus, a topic for further investigation.

Streptelasma sheridanensis n. sp.

Figure 17; Plate 5, Figures 2-8

[?]*Streptelasma rusticum* (Billings), Bassler, 1950, Geol. Soc. America, Mem. 44, p. 20.

Species diagnosis.--Medium sized (55 mm long), straight, trochoid corallum with slight flattening paralleling cardinal-counter plane; calyx shallow, inclined to axis with slight columellar boss, with 54 dilated major septa conspicuously twisted to form axial vortex; minor septa buried within thin peripheral stereozone; columella composed of vermiform and adjacent or abutted axial ends of twisted major septa; tabulae steeply inclined near corallum periphery, incomplete, convex.

Description of material.--One, poorly-preserved corallum (holotype, UND 13634.), 55 mm long, is a straight trochoid type, slightly flattened parallel to the cardinal-counter septum plane (Plate 5, Figures 1, 2). Little remains of the corallum wall (Figure 17). Only a portion of the wall remains in the alar-counter septum region near the calyx. Due to loss of most of the wall, the remaining corallum exterior consists of the peripheral margins of the septa. A preserved portion of the exterior exhibits no septal furrows or transverse annulations.

Corallum width is greater than height throughout the length of the entire corallum. The corallum angle is at a maximum (75 degrees) within 2 mm of the corallum apex. From 2 to 10 mm from the apex, the angle decreases to approximately 60 degrees, and beyond 10 mm, the angle decreases to 30 degrees.

The calyx inclined at an angle of 45 degrees to the corallum axis; and may have been shallow, with a columellar boss projecting from the calicinal floor.

Fifty-four major septa occur at the calyx. The maximum rate of septal insertion occurs in the apical 3 mm of the corallum, approximately six per millimeter of corallum length. From 3 to 10 mm from the apex, the insertion rate decreases to 2.5 per millimeter of length. More than 10 mm from the apex, the rate decreases to approximately one septum per 2.5 mm length (0.4 septa per mm.). Abrasion of the corallum exterior prevented determination of the region of insertion of the minor septa. They were first observed in a transverse section 25 mm from the apex. Here they are short and completely immersed in the peripheral stereozone. All major septa exhibit pronounced counter-clockwise twisting (Figure 17). This twisting was initiated during the earliest stages of septal development and is discernable within 1 mm of the apex.

Septal microstructure 10 mm from the apex consists of prominent fibers in chevron fashion, with the apices of the chevrons directed toward the corallum periphery. At 25 mm from the apex (Plate 5, Figure 4), peripheral portions of septa exhibit zig-zag suture patterns between the central plane and flanking sclerenchymal layers. Septa viewed in longitudinal sections show central planes composed of poorly-defined bundles of subparallel fibers arranged in poorly-defined, chevron-like patterns discernable only under cross nicols. These bundles appear to be "primitive" septal trabeculae whose lateral fibers are continuous with those of the flanking sclerenchymal layers. End-on views of septa cut by the plane of longitudinal sections show no discernable boundaries between trabecular and schlerenchymal regions.

Major septa are so dilated that they are in lateral contact with each other or are within close proximity. The columella exhibits two basic modes of construction (Figure 17). Within 2.5 to 4 mm of the apex, it consists of the merged axial ends of major septa arranged in an axial vortex--twisted about the corallum axis. At distances of greater than 4 mm from the apex, the columellar structure still exhibits the vortex-like twisting at its periphery, but its central portion consists of irregular, vermiform ends of major septa that extend from bundles of two to six septa merged at their axial ends. Columellar width, a function of corallum width, remains relatively constant, 0.35 times the corallum width.

The peripheral stereozone is thin, and consists of thin lamellae arranged in U fashion, with the U opening toward the corallum axis. Lamellae at lateral margins of the stereozone abut fibers of the septal sclerenchyme at a zig-zag suture surface. Minor septa are completely embedded within the stereozone.

Tabulae are incomplete and convex. Near the corallum periphery, they are steeply inclined--45 degrees to the corallum axis. Tabular spacing, measured close to the axis and based on three available counts, is 0.66 to 1.4 mm with a mean of 0.93 mm.

Type.--Holotype, UND 13634.

Occurrence.--Collected from 0.1 m (0.4 ft) below the top of the Hunt Mountain beds near the top of the Bighorn Formation, near the summit of Hunt Mountain, western side of the Bighorn Mountains, Sheridan

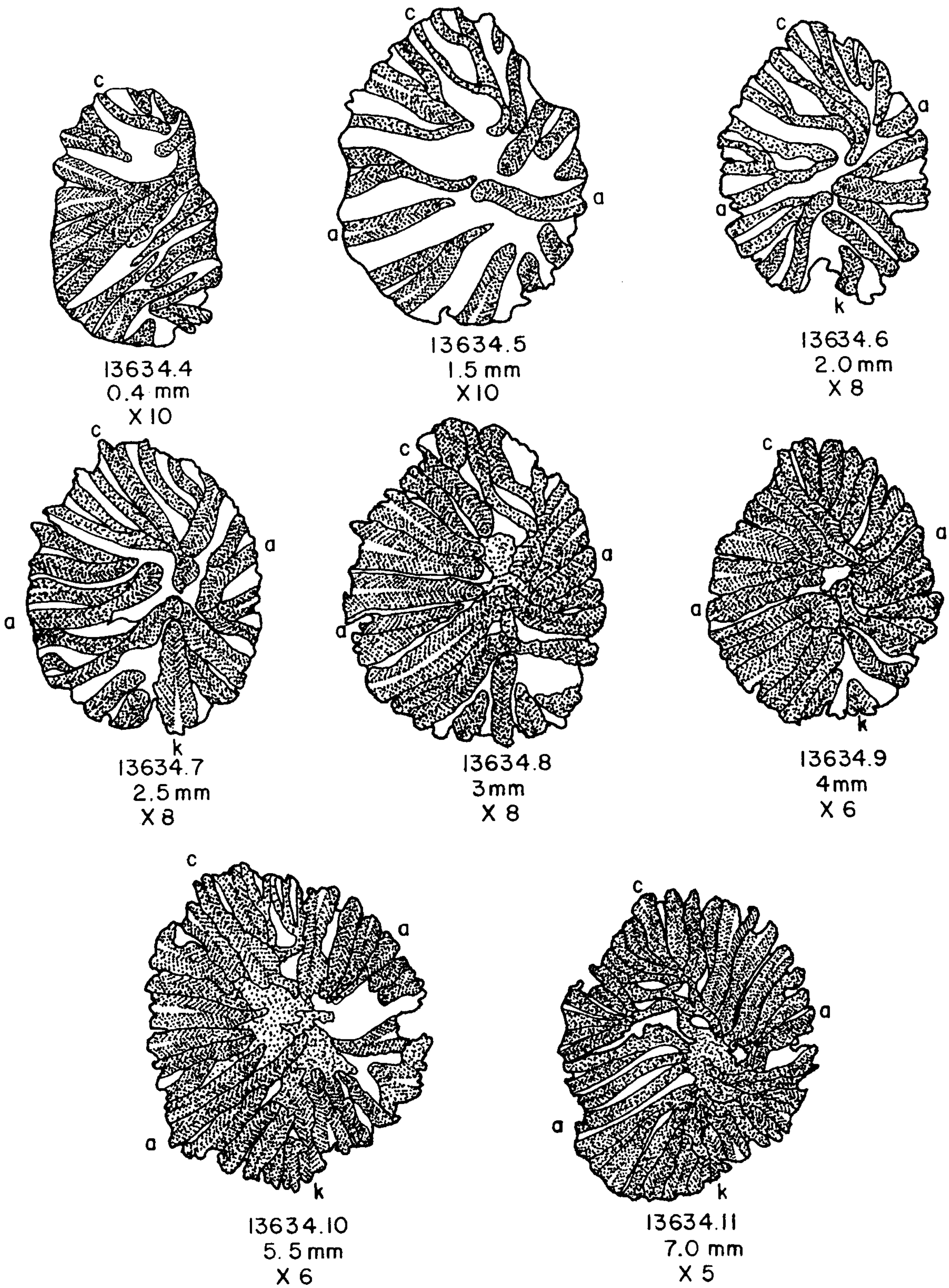


Figure 17-Serial peel tracings of the holotype of *Streptelasma sheridanensis* n. sp., UND 13634. Patterned stippling shows microstructure: c=cardinal septum, a=alar septum, k=counter septum. Distance from apex and scale given for each peel.

County, Wyoming (Appendix A, locality A549).

Etymology.--*Streptelasma sheridanensis* is named for the nearest large city in Wyoming adjacent to the Bighorn Mountains from which the holotype was collected.

Discussion.--Although the exterior surfaces and calicinal portions of the holotype corallum are poorly preserved, the straight, trochoid corallum with the slightly-flattened, transverse profile; the shallow, inclined calyx, the pronounced twisting of the major septa, and the *Grewingkia*-like columella are sufficiently unique to warrant designation of a new species, even though ordinarily one corallum would be insufficient to warrant such designation. *Streptelasma sheridanensis* n. sp., is named for the northern Wyoming county from which the holotype was collected.

Streptelasma sheridanensis n. sp. is closely related to *Grewingkia rustica* (Billings) and *S. poulseni* Cox in that all three species share the same type of columella. *Streptelasma sheridanensis* differs from the other two in having: (1) A straight corallum, whereas coralla of the other two are curved; (2) Markedly twisted major septa, whereas those of the other two species are either straight or only slightly twisted.

Streptelasma sheridanensis may be a descendant of *S. poulseni* from the Red River Formation, since both species occurred in the Red River-Stony Mountain Province at differing times during the Ordovician. The evolution of *S. sheridanensis* from *S. poulseni* would have involved straightening of the corallum, compression of the corallum along the cardinal-counter septal plane, inclination of the polyp basal disc to the corallum axis, and the twisting of the polyp mesentaries--resulting in the production of the twisted septa (see note regarding relationships with *Dinophyllum* under previous species discussion).

The inclination of the calyx may have been an attempt to enable the polyp to orient itself obliquely to the sediment surface. Since only an alar portion of the calicinal rim is preserved, the complete original character of the calyx is indeterminable and the possibility that the inclination of the calyx may be in part due to lack of preservation or deformation cannot be ignored. The probability that the calyx was originally inclined is indicated by the inclined calicinal floor, wherein the distal margins of the septa and columella are inclined.

The conspicuous twisting of the major septa may have been the result of an increase of the length of the mesentaries within the polyp. The twisting resulted in greater septal lengths than would have been possible if they were arranged in simple radiating fashion. This may reflect an increase in absorptive area within the polyp's gastrovascular cavity without an increase in the number of mesentaries or increase in body column diameter.

Genus ***Palaeophyllum*** Billings, 1858

Palaeophyllum sinclairi n. sp.

Figure 19; Plate 6, Figures 1-5

Diagnosis.--Small cateniform corallum, corallites commonly grouped in cerioid, agglutinative patches; corallites small; mean diameter 3.5 mm in cateniform and cerioid corallum regions, with subrectangular or moniliform corallites in uniserial ranks, polygonal in agglutinative patches, circular when free standing; 13 to 17 major or minor septa per corallite, mean of 15; major septa commonly extending to corallite axis and fusing about septal plane of bilateral symmetry, predominantly uniformly thin from corallite wall to axial margin; amplexoid septal retreat rare or absent; minor septa short, embedded in sclerenchyme, mean total length 0.15 times the corallite radius, not intersecting elevated portions of tabulae; thick walls with well-defined, axial plate; tabulae all complete, transvere to corallite axis, with rounded or planar, elevated central platform; spacing in poorly-defined zones of crowded and less closely-spaced tabulae.

Description of material.--The holotype corallum (UND 13706.) is small, 10 cm wide by 9 cm long, with a height of 5 cm width with an overall flattened, hemispherical outline. Corallites radiate outward and upward from the point of origin of the colony. Cateniform portions of the corallum contain corallites arranged in uniserial ranks, with no marked elongation parallel to rank direction. Merging of numbers of ranks produced agglutinative patches of cerioid corallites with an alternate biserial arrangement of corallites within them. Ranks in and near the central portion of the corallum often completely enclose lacunae that are oval or subcircular in transverse outline.

Corallites in cateniform ranks are subrectangular or moniliform in cross section, whereas those in the cerioid regions of the corallum are polygonal. Diameters of adult corallites in both cateniform and cerioid regions range from 2.46 to 4.6 mm with a mean of 3.6 mm. Budded corallites are approximately 2.2 mm in diameter. Mode of budding is extra-tentacular, with the offset arising from the nearest parent corallite's periphery.

Fourteen to 17 major (and an equal number of minor) septa occur in each corallite, and more in corallites of larger diameter (Figure 18). Major septa exhibit very little amplexoid retreat. Only 10 major septa in two corallites observed showed evidence of retreat. The remainder of all observed major septa merge at or near the corallite axis. The pattern defined by merging is commonly bilaterally symmetrical. A central, cardinal-counter septal plane bisects the corallite lumen, and the remaining major septa tend to merge symmetrically on either side of the plane. All major septa are uniformly thin throughout their extent. Peripheral septal margins are embedded in stereoplasm that tends to remain structurally distinct from the septa. Wall thickening was due to the addition of wall stereoplasm on the flanks of the septa (Figure 19). Minor septa are short, with approximately half of their length buried in stereoplasm; the mean extension of this type of septum is 0.15 times the corallite radius. Observation of both major and minor types of septa under plane polarized light and cross nicols rarely showed a two-layered character to the septa. Septal fibers diverge outwardly and axially from a septal plane formed by the interior ends of the septal fiber sets (Figure 19).

The presence or lack of stereoplasm in both the outer corallite wall in cateniform corallite ranks, and the intercorallite wall between adjacent corallites results in varying types of wall structures. Walls without stereoplasm appear to be composed of two layers; an epitheca or axial plate and a flanking layer of fibrous sclerenchyme--the rugosan wall. This type of wall is also present in such forms as *Paleofavosites* spp. and *Cyathophylloides hollandi* n. sp. Addition of stereoplasm to the corallite walls results in a third, structurally-separate, fibrous layer, with fibers directed axially and downward into the corallite (Figure 19).

Tabulae are complete and oriented normal to the corallite axis. They are predominantly elevated above their level of attachment with the corallite wall. A domed or planar platform above that level has a width nearly half the corallite diameter, with no sagging in the axial region. Tabulae are closely spaced, from 0.16 to 1.1 mm, and are grouped into poorly-defined zones of crowded and widely-spaced forms (Table 9).

Type.--Holotype, UND 13706.

Occurrence.--The holotype was collected as float, 9.8 meters (32 ft) above the top of the Hunt Mountain beds in the upper portion of the Bighorn Formation, east of Hunt Mountain, Bighorn Mountains, Wyoming (Appendix A, locality A456).

Etymology.--*Palaeophyllum sinclairi* n. sp. is named for Dr. G. Winston Sinclair of the Geological Survey of Canada.

Discussion.--Species of *Palaeophyllum* with a cateniform growth habit are generally confined to the

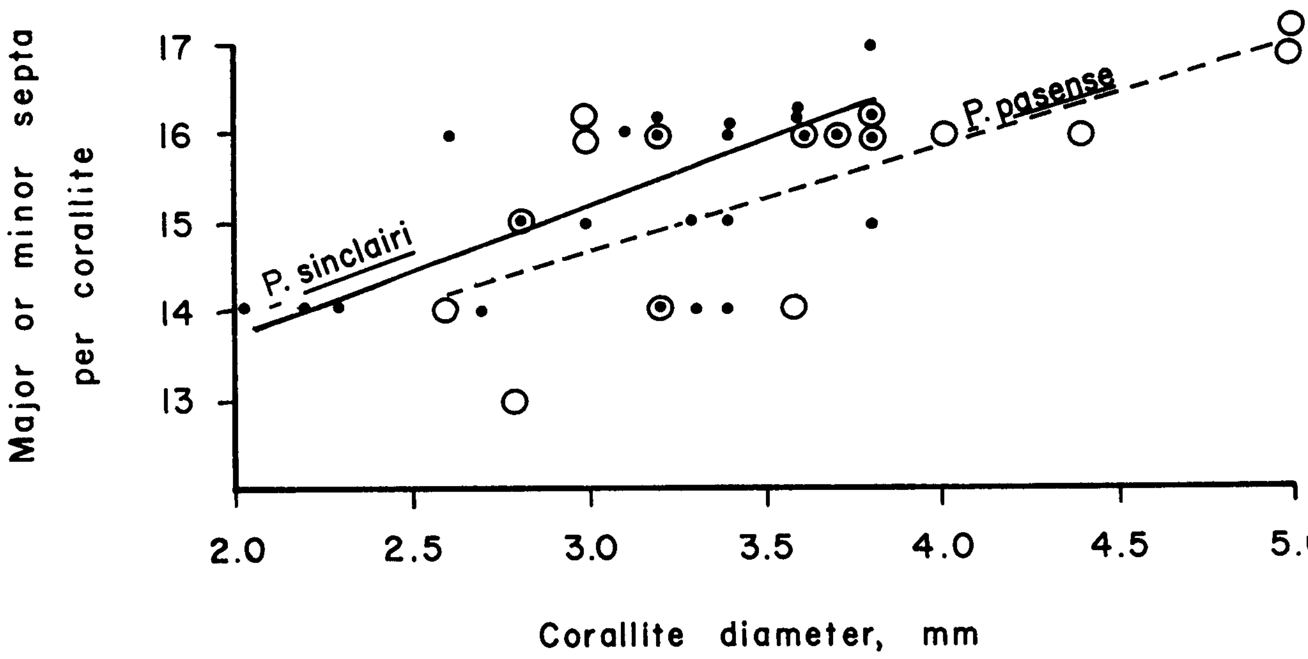


Figure 18-Scatter diagram and estimated lines for septal counts plotted against corallite diameter for *Palaeophyllum sinclairi* n. sp. (dots; UND 13706.) and *P. pasense* (circles; UND 13705.).

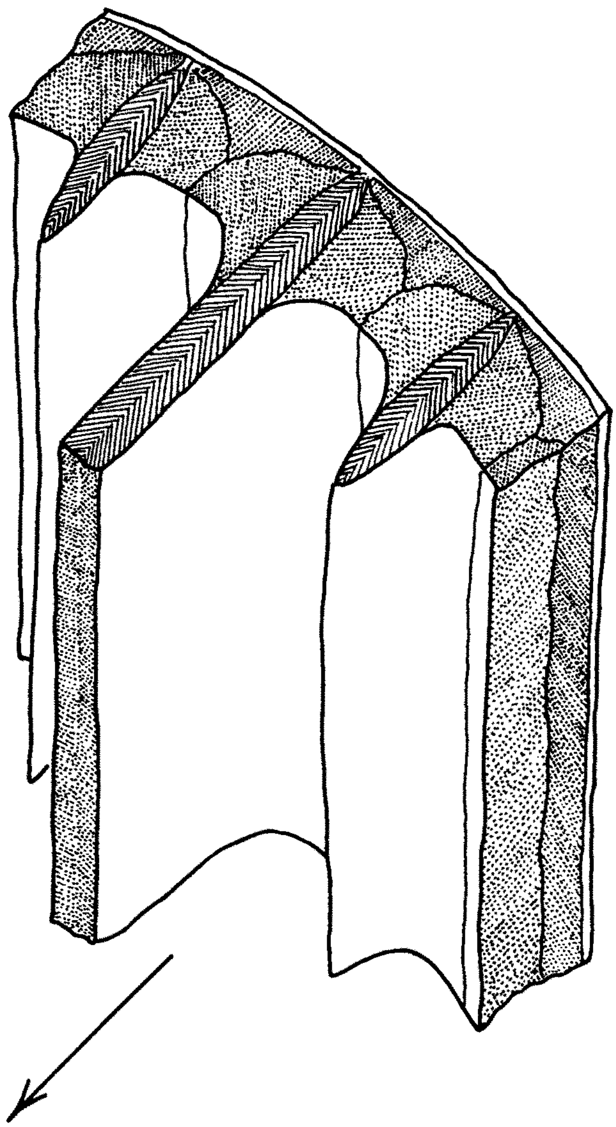


Figure 19-Portion of wall and septa of *Palaeophyllum sinclairi* n. sp. Fibrous septal structure shown by hachures. Patterned stippling shows wall fiber orientation. Clear area represents epitheca. Arrow toward corallite axis. Approximately X47.

Richmondian Stage (Stearn, 1956, p. 90), possibly indicating an evolutionary advancement over older species of *Palaeophyllum*. These older forms are more commonly characterized by phaceloid growth in which cylindrical corallites, separated from each other and frequently connected by tubules, are oriented in subparallel fashion with respect to each other (Moore, et al., 1956, p. F248, F249). Transition with geologic time to a cateniform habit (Moore, et al., 1956, p. F246) reflects increasing intercommunication between adjacent polyps, resulting in lesser amounts of skeletal material necessary to support a given number of polyps in closer proximity than in polyps in the phaceloid corallum form. In phacelloid coralla, communication between polyps was possible only if interconnecting tubules supported the continuity of interpolyp coenosarc. Flower (1961) described and listed four species of *Palaeophyllum* from the Montoya Group of New Mexico and west Texas. Of these four, only *P. cateniforme* Flower exhibits the cateniform growth habit. This occurs in the Second Value Formation, which contains a coral fauna notably similar to that of the Selkirk Member of the Red River Formation in southern Manitoba. Only *P. argus* is known from the Selkirk. Therefore, the cateniform habit of *P. cateniforme*, in a fauna correlative to that of the Selkirk, shows that the genus *Palaeophyllum* in the Selkirk may not have had or needed the capability to form cateniform coralla. The ability for the genus to form these coralla was established at the time that the fauna in the Selkirk and its correlative faunas existed. This ability persisted up to the time that *P. pasense* and *P. sinclairi* existed.

Only *P. pasense*, a closely-related species, is closely comparable to *P. sinclairi*. These are the only cateniform species of *Palaeophyllym* found in the Bighorn Formation. Comparison of these two species reveals these differences:

1. *Palaeophyllum sinclairi* exhibits corallites in closer lateral contact and cerioid patches of corallites, whereas Stearn's illustration of *P. pasense* (1956, plate 16, figure 17) shows corallites in less intimate contact. This may indicate that in the generic trend from phacelloid to cateniform coralla, *P. sinclairi*, with its agglutinative patches and enclosed lacunae may be more advanced than the other species.

2. Major septa of *P. pasense* are not fused at or near the corallite axis (Stearn, 1956, p. 89). *Palaeophyllum sinclairi* has the great majority of major septa fused in a bilaterally-symmetrical pattern about a probable cardinal-counter septal plane.

3. Tabulae of *P. pasense* are convex, whereas those of *P. sinclairi* are strongly arched upward, commonly having a prominent axial platform or dome.

The walls of *P. sinclairi* contain two sets of fibers (Figure 19), forming chevron-like sets with their apices directed distally. Flower (1961, p. 88) mentioned the presence of "a fibrous lining with obscure radial units, obscurely trabecular." Fiber orientation in this species is very faint (Plate 6, Figure 5). In other Tabulata and colonial Rugosa with the rugosan wall, an axial plate of epitheca is flanked on one or both sides by fibrous sclerenchyme with fibers oriented upward and inward

TABLE 9

Biometrics of the holotype and a hypotype of Palaeophyllum pasense Stearn and the holotype of P. sinclairi n. sp.

SPECIES	*P. pasense*	*P. pasense*	*P. sinclairi*
SPECIMEN	HOLOTYPE GSC No. 10403	HYPOTYPE UND 13705	HOLOTYPE UND 13706
Corallum form	fasciculate-cateniform	cateniform	cateniform
Corallum width, length	8 cm.	14x14 cm. (est.)	9x10 cm.
Corallum height		5.0 cm.	5.0 cm.
Immature corallite diameter		2.2 mm. n=1	1.7-2.7 mm. mean=2.2 mm. n=14
Mature corallite diameter	3.0-4.5 mm.	2.6-4.6 mm. mean=3.44 mm. n=37	2.46-4.6 mm. mean=3.56 mm. n=60
Major or minor septa per corallite	15	13-17 mean=15.5 n=16	14-17 mean=15.4 n=25
Major septal length-retreated position (amplexoid)	not joined at center	0.68-1.9 mm. mean=1.25 mm. n=29	0.45-1.8 mm. mean=1.06 mm. n=10
Major septal extension, retreated position (rad.=corallite radius)		0.37-0.82 rad. mean=0.6 rad. n=29	0.3-0.92 rad. mean=0.59 rad. n=10
Minor septal length	ridges	0.3-0.7 mm. mean=0.41 mm. n=28	0.1-0.5 mm. mean=0.32 mm. n=30
Minor septal extension - rad.		0.12-0.33 rad. mean=0.2 rad. n=28	0.03-0.25 rad. mean=0.15 rad. n=30
Outer corallite wall thickness		0.13-0.3 mm. mean=0.2 mm. n=14	0.1-0.35 mm. mean=0.2 mm. n=49
Epithecal thickness		0.02 mm. n=4	0.02=0.06 mm. mean=0.03 n=20
Common wall thickness		0.23-0.32 mm. mean=0.26 mm. n=8	0.2-0.35 mm. mean=0.27 mm. n=16
Axial plate thickness		0.02 mm. n=4	0.02-0.03 mm. n=9

TABLE 9

Continued

SPECIES	*P. pasense*	*P. pasense*	*P. sinclairi*
SPECIMEN	HOLOTYPE GSC No. 10403	HYPOTYPE UND13705	HOLOTYPE UND 13706
Wall fiber orientation (with respect to corallite axis)		20-74 deg. mean=48 deg. n=20	35-68 deg. mean=54 deg. n=22
Stereoplasm fiber orientation (with respect to corallite axis)		134 deg.	119-161 deg. mean=138 deg. n=16
Closely spaced tabulae	0.07 mm. (?)	0.32-0.95 mm. mean=0.59 mm. n=25	0.16-0.62 mm. mean=0.49 mm. n=32
Widely spaced tabulae		0.7-1.7 mm. mean=1.23 mm. n=21	0.5-1.1 mm. mean=0.74 mm. n=28
Tabular form	flat, with down-turned margins	broad, flat central platform	rounded central platform, highly developed
Tabular platform width		1.6-2.1 mm. mean=1.86 mm. n=11	0.6-1.7 mm. mean=1.35 mm. n=16
Tabular platform width (x corallite diameter)		0.4-0.68 dia. mean=0.52 dia. n=11	0.26-0.65 dia mean=0.45 dia n=16

toward the corallite axis. In *P. sinclairi*, the sclerenchymal layer is bounded laterally by the peripheral ends of the septa. Septal ends appear to merge or abut the epitheca or axial plate, isolating the sclerenchymal layer. Inward of the fibrous sclerenchyme, fibrous skeletal stereoplasm forms a third element in the corallite wall structure. Examination of the thickened corallite wall in longitudinal section revealed two sets of fiber orientations. Sclerenchyme has the orientation discussed above. The second, the stereozone, exhibits fibers oriented approximately 90 degrees away from those of the sclerenchyme (Plate 6, Figure 5). In longitudinal section, these are oriented upward and outward from the corallite axis (Figure 19). In transverse section, extremely faint longitudinal sutures are seen between each septum, defining a fiber set on each side of the suture. Fibers are directed away from the suture and appear to abut the flanks of the septa. The difference in fiber orientation between the sclerenchymal and stereoplasm layers indicates that the latter were formed by a process and basal plate location differing from that by which the sclerenchymal layers formed--the stereoplasm is not simply a continuation of the sclerenchymal layer.

Flower (1961) discussed the relationship between septa and wall structures in *Palaeophyllum*, and noted an increase in specialization of septal fibers as species and septa grew larger. *Palaeophyllum sinclairi*, like *P. margaretae* Flower and *P. cateniforme* Flower, has septal fibers that are separate from the wall structure (Figure 19; Flower, 1961, figure 5c). However, *P. sinclairi* does not show septal fibers aligned radially about the peripheral tip of axial planes within septa. This species seems to have the peripheral ends of the septa merging with the axial plate or its homologue--the epitheca. Thus the character of the peripheral ends of the septa varies within the genus.

Suborder **COLUMNARINA**

Family **STAURIDAE**

Genus ***Cyathophylloides*** Dybowski, 1873

Cyathophylloides hollandi n. sp.

Figure 20; Plate 6, Figures 6, 7

Diagnosis.--Large sub-globose corallum with corallite diameters of 1.7 to 5.8 mm, with mean of 3.6 mm; corallites radiating from growth center of colony, those in basal peripheral portion of colony with alveolitid outline, and those in central and distal portions of colony having a polygonal outline; scattered corallites projecting less than 3 mm above the corallum growth surface, retaining polygonal outline; ten to 16 major septa, with an equal number of minor septa per corallite, and with a mean of 13 of each type of septum; major septa long, commonly extending nearly to corallite axis; major septa showing slight amplexoid retreat above tabular surface; minor septa short, length averaging 0.1 times mean corallite radius, spinose on axial margins; tabulae complete, normal to corallite axis, in zones of closely- and widely-spaced types, commonly downturned at periphery; planar tabulae less common.

Description of material.--The large, cerioid, subglobose holotype (UND 13727.) adheres at its proximal surface to a small favositid corallum. Corallites in the mature portions of the corallum are polygonal, whereas those in the basal and peripheral portion of the holotype corallum have an alveolitid outline, which was formed by the upper, arched wall of the corallite having been supported by the arched walls of the underlying corallites.

The corallites radiate out from the point of origin of the colony. Immature corallites alter their outline with increasing diameter, from subtriangulate to rectangular or trapezoidal, and to polygonal with maturity. Scattered, mature corallites project from the corallum growth surface and exhibit longitudinal, septal furrows on the corallite walls.

Corallite diameters are 1.7 to 5.8 mm, with a mean of 3.6 mm (Table 10). Corallite walls are uniformly thin and transversely crenulate, with a crenulation amplitude no greater than 0.5 times the wall thickness. The uniformly thin and continuous axial plate in the corallite wall is flanked by fibrous sclerenchyme.

Ten to 16 major septa and an equal number of minor septa are present in each corallite. Major septa are longitudinally continuous along the corallite wall and often merge in adjacent pairs at or immediately above a tabular surface. Scattered corallites show one or two exceptionally-elongated septa opposite each other, which tend to merge with each other or other septa, giving the appearance of a cardinal-counter septal plane. Above the tabular surface major septa exhibit a restricted type of amplexoid retreat (Figure 20), with maximum retreat resulting in septal lengths ranging from 0.4 to 0.9 (mean 0.7) times the mean corallite radius. The septa remain uniformly thin save for a slight thickening at their peripheral edges. Axial deflection of these septa is shown as a right- or left-hand twisting, symmetrical about the cardinal-counter septal planė. Minor septa, where developed, extend 0.06 to 0.14 times the corallite radius into the lumen (mean=0.09). They are longitudinally continuous between tabulae and bear

TABLE 10

Biometrics of the holotype of <u>Cyathophylloides</u> <u>hollandi</u> n. sp.

SPECIMEN	HOLOTYPE UND 13727
Corallum width, length	11x17 cm.
Corallum height	8.0 cm.
Corallite diameter	1.7-5.8 mm. mean=3.56 mm. n=69
Major septa per corallite	10 to 16 n=20
Minor septa per corallite	10 to 16 n=20
Major septa, maximum amplexoid retreat (x corallite radius)	0.42-0.86 rad. mean=0.7 rad. n=36
Major septal length	0.8-2.3 mm. n=36
Minor septal extension (x corallite radius)	0.06-0.14 rad. mean=0.09 rad n=27
Minor septal length	0.1-0.4 mm. mean=0.22 mm. n=27
Wall thickness	0.14-0.28 mm. mean=0.21 mm. n=26
Wall fiber orientation (with respect to corallite axis	45-80 deg. mean=60 deg. n=19
Axial plate thickness	0.02-0.04 mm. mean=0.03 mm. n=19
Closely spaced tabulae	0.5-1.1 mm. mean=0.83 mm. n=40
Widely spaced tabulae	1.04-2.3 mm. mean=1.37 mm. n=48

short spines on their margins (Figure 20).

All tabulae are complete and transverse to the corallite axis. Those in the central and upper portions of the corallum are predominantly downturned at their edges, or have a raised central platform with a planar or slightly depressed center. Planar types are uncommon. Tabulae are grouped into indistinct zones of crowded and widely-spaced forms. Mean spacing values for these forms are 0.83 and 1.37 mm., respectively. (Table 10).

Type.--UND 13727.

Etymology.--The species *Cyathophylloides hollandi* n. sp. is named for Dr. F. D. Holland, Jr., Professor Emeritus of Geology at the University of North Dakota, Grand Forks.

Occurrence.--The holotype of *Cyathophylloides hollandi* n. sp. was collected as float on the Bighorn Formation about 4 meters (13 ft) above the top of the Hunt Mountain beds in the Bighorn Range, northern

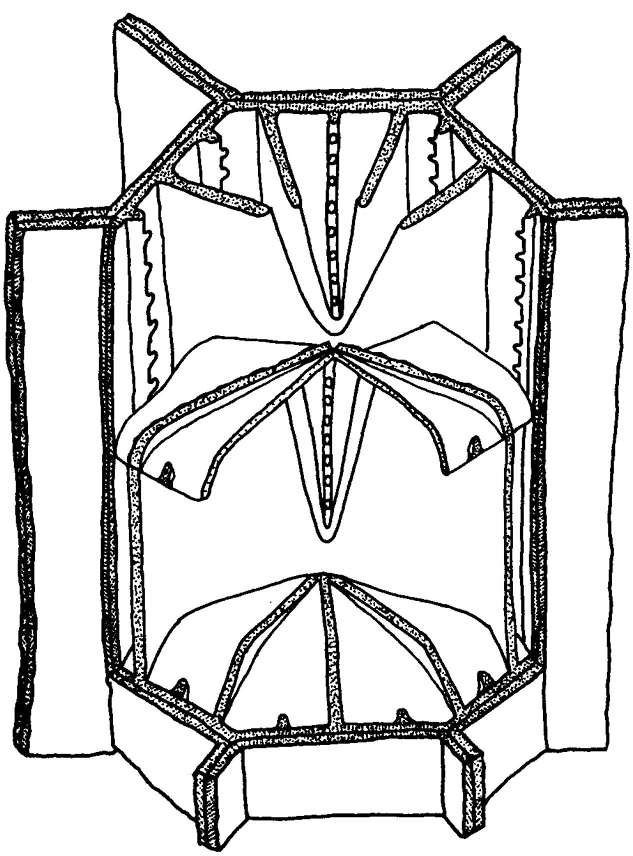


Figure 20-Portion of corallite of *Cyathophylloides hollandi* n. sp. Cut away shows disposition of amplexoid major septa, minor septa, and tabulae. Approximately X16.

Wyoming (Appendix A, locality A545).

Discussion.--Browne (1965) described several individuals of *Favistina* from the Richmond Group of north-central Kentucky, west of the Cincinnati Arch, and assigned them to *Cyathophylloides* because of an emended diagnosis of the genus. Her biometrics of the North American species of *Cyathophylloides* (1965, table 2) permit comparison with the Wyoming holotype. *Cyathophylloides crenulata* (Flower) from Kentucky, most closely resembles *C. hollandi*. However, these differences between the two species can be observed:

1. *Cyathophylloides crenulata* has parallel corallites, whereas those in *C. hollandi* are radiating, reflecting a different mode of budding and corallum form.

2. Corallite walls of *C. crenulata* are distinctly crenulate and thicker than those in *C. hollandi*.

3. Tabular spacing differs.

Cyathophylloides burksae Flower is the only representative of the genus that has been documented (Fower, 1961) in the Montoya Group. It occurs in the Aleman Formation in New Mexico. Together, *C. hollandi* and *C. burksae* are the only two representatives of the genus in the New Mexico-Greenland belt of Ordovician strata. Comparison of the two species shows these differences:

1. *Cyathophylloides burksae* has generally parallel corallites, unlike the radiating ones of *C. hollandi*.

2. There are smaller corallites and fewer septa per corallite in *C. burksae* than in *C. hollandi*.

3. Corallite walls of *C. burksae* are thicker than those in the other species.

4. Major septa of *C. burksae* are long and thick, commonly merging at the corallite axis, whereas those in *C. hollandi* are long, but thinner, and exhibit lengthening of the cardinal and counter septa.

5. Minor septa of *C. burksae* are up to half the length of the major forms, whereas *C. hollandi* has minor septa up to 0.2 times the major septal length.

A notable characteristic of the holotype is the projection of some of the polygonal corallites a short distance above the main corallum surface. Free-standing corallites occur singly or in adjacent pairs, and do not result from post-mortem reworking, diagenetic, or weathering processes, although silification has occurred on the surfaces of the projecting corallites. Another feature of the species is the wide range of septal counts within corallites (Table 10).

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APPENDIX

Localities described in this section are sites of fossil and lithologic sample collections. The numbers prefixed by "A" refer to the Accession Catalogue Numbers of the Department of Geology and Geological Engineering of the University of North Dakota. These numbers describe a geographic locality, stratigraphic horizon, collector, and date of collection. Several numbers are listed if more than one horizon was involved.

HECLA ISLAND CAUSEWAY QUARRY

A965 (Locality 3, Figure 1).--NW 1/4, Sec. 23, T. 24 N., R. 4 E., immediately south of Manitoba Provincial Road 332, approximately 3.5 miles (5.6 km) southwest of the mainland end of the Hecla Island causeway, Manitoba, Canada; Hecla, Manitoba, 1:250,000 quadrangle.

GARSON QUARRY

A884, A897 (Locality 8, Figure 1).--Gillis Quarries Ltd., Garson Quarry, NW 1/4, NW 1/4, Sec. 3, T. 13 N., R. 6 E., immediately southeast of junction of Manitoba Provincial Highway 44 and Provincial Road 306 on the eastern edge of the village of Garson, Manitoba, Canada; Selkirk, East Half, 15 minute quadrangle.

TYNDALL QUARRY

A889 (Locality 8, Figure 1).--Gillis Quarries Ltd., Tyndall Quarry, NW 1/4, Sec. 3, T. 13 N., R. 6 E., 0.8 mile (1.3 km) east of center of village of Garson, Manitoba, Canada; Selkirk, East Half, 15 minute quadrangle.

MUNICIPALITY OF WINNIPEG AGGREGATE PLANT WEST QUARRY

A576, A584, A841 (Locality 7, Figure 1).--West Quarry at the Municipality of Winnipeg Aggregate Plant (now abandoned), SE 1/4, SE 1/4 Sec. 14, T. 13 N., R. 2 E., approximately 0.7 miles (1.1 km) north-northwest of the center of the village of Stony Mountain, Manitoba, Canada.

HUNT MOUNTAIN LOCALITY

A539, A542, A545, A546, A549 (Locality 9, Figure 1).--South-facing cirque wall on an eastwardly-extending spur, S 1/2, SW 1/4, SE 1/4, Sec. 18, T. 55 N., R. 90 W., overlooking valley of Wallrock Creek, west flank of Bighorn Mountains at approximately 9600 ft elevation, Sheridan County, Wyoming; Hidden Tepee Creek 7.5 minute quadrangle.

NORTH SIDE, SHELL CREEK CANYON

A531 (Locality 10, Figure 1).--North side of Shell Creek Canyon, SE 1/4, NW 1/4, SE 1/4, Sec. 7, T. 53 N., R. 90 W., approximately 4.0 miles (6.4 km) east of village of Shell, Bighorn County, Wyoming; Black Mountain, Wyoming 7.5 minute quadrangle.

PLATES

All specimen numbers designated "UND" are from the paleontological collection of the Department of Geology and Geological Engineering, University of North Dakota, at Grand Forks, North Dakota.

PLATE 1

Figures 1-4.-*Trabeculites manitobensis* n. sp. (UND 13561.).

1. Transverse section showing corallite walls with trabeculae expanded at their central regions. Septal spines are shown as lateral expansions of wall trabeculae, X4.7.

2. Longitudinal section with tangentially sectioned wall trabeculae shown by dark, vertical lines, X7.3.

3. Longitudinal section through corallite wall trabecula, axial rod shown as clear central area, fiber orientation shown by arrows. Septal spine is an extension of sclerenchymal fibers, crossed nicols, X150.

4. Transverse section of trabeculate corallite walls showing axial plates at trabecular centers. Arrow illustrates boundary between a trabecular pair, crossed nicols, X47.

Figures 5-7.-*Nyctopora fissisepta* n. sp. (UND 13703.).

5. Longitudinal section with wall trabeculae cut tangentially, as is shown by dark, vertical lines, X6.

6. Transverse section showing walls and prominent septa. Trabeculae within walls distinguishable by variations in shading, X6.9.

7. Transverse section with corallite walls and bifurcate septa (shown by arrows), X150.

Plate 1

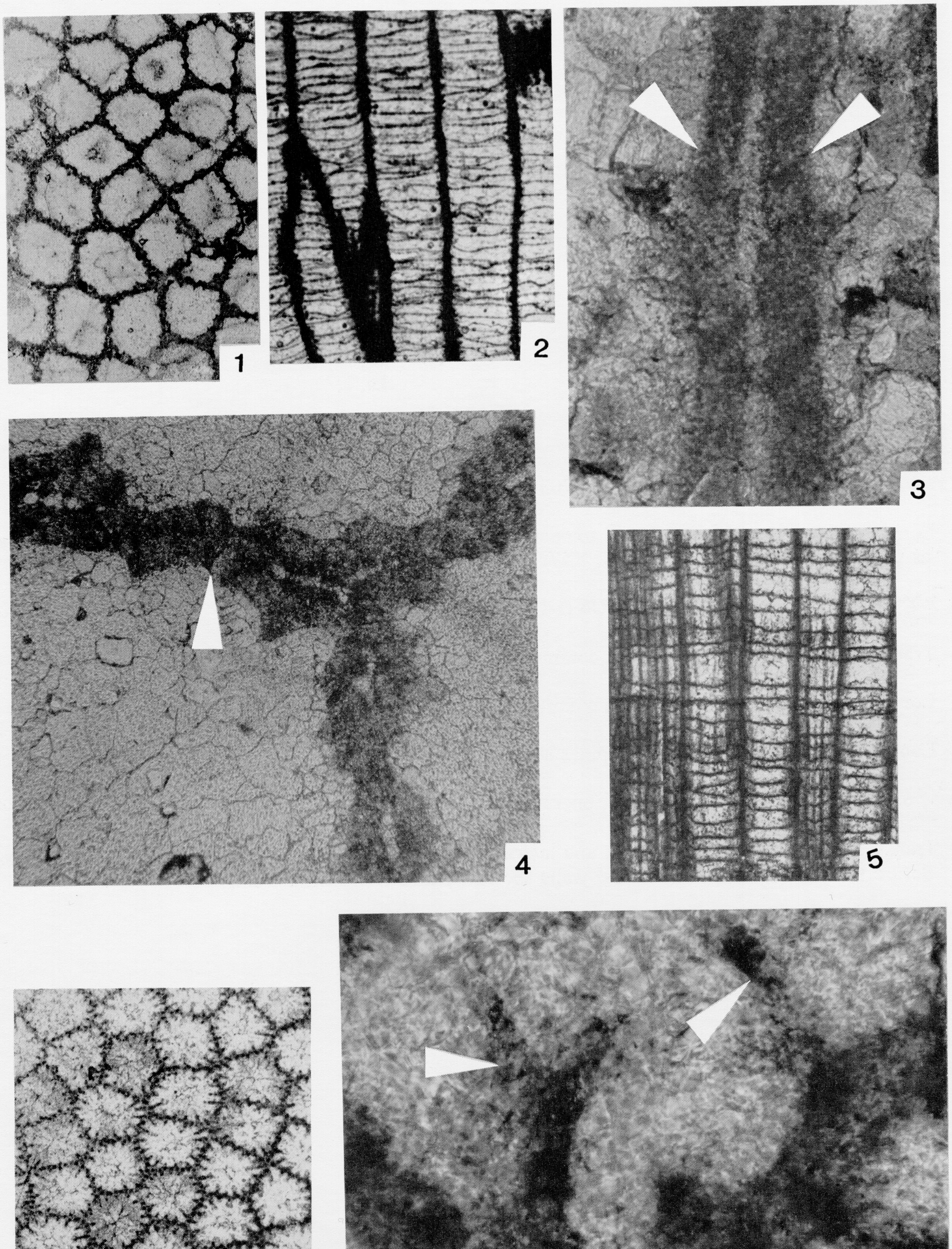


PLATE 2

Figure 1.-*Nyctopora fissisepta* n. sp. (UND 13703.).

1. Longitudinal section through a wall trabecula with closely packed septal spines having the same orientation as trabecular fibers, crossed nicols, X47.

Figures 2-4.-*Manipora garsonensis* n. sp. (UND 13766.).

2. Transverse section showing septate common walls, and convex lateral walls, X3.1.

3. Longitudinal section with crenulate common walls shown by zig-zag pattern, X3.0.

4. Longitudinal section with tabular spines set in tabular stereozone, X150.

Figures 5, 6.-*Manipora bighornensis* n. sp., encrusted by *Coccoseris* sp. (UND 13662.).

5. Transverse section cutting common and lateral walls of *M. bighornensis*, and trabeculae of *Coccoseris* sp. Suture between common and lateral walls shown by arrows, crossed nicols, X47.

6. Longitudinal section of M. *bighornensis*, X3.5.

Plate 2

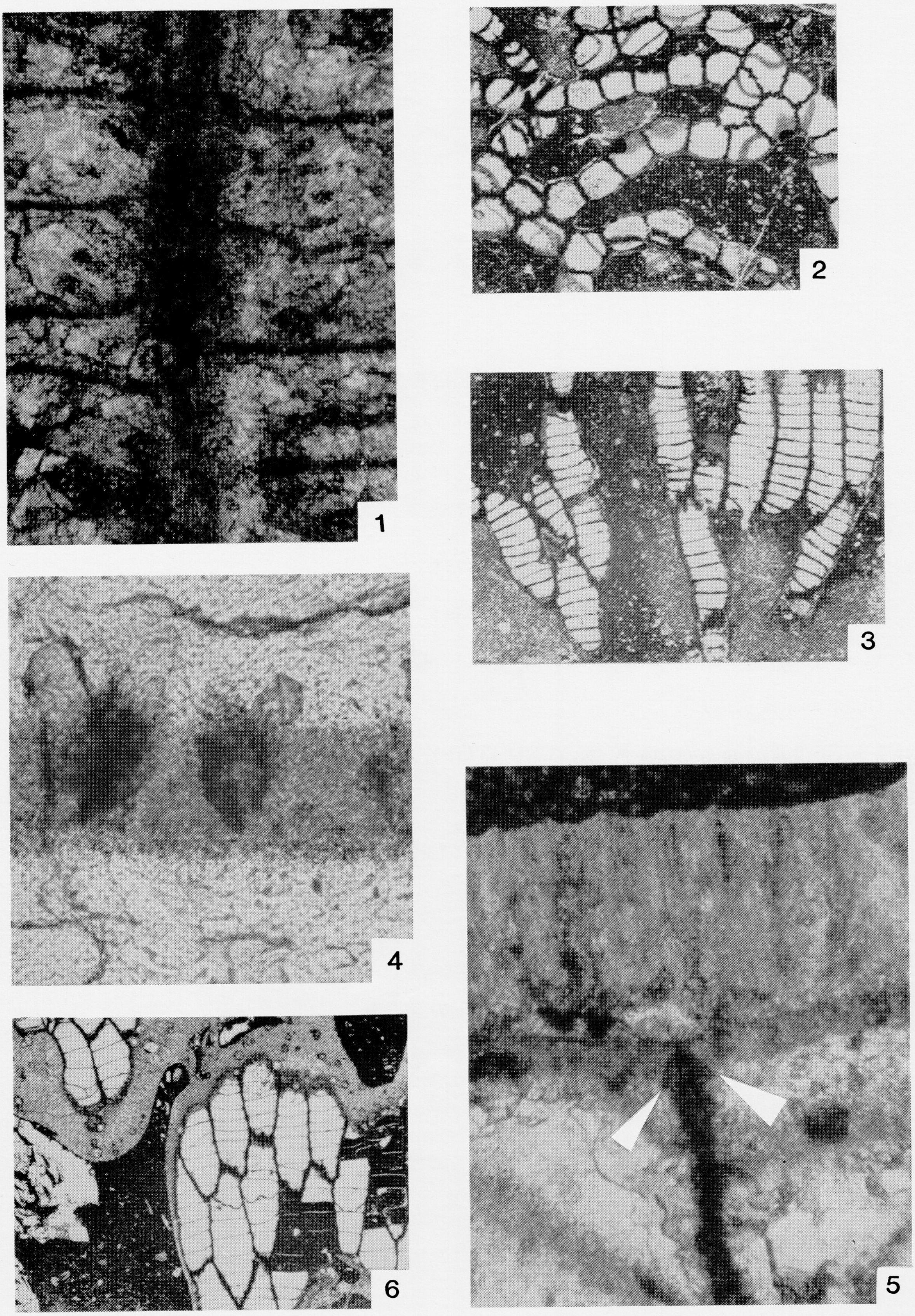


PLATE 3

Figures 1, 2.-*Manipora bighornensis* n. sp., encrusted by *Coccoseris* sp. (UND 13662.).

1. Transverse section of *M. bighornensis*, X3.5.
2. Transverse section of *M. bighornensis*, X3.5.

Figures 3-5.-*Angopora wyomingensis* n. sp., (UND 13754.).

3. Longitudinal section showing closely-spaced tabulae, X7.3.
4. Longitudinal section with crenulate wall, septal spines, and lamellar septa (arrow), crossed nicols, X47.
5. Oblique section, X7.2.

Figures 6-8.-*Favosites manitobensis* n. sp., (UND 13751.).

6. Transverse section, X4.8.
7. Corallite wall on basal surface of corallum, rows of mural pores shown by rows of light gray dots, X4.0.
8. Longitudinal section with trabeculae in obliquely-cut walls (arrow) and crenulate tabular margins, X3.9.

Plate 3

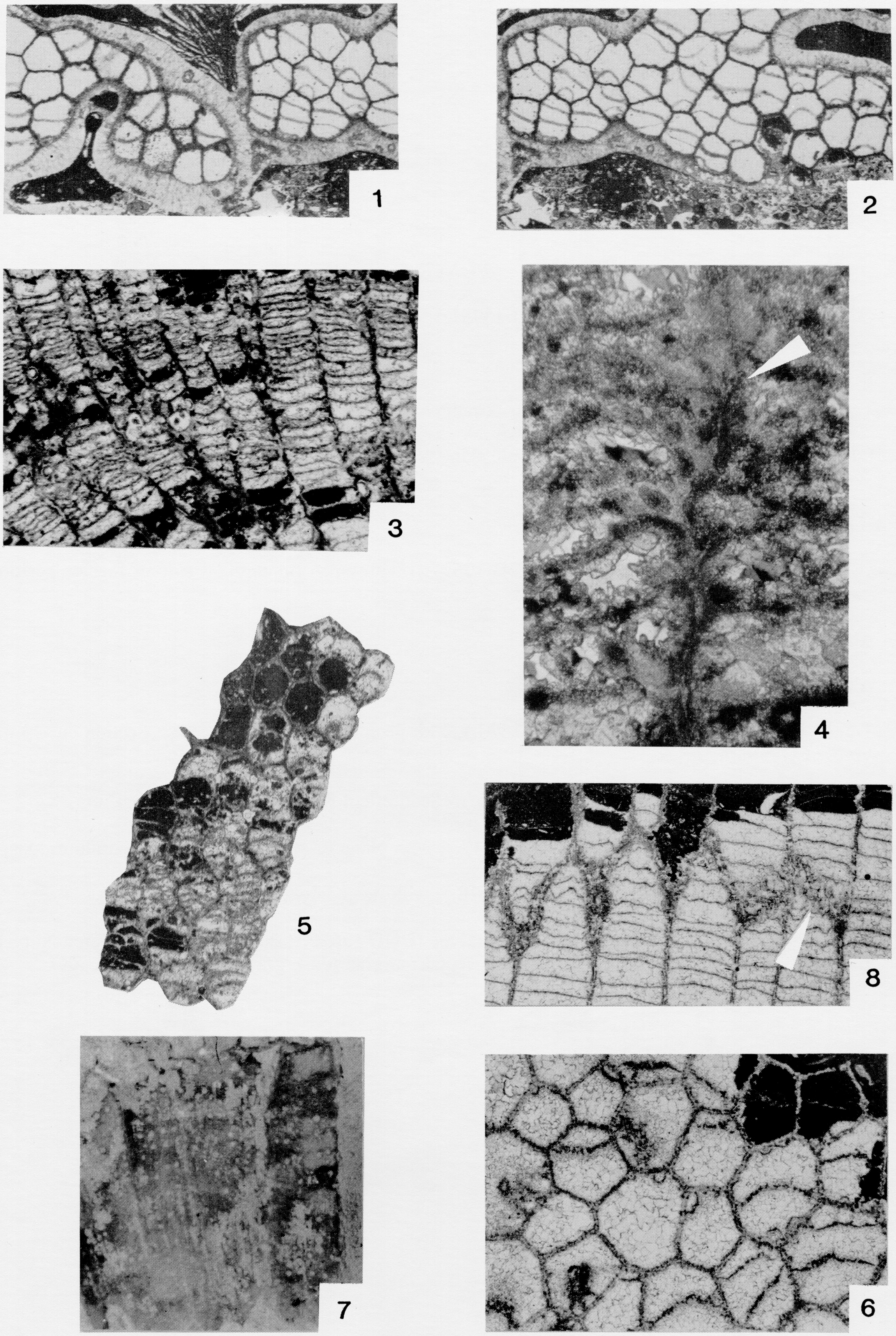


PLATE 4

Figures 1-3.-*Favosites manitobensis* n. sp., (UND 13751.).

1. Longitudinal section with trabecular expansions of axial plate, crossed nicols, X47.
2. Transverse section at intersection of four corallites, crossed nicols, X47.
3. Longitudinal section obliquely cutting wall plane with three trabeculae (outlined in black), crossed nicols, X47.

Figures 4-11.-*Streptelasma kelpinae* n. sp.

4. Cardinal side of corallum (paratype, UND 13697.), with notch on cardinal side of former position of calicinal rim, X1.
5. Alar side of paratype (UND 13697.), X1.
6. Alar side of holotype (UND 13699.). X2.
7. Transverse section of paratype (UND 13620.), with prominent cardinal fossula. Section cut 13 mm from apex of corallum, X3.9.
8. Transverse section of paratype (UND 13615.). Section cut 8 mm from apex of corallum, X4.2
9. Longitudinal section of paratype (UND 13617.), with plane of section eccentric to corallum axis, X1.9.
10. Longitudinal section of paratype (UND 13618.), with deep calyx, X2.6.
11. Transverse section of three major septa of paratype (UND 13620.), showing textural differentiation between trabeculate centers of septa (light gray) and septal margins (dark gray), crossed nicols, X47.

Plate 4

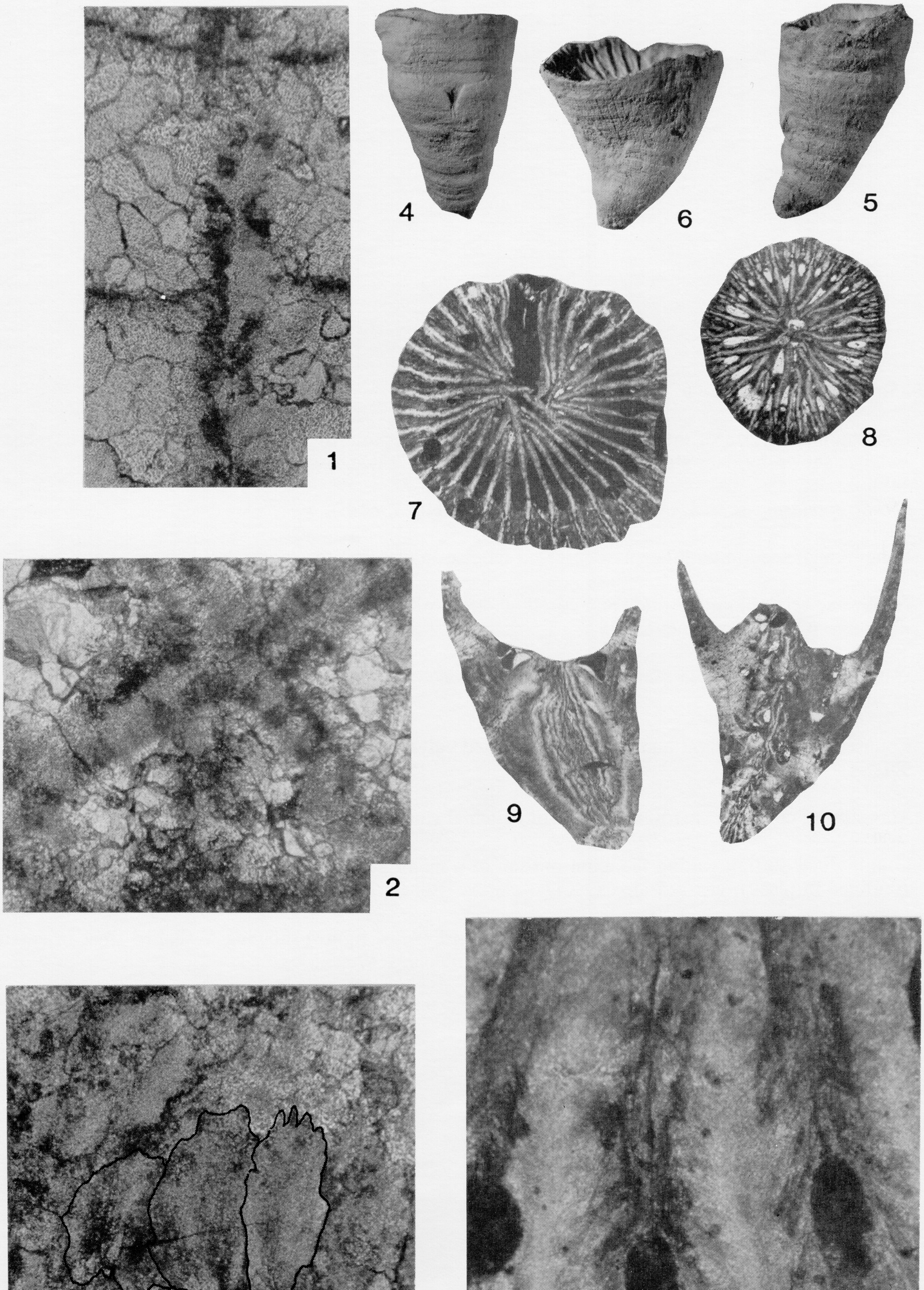


PLATE 5

Figure 1.-*Streptelasma kelpinae* n. sp.

1. Longitudinal section of the central portion of a major septum of paratype (UND 13617.). Trabeculate bundles shown by dark streaks, corallum axis toward right, crossed nicols, X47.

Figures 2-8.-*Streptelasma sheridanensis* n. sp., holotype (UND 13634.).

2. Longitudinal section with deeply-depressed tabulae in cardinal fossula on left side of columella, X2.6.
3. Transverse section, cut 10 mm from corallum apex, with slight flattening in alar plane, and cardinal septum at twelve o'clock position, X2.9.
4. Transverse section, cut 25 mm from apex, with pronounced axial vortex, and cardinal septum at one o'clock position, X2.3.
5. Counter side of corallum and portion of inclined calyx, portion of calicinal rim remains on cardinal side, X1.
6. Alar side of corallum, cardinal portion of calicinal rim, and mound-like columella, X1.
7. Longitudinal section cutting the axial portion of a major septum, showing three trabecular boundaries (outlined in black), crossed nicols, X47.
8. Transverse section of two major septa (axis toward top of figure) showing V-shaped fiber orientation and zonation of fiber textures in trabeculae, crossed nicols, X47.

Plate 5

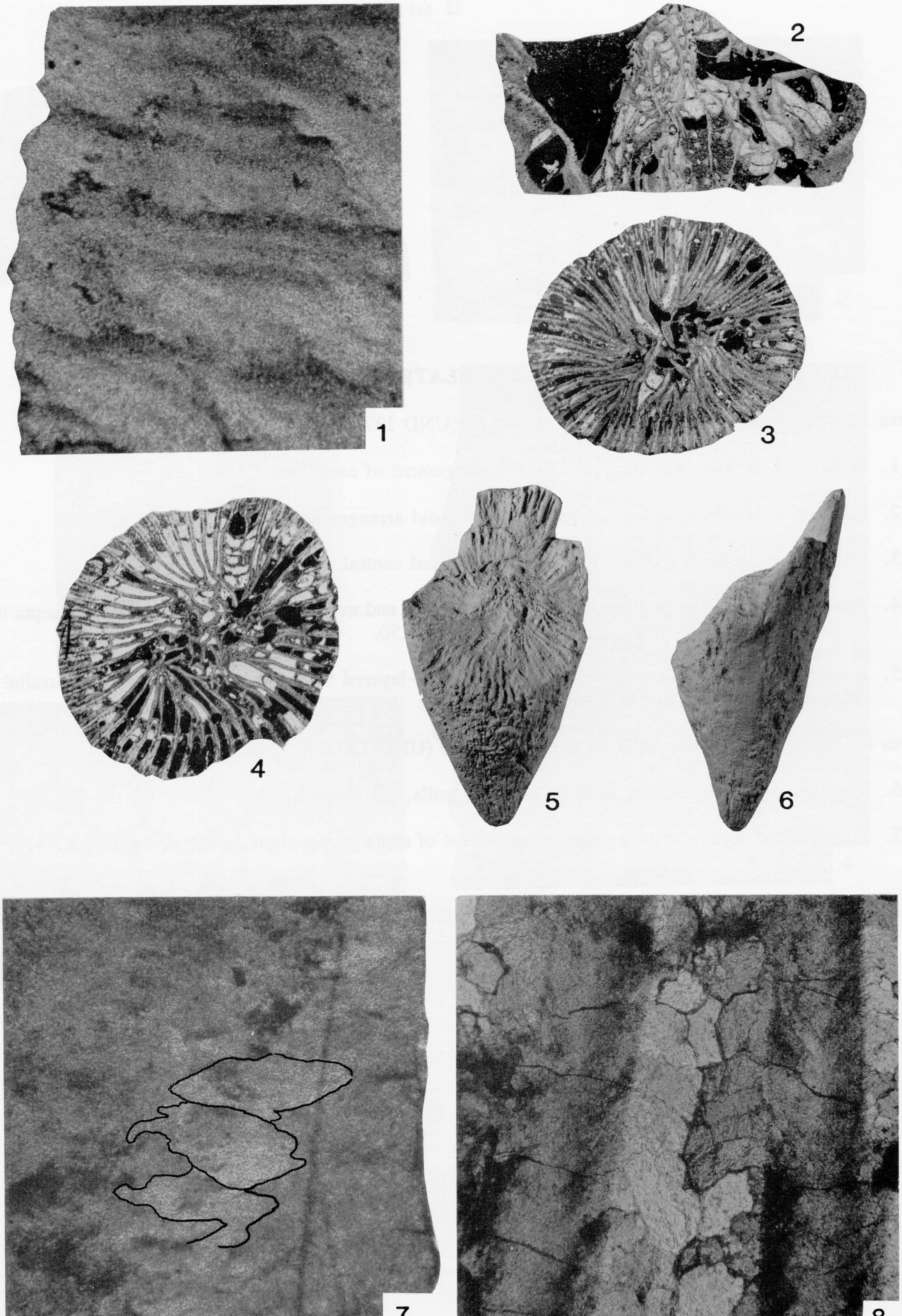


PLATE 6

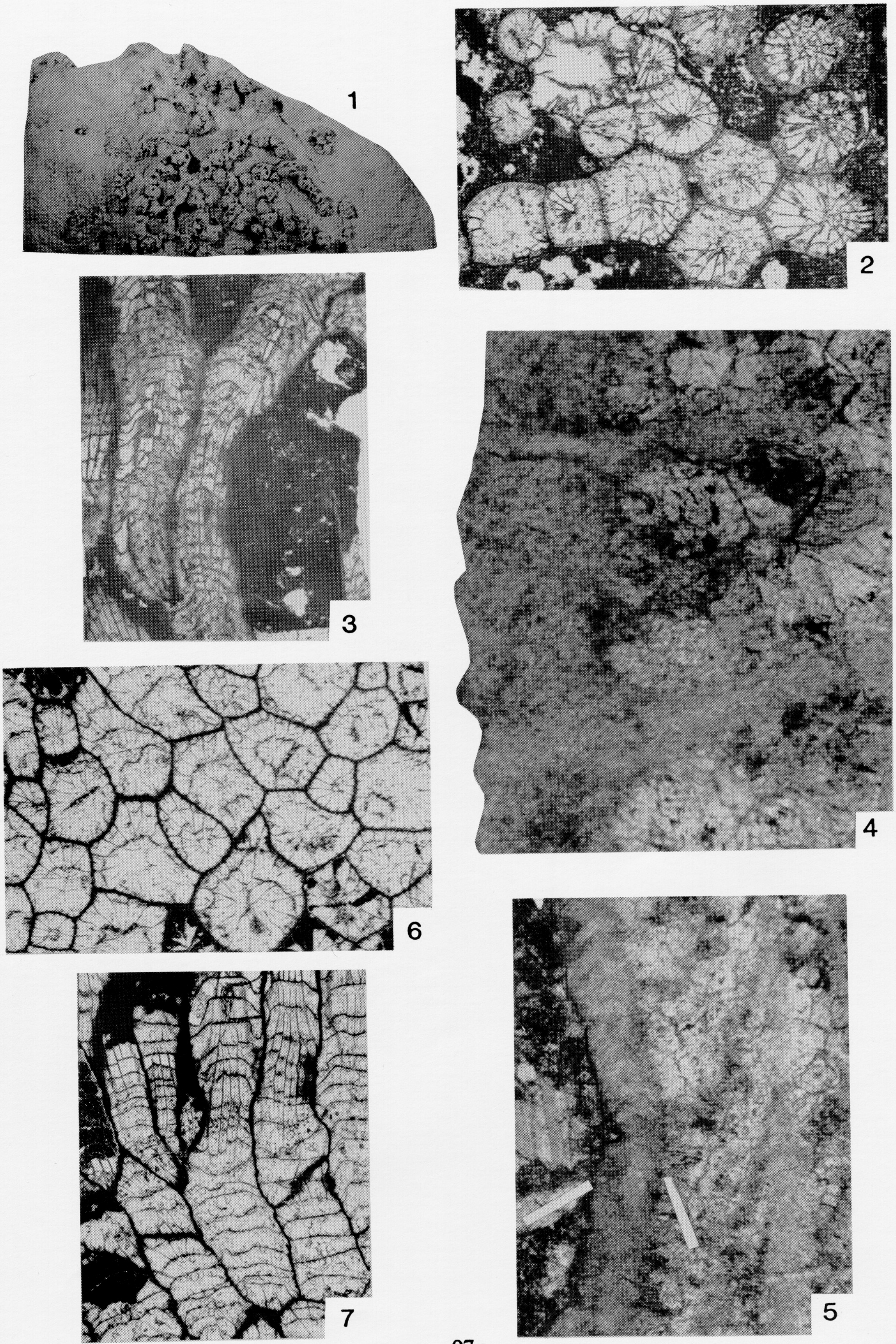
Figures 1-5.-*Palaeophyllum sinclairi* n. sp., holotype (UND 13706.).

1. Portion of corallum showing cateniform arrangement of corallites, X1.3.
2. Transverse section showing cateniform and cerioid arrangement of corallites, X3.3
3. Longitudinal section showing tabulae with elevated central platform, X3.8.
4. Transverse section through corallite wall, and major and minor septa showing insertion of septa in corallite wall, corallite axis toward right, crossed nicols, X150.
5. Longitudinal section of corallite wall showing two-layered fiber orientation (white lines parallel to fiber orientation), crossed nicols, X47.

Figures 6, 7.-*Cyathophylloides hollandi* n. sp., holotype (UND 13727.).

6. Transverse section showing rounded corallite walls, X3.4.
7. Longitudinal section showing amplexoid retreat of septa (upper right corner of figure), X2.4.

Plate 6



ARTHROSTYLIDAE (BRYOZOA: CRYPTOSTOMATA) FROM THE GUNN MEMBER, STONY MOUNTAIN FORMATION (UPPER ORDOVICIAN), NORTH DAKOTA AND MANITOBA

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ABSTRACT

The Gunn Member of the Stony Mountain Formation (Upper Ordovician) has long been known to contain an abundant and diverse fauna in outcrop. In the subsurface, the Gunn Member underlies most of North Dakota and contains an even more diverse fauna in some respects than does the outcrop, but it has never been looked at from a paleontological perspective.

In this paper on the Arthrostylidae (Bryozoa: Cryptostomata) of the Gunn Member, two new genera (*Arthrotrypa* and *Nematoporella*) are erected, and a third genus (*Ulrichostylus*) is redefined. Nine species are described: *Arthroclema brevis* n. sp., *A. pentagonalis* n. sp., *Arthrotrypa ovata* n. sp., *Nematoporella ulrichi* n. sp., *N. falcata* n. sp., *Sceptropora facula* Ulrich, *S. florida* Kiepura, *Ulrichostylus costatus* n. sp., and *U. dakotensis* n. sp.

INTRODUCTION

The Upper Ordovician Gunn Member of the Stony Mountain Formation crops out about 10 km north of the city of Winnipeg, Manitoba, on the outskirts of the village of Stony Mountain. It exists in the subsurface throughout most of North Dakota and in southeastern Manitoba, southwestern Saskatchewan, eastern Montana, and a small portion of northwestern South Dakota. The unit exceeds 30 m in thickness in eastern North Dakota, just west of its erosional margin, and thins to the north and west. The northern and western limits of the Gunn Member are depositional. Throughout its extent, the Gunn Member overlies the Red River Formation and is overlain by the Penitentiary Member of the Stony Mountain Formation in outcrop, and by the Gunton Member in the subsurface. The fauna of the Gunn Member is abundant and diverse, but surprisingly little of that fauna has received any sort of comprehensive or modern treatment.

The Gunn Member is composed of thin, relatively pure bioclastic limestone interbedded with calcareous shale or very argillaceous limestone. The shale or argillaceous limestone is largely reddish purple in outcrop. In the subsurface, it is medium olive gray or pinkish gray in eastern North Dakota, becoming darker olive gray in the central part of the state and almost black in the deepest wells in western North Dakota.

In outcrop, the fauna consists of an articulate brachiopod-solitary coral assemblage. Articulate brachiopods and solitary corals are abundant, trepostome and cryptostome bryozoans and gastropods are common, tabulate corals and cephalopods are uncommon, and pelecypods and identifiable trilobites are rare.

In the subsurface, the fauna may be characterized as an articulate brachiopod-bryozoan assemblage. Articulate brachiopods and trepostome and cryptostome bryozoans are abundant, solitary corals are common, tabulate corals and mollusks (except for abundant microscopic mollusks in core from four wells) are un-

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common, and inarticulate brachiopods and identifiable trilobites are rare.

The presence of several species of distinctive Richmondian fossils indicates that the Gunn Member is Richmondian (late Ashgillian) in age (Lobdell, 1988).

PREVIOUS WORK

The first report of fossils from the Gunn Member was a sketchy faunal list published by Whiteaves (1880), who reported on two collections made in the 1870's. Ulrich (1889) did the first systematic paleontology on fossils of the Gunn Member; he described a collection of bryozoans and ostracodes sent to him by Whiteaves. Whiteaves (1895) published an annotated faunal list, much more complete than his earlier one, and Dowling (1900) also published a faunal list in conjunction with his lithologic and stratigraphic descriptions. Wilson (1938) illustrated the only gastropod from the Gunn Member ever to be pictured. Okulitch (1943) published faunal lists for the several members of the Stony Mountain Formation and described and named two species each of brachiopods and corals. Leith (1952) described two species and one new genus of heliolitide corals from the Gunn Member. Ethington and Furnish (1960) did a sketchy study of conodonts from the Gunn Member. Macomber (1970) described and illustrated a number of Gunn Member specimens in his study of articulate brachiopods from the Bighorn Formation of Wyoming, and Elias (1983) described and illustrated all four species of solitary corals from the Gunn Member. From the subsurface, Ross (1957) illustrated a small fauna from the Gunn Member in eastern Montana, and Brindle (1960) did the same from well cores in Saskatchewan.

ARTHROSTYLID BRYOZOANS

The Arthrostylidae are a family of small, twig-like, commonly articulated cryptostome bryozoans. They are represented in the Gunn Member of the Stony Mountain Formation by nine species in five genera and are extremely abundant in places: more than 7,000 specimens were collected from the subsurface of North Dakota. Collecting localities are shown in Figure 1 and are listed in Appendix I.

Of the nine arthrostylid species found in the Gunn Member, seven are previously undescribed; only the two species of *Sceptropora* have been reported beyond the limits of the Stony Mountain Formation. Only six of these species were found in outcrop, and only *S. facula* Ulrich is common there. In the subsurface, *S. facula* is the most abundant bryozoan, and *S. florida* Kiepura and *Arthroclema pentagonalis* n. sp. are also abundant. The geographic distribution of the fauna is summarized in Table 1.

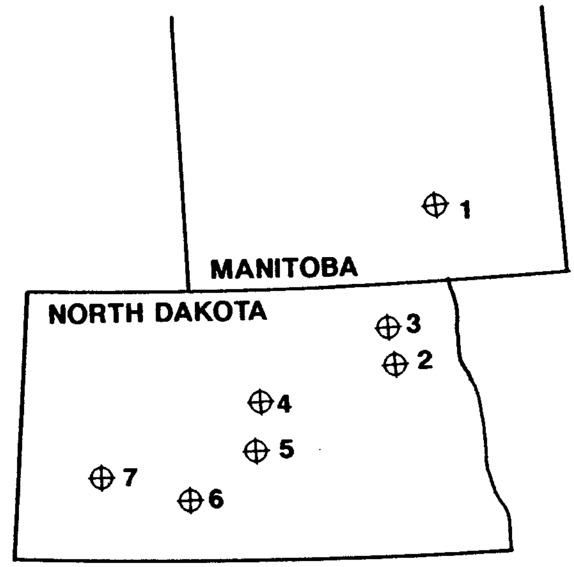

Figure 1-Location of collecting sites of arthrostylids from the Gunn Member. For detailed description of collecting localities, see Appendix.

Few wells have a completely cored section of the Gunn Member, and of those that do, only those at localities 2 and 4 (in Ramsey and McHenry Counties, North Dakota, respectively) have contributed enough specimens to be worth consideration biostratigraphically. Locality 2 is in northeastern North Dakota, in an area inferred to have been a rather shallow shelf, and locality 4 is in central North Dakota, where the water is inferred to have been somewhat deeper than at locality 2. Regardless of whether inferences as to water depth are correct, these two sites seem to have some differences in relative abundances of arthrostylid bryozoans, summarized in Table 2. Particularly striking are the differences between the two species of *Arthroclema* and between the two species of *Sceptropora*. It is not possible to determine whether these differences reflect water depth, turbulence, or merely geographic separation and patchy distribution of the fauna (the two localities are separated by about 175 km).

While the arthrostylids do seem to show some variation in their vertical distribution the only distinctive stratigraphic fossil among them is *Sceptropora facula* Ulrich, generally found in Richmondian strata over much of northeastern and north-central North America, as well as in the Baltic area. *Sceptropora facula* is found throughout the entire vertical extent of the Gunn Member at locality 2, but it is restricted to the upper three-quarters of the interval at locality 4. However, this absence from the lowest 5.6 m of the section at locality 4 seems more likely to be due to local conditions rather than to an age difference; only

Table 1-Geographic distribution of Gunn Member arthrostylids.

Location	1	2	3	4	5	6	7
Arthroclema brevis n. sp.		X		X		X	
A. pentagonalis n. sp.	X	X	X	X	X	X	
Arthrotrypa ovata n. sp.	X	X	X				
Nematoporella ulrichi n. sp.	X	X	X	X		X	
N. falcata n. sp.	?	X	X	X			
Sceptropora facula Ulrich	X	X	X	X		X	X
S. florida Kiepura	X	X	X	X		X	
Ulrichostylus costatus n. sp.		X		X		X	
U. dakotensis n. sp.		X		X			

Table 2-Relative abundances of arthrostylid bryozoans, localities 2 and 4, expressed as percentages of identified arthrostylid specimens.

Species	Locality 2	Locality 4
Arthroclema brevis n. sp.	4.5%	28.2%
A. pentagonalis n. sp.	19.8	1.5
Arthrotrypa ovata n. sp.	0.9	-
Nematoporella ulrichi n. sp.	0.9	1.1
N. falcata n. sp.	1.6	2.0
Sceptropora facula Ulrich	56.3	28.4
S. florida Kiepura	15.2	28.4
Ulrichostylus costatus n. sp.	0.1	2.0
U. dakotensis n. sp.	0.7	8.3

four specimens of all species of cryptostomes were collected from this lower interval.

Among the other arthrostylids, only *Arthrotrypa ovata* n. sp. and the two species of *Ulrichostylus* show any possibility of being stratigraphically useful. *Arthrotrypa ovata* is restricted to the lowest 10 m at locality 2, and is not found west of there. *Ulrichostylus costatus* and *U. dakotensis* are also restricted to the lowest 10 m at locality 2, but have a distribution similar to the other arthrostylids at locality 4. However, these species seem to be endemic to the Gunn Member, and therefore have no utility beyond its limits.

SYSTEMATIC PALEONTOLOGY

In the synonomies I have listed the authors and works in which a description or illustration of a given species may be found. I have not included in synonomy faunal lists or comprehensive compilations, although compilations such as those by Nickles and Bassler (1900) and Bassler (1915) proved very helpful in searching the literature.

Under "Material and Occurrence" I give a close estimate of the number of specimens, their general condition, and the localities where they were collected.

I wanted to inform others whether the species descriptions are founded on one fragmentary specimen, several well-preserved specimens, or a population of 50 or 500 individuals. Such information is important in the evaluation of the systematics.

The diagnosis gives those features by which a species may be most readily distinguished from congeneric species. Where possible, it is based on features seen in many specimens; the approach is population-based rather than typological. Particular characters by which the species under consideration may be differentiated from similar-appearing species are given in the discussion. The discussion also contains the reasoning that supports my taxonomic decisions.

Type specimens are reposited at the United States National Museum, and those numbers are prefixed with USNM. Other illustrated specimens are in the collections of the Department of Geology and Geological Engineering, University of North Dakota, and are prefixed by UND.

Phylum **BRYOZOA** Ehrenberg, 1831
Class **STENOLAEMATA** Borg, 1926
Order **CRYPTOSTOMATA** Vine, 1884
Suborder **RHABDOMESINA** Astrova and Morozova, 1956
Family **ARTHROSTYLIDAE** Ulrich, 1888 (1882)

Discussion.--The name Arthrostylidae was proposed by Ulrich (1888, p. 230) as a replacement for Arthronemidae (Ulrich, 1882, p. 151) because the latter had been based on a generic name that was a junior synonym. Following Recommendation 40A of the International Code of Zoological Nomenclature (International Commission on Zoological Nomenclature, 1985, p.81) both dates are given above.

Genus ***Arthroclema*** Billings, 1862

Type Species.--*Arthroclema pulchellum* Billings, 1862 (by monotypy).

Discussion.--Blake (1983, p. 554-555) has recently published a thorough description of *Arthroclema*; his concepts are followed herein.

Arthroclema brevis n. sp.
Plate 1, figs. 1-14, 24

Etymology.--From the Latin *brevis*, short, referring to the unusually short segments of this species.

Diagnosis.--*Arthroclema* having exceptionally short, stubby segments and a smooth exterior.

Description.--Zoarium articulated, probably consisting of primary, secondary, and tertiary segments; growth form unknown. Segments usually having six ranges of zooecia, commonly (in about 20% of the specimens) with seven, rarely with five. Proximal terminus slightly convex; distal terminus flat to shallowly concave; ends vary from having same diameter as rest of segment to being moderately enlarged; segment faces slightly concave. Primary segments 2.5 to 4 mm long, averaging 3.1 mm, and fairly uniformly about 0.7 mm thick; zooecia commonly poorly defined. Zooecial apertures elongate-ovate, about 0.2 mm long and 0.08 to 0.12 mm wide; 4 to 6 zooecia in 2 mm, average 5. Peristomes faint to moderately strong, in some cases produced into small, spine-like protuberances proximally. Surface ornamentation usually subdued; lateral sockets commonly not well defined. Rare, stubby segments (USNM 449130 and 449131; plate 1, figs. 12 and 14) may be as much as 1.0 mm thick and 1 to 2 mm long; zooecia rare on these segments, interpreted as aberrant primary segments. Secondary segments 1.8 to 4.0 mm long, average length of 21 measured segments is 2.4 mm, and 0.45 to 0.7 mm thick, average is about 0.56 mm. Tertiary segments 1.35 to 2.1 mm long, average length about 1.75 mm, and 0.35 to 0.5 mm thick (average about 0.45 mm).

Discussion.--The major problem with identifying and describing species assigned to *Arthroclema* is that partial or complete zoaria are known for only two species. Thus, it is not possible to document within-colony and between-colony variation. However, the lateral sockets and overall morphology identify these segments as *Arthroclema*, and they differ sufficiently from all known species to be regarded with fair confidence as a separate species.

Arthroclema brevis has shorter segments with a larger width to length ratio than any other species of *Arthroclema* except *A. cornutum*; the latter species is five-sided and has a papillose exterior (Ulrich, 1893). *Arthroclema brevis* also has an unusually smooth exterior.

Material and Occurrence.--Approximately 400 segments or fragments of segments were collected, all from the subsurface of North Dakota. Six specimens were collected from locality 6, about 100 from locality 4, and the remainder from locality 2. All specimens appear to be abraded to a greater or lesser degree, but otherwise preservation is quite good.

Specimen USNM 449127 is here designated the holotype, and specimens USNM 449128 through USNM 449141 are designated paratypes. The interval between 26.5 ft (8.1 m) and 29.5 ft (9.0 m) above the base of the Gunn Member at locality 3 is designated the type horizon and locality.

Arthroclema pentagonalis n. sp.
Plate 1, figs. 15-23, 25-28

Arthroclema angulare (*non*) Ulrich, 1889, p. 45 (*nomen nudum*).
Arthroclema angulare Ulrich Whiteaves, 1895, p. 117.

Etymology.--From the Greek *penta*, five, referring to the number of zoarial sides normally possessed by this species.

Diagnosis.--Five-sided *Arthroclema* having long, relatively thin segments and a pronounced projection of the proximal portion of the peristome.

Description.--Zoarium articulated, probably consisting of primary, secondary, and tertiary segments; growth form unknown. Sections more or less pentagonal in cross section, rarely hexagonal. Primary segments more obscurely pentagonal than either secondary or tertiary segments. Length of segments unknown. Zooecial apertures elongate-ovate, about 0.1 mm by 0.2 mm; 4 to 5 zooecia in 2 mm longitudinally. Primary segments about 0.5 to 0.6 mm thick; some fragments exceed 4 mm in length. Peristome not well developed. Proximal terminus swollen and rounded; distal terminus flared into a five-sided flange, usually bearing a planar surface or a shallow socket; lateral sockets oval, and may be more than 0.5 mm in all dimensions; surface ridged. Secondary segments 0.4 to 0.5 mm thick; angles between faces sharply defined and flaring into projections at distal end, giving the distal terminus the appearance of a five-pointed star; proximal portion of peristome commonly produced into a spine-like projection; proximal terminus rounded and slightly swollen; striae strong; lateral sockets uncommon, oval, about 0.2 by 0.3 mm. Tertiary segments 0.2 to 0.35 mm thick; peristomes and their distal projections relatively less pronounced than those of secondary segments, otherwise like small secondary segments.

Discussion.--The difficulties attendant upon working with isolated segments of *Arthroclema* and in identifying and describing new species have been discussed above for *A. brevis*. These difficulties are even more pronounced in the case of the present species; unbroken segments are unknown. However, the lateral articulation sockets and overall morphology identify these segments as *Arthroclema*, and the segments differ sufficiently from all known species of *Arthroclema* so that they may be considered with reasonable confidence to be a distinct species.

It should be recognized that identification of primary, secondary, and tertiary segments represents a somewhat arbitrary exercise of judgment, as examples of intact colonies, and even whole segments, are lacking. Especially, it may be that the slender segments here regarded as tertiary segments actually represent a separate species assignable to *Arthroclema* or *Ulrichostylus*.

Arthroclema pentagonalis differs from *A. angulare*, the only previously described Cincinnatian species of *Arthroclema*, by possessing substantially slenderer segments and by normally being five-sided rather than six-sided. I have tentatively included Ulrich's (1889) *A. angulare* from the Stony Mountain, and the subsequent citation of that work, in synonymy as I have not seen any undoubted specimens of that species in my collections. I believe it likely that Ulrich misidentified a few poorly preserved specimens of *A. pentagonalis* as being conspecific with the only Cincinnatian species of *Arthroclema* known to him.

Arthroclema pentagonalis has much longer segments and a rougher exterior than *A. cornutum* (Ulrich, 1890, 1893). *Arthroclema pentagonalis* has longer and thinner segments than *A. striatum* (Ulrich, 1893) and is more strongly ornamented. *Arthroclema armatum* (Ulrich, 1890) has an appearance similar to that of *A. pentagonalis* but is six-sided, as is *A. pulchellum*. *Arthroclema billingsi* has shorter segments and four lateral sockets in each primary segment.

Material and Occurrence.--Approximately 1500 segments definitely or probably assignable to this species have been collected. The vast majority of these (about 1300) come from subsurface locality 2. Another 120 were from locality 3, and several specimens each were collected from localities 4, 5, and 6. Only 22 specimens were collected from outcrop. Many of the specimens from the lower portion of the Gunn Member in the subsurface are excellently preserved, except for being broken; those from the upper strata and from outcrop are commonly coated with matrix that obscures surface detail.

Specimen USNM 449142 (plate 1, fig. 18) is here designated the holotype of *Arthroclema pentagonalis*. This specimen lacks both distal and proximal ends, but does show two lateral sockets. It displays the typical primary segment morphology proximal to the more distal socket, and the typical secondary segment morphology distal to that socket. Other features, such as the distal and proximal ends, the spinose projections of the peristomes, and the typical forms of primary, secondary, and tertiary segments, together with internal features, are shown by USNM 449143 through USNM

449156, here designated paratypes. The lowest three feet (0.9 m) of the Gunn Member at locality 2 is the type horizon and locality.

Genus ***Arthrotrypa*** n. gen.

Helopora Hall Ulrich, 1888, 1890, 1893 (*partim*); Bassler, 1953 (*partim*); Astrova, 1965 (*partim*); Goryunova, 1985 (*partim*).
Nematopora Ulrich Blake, 1983 (*partim*).

Etymology.--From the Greek *arthron*, joint, and *trypa*, hole, referring to the segmented form of these zoaria.

Type species.--*Helopora harrisi* James, 1883 (here designated).

Diagnosis.--Articulated arthrostylids having long, thin segments; lateral articulation lacking; peristome thin, of equal height all around; zooecia alternating on adjacent faces.

Description.--Zoarium segmented, jointed longitudinally; lateral articulation unknown but branching probably occurred at segment ends; segments slender, less than 0.5 mm thick, and exceeding 3 mm in length; zoaria arranged in six longitudinal rows, each face slightly concave and separated from adjacent faces by a longitudinal ridge, giving the segment a hexagonal cross section; zooecia alternate in position on adjacent faces, so that each zooecium is flanked by interzooecial skeleton; proximal ends of segments slightly to moderately tapered and striated; distal terminus somewhat infalted and bearing one or two articulation surfaces.

Discussion.--This genus has been erected to accommodate segmented species that are lacking features such as ornamentation and apertural shape and arrangement that would justify their being assigned to *Ulrichostylus*. Specifically, in *Arthrotrypa* the peristome is a thin, fine structure of about equal height throughout, whereas in *Ulrichostylus* that structure is much thicker and commonly produced proximally into a spine-like projection. *Arthrotrypa* has zooecia arranged in an alternating pattern; in *Ulrichostylus*, the zooecia on adjacent faces are each at about the same level, or only slightly offset from that level, producing a gentle spiral arrangement of zooecia. At present only two species, *Arthrotrypa harrisi* (James, 1883) and *A. ovata* n. sp., are assigned to this genus, although I suspect that, as Ordovician members of this family become better known, more species will be placed here.

The generic placement of James's (1883) *Helopora harrisi* has presented a bit of a problem. The genus *Helopora*, as constituted in the 19th century, was divisible into at least two genera, as recognized and discussed by Ulrich (1893, p. 189-191). Bassler (1952) erected a second genus, *Ulrichostylus*, to accommodate Ordovician species previously assigned to *Helopora*, but this still left *H. harrisi* uncomfortably placed. The latter species seems to differ from others assigned to *Ulrichostylus* in apertural shape and arrangement, segment thickness, and ornamentation. Blake (1983, p. 592) assigned *H. harrisi* to *Nematopora*, making *N. harrisi* the only species of *Nematopora* to be segmented and not known to bifurcate. This seems an unsatisfactory arrangement also. I am therefore erecting the genus *Arthrotrypa* to accommodate *Helopora harrisi* and the new species, *Arthrotrypa ovata*. As *A. harrisi* is better known and was the species first described, I am here designating *Helopora harrisi* James, 1883, the type species of *Arthrotrypa*.

Arthrotrypa ovata n. sp.
Plate 1, figs. 29-35

Helopora Harrisi James. Ulrich, 1889, p. 45-46.
Helopora Harrisii James. Whiteaves, 1895, p. 117.

Etymology.--From the Latin *ovatus*, egg-shaped, referring to the shape of the zooecial aperture.

Diagnosis.--*Arthrotrypa* having more abundant zooecia and thicker segments than the type species.

Description.--Segments about 0.25 to 0.35 mm thick; length probably about 3.5 mm, possibly somewhat longer; strong longitudinal ridges mark angles between faces; zooecial apertures oval and rimmed by sharp, distinct peristome of low, uniform height, the peristome, in some cases, appearing to merge into the longitudinal ridges; zooecial apertures about 0.1 mm by 0.2 mm, about 7 in 2 mm, separated longitudinally by about half their length.

Discussion.--This species bears a strong resemblance to *Arthrotrypa harrisi* (James, 1883) as described and illustrated by Ulrich, (1890, 1893). The size and shape of the segments are quite similar, as are the number of ranges, the longitudinal ridges on the angles between the faces, and the proximal termination. The distal termination appears slightly different. It seems apparent that the two species were closely related. Certainly Ulrich (1889, p. 45) can not be faulted for referring "a number of very slender segments . . . not in a very good state of preservation" to *Helopora harrisi*. If his material was as poorly preserved as are my outcrop specimens, he would have been on very shaky ground in attempting to describe a new species. Fortunately, the subsurface material is considerably better preserved.

The major difference between the two species is that *Arthrotrypa ovata* has almost twice as many zooecia as does *A. harrisi*: 7 in 2 mm compared to 4 in 2 mm (Ulrich, 1893, p. 195). The peristomes are more distinct in *A. ovata*, and the segments somewhat thicker. These differences serve to distinguish the two species.

Material and Occurrence.--More than 100 specimens, all fragmentary, have been collected. Four of these, poorly preserved and encrusted with matrix, are from outcrop and are questionably assigned here. An additional 40 or so specimens are from subsurface locality 3, and the remainder from locality 2. The specimens from the subsurface are generally preserved fairly well, although commonly fine detail is obscured.

Specimen USNM 449157 is here designated the holotype; USNM 449158 through 449164 are designated paratypes. The type locality is locality 3, and the type horizon is from 11.0 ft (3.4 m) to 13.5 ft (4.1 m) above the base of the Gunn Member.

Genus ***Nematoporella*** n. gen.

Etymology.--From the Latin suffix *ella*, small, appended to the genus name *Nematopora*.

Type species.--*Nematoporella ulrichi* n. sp., here designated.

Diagnosis.--Arthrostylids lacking segmentation and branching.

Description.--Zoarium unbranched, unjointed, articulated only basally. Zoaria slender, diameters about 0.2 mm to 0.6 mm. Cross section polygonal to subcircular. Zoarial apertures usually in 4 to 6 longitudinal ranges. Longitudinal ridges commonly strong between ranges. Peristomes usually present. Linear axis well defined.

Discussion.--As it has been the practice, for this family, to consider segmentation and branching to be characters of generic significance, this genus has been erected to accommodate unbranched, unsegmented arthrostylids. It may be, however, that these genera bear little relation to the actual phylogeny within the family. This merely emphasizes the need for a family-level monograph; however, this would require much more collecting and processing of samples.

For the present, I am restricting this genus to the two species described below. However, it is possible that other species, previously referred to *Helopora* and now assigned to *Ulrichostylus*, actually belong here. For instance, Ulrich (1890, p.191-192) named and illustrated *Helopora mucronata* and *H. alternata*. He considered them segmented but did not describe the distal termination of the segments. *Helopora alternata*, particularly, seems a good candidate for assignment to *Nematoporella*, but I have not examined the type material.

Nematoporella ulrichi n. sp.
Plate 2, figs. 23-28

Nematopora (?) n. sp. Ulrich, 1889, p. 47.

Etymology.--Named in honor of E. O. Ulrich, who first described this species.

Diagnosis.--Long species of *Nematoporella* having pronounced longitudinal ridges that are displaced by zooecial apertures.

Description.--Zoarium slender, about 0.2 to 0.3 mm thick. Zooecial apertures elongate-ovate, about 0.1 by 0.2 mm, with about 3 in 1 mm longitudinally. Zooecia usually in 6 ranges, occasionally in 5, separated by longitudinal ridges displaced by zooecial apertures. Second set of ridges forms lateral margins of apertures; third range sometimes present. Proximal articulation a blunt planar surface, about 0.1 mm thick, tapering gradually over initial 0.5 mm of the zoarium. Distal ends pointed.

Discussion.--This is undoubtedly the unnamed species described briefly by Ulrich (1889, p. 47). He reported it as being five-sided. The majority of my specimens are six-sided, but this is not an insurmountable obstacle to considering them the same species: a few are indeed five-sided, and Ulrich's specimen was imbedded in matrix.

Material and Occurrence.--About 75 specimens have been recovered, most from locality 2. The outcrop and localities 3, 4, and 6 have each contributed one to several specimens. Preservation ranges from poor to good, with the specimens from outcrop and those from locality 2 being better preserved.

I have no specimen definitely retaining both the distal and proximal terminations. I am therefore selecting as the holotype a specimen having the proximal termination (USNM 449165; plate 2, fig. 25); USNM 449166 through 449169 are designated paratypes. These specimens are all from the type locality and horizon (locality 2, about 38 ft [11.6 m] above the base of the Gunn Member). This locality and horizon were chosen because the material is abundant (more than 40% of the specimens were from here) and quite well preserved.

Nematoporella falcata n. sp.
Plate 2, figs. 29-34

Etymology.--From the Latin *falcatus*, sickle-shaped, referring to the usual shape of the zoarium.

Diagnosis.--*Nematoporella* having short, curving zoaria.

Description.--Zoarium usually gently curved, a few straight; short, 1 mm to 2.5 mm long, 0.2 to 0.3 mm thick; zooecia in 6 ranges, alternating in position so that zooecial apertures in one face are at same level as interzooidal spaces on adjacent faces; apertures oval, about 0.13 by 0.20 mm, 3 in 1 mm longitudinally; peristome thin, sharp, commonly with low, rounded projection proximally; lateral peristome ridges continuous longitudinally, giving the appearance of demarking the margins of faces; proximal ends of segments tapering, narrowly rounded to acute, striated; distal end apparently surface of growth cessation, having no area for articulation.

Discussion.--It is possible that the shorter zoaria (1 to 1.5 mm long) represent a different species than those that are longer; lengths seem to be bimodally distributed. This could also be due to shorter colonies being more susceptible to smothering by sediment. There does not seem to be sufficient well-preserved material to make such a determination; I am therefore placing these forms in one species.

Material and Occurrence.--More than 100 specimens have been collected from subsurface at locality 2. An additional 13 specimens are from locality 3, and 7 from locality 4. Other specimens, including a few from outcrop, may questionably be assigned here, but most of these are too fragmentary or encrusted with matrix to be positively identified. Preservation is poor to good in material from localities 2 and 3, and poor elsewhere.

Specimen USNM 449170 is here designated the holotype, and locality 2, 34 ft (10.4 m) to 37 ft (11.3 m) above the base of the Gunn Member, is designated the type locality and horizon. Specimens USNM 449171 through 449175 are designated paratypes.

Genus *Sceptropora* Ulrich, 1888

Type species.--*Sceptropora facula* Ulrich, 1888 (by original designation).

Discussion.--Ulrich's (1888, p. 228) original generic description has been expanded upon by Blake (1983, p. 565). These authors' concepts are followed herein.

Sceptropora facula Ulrich, 1888
Plate 2, figs. 1-5

Sceptropora facula Ulrich, 1888, p. 228-229, fig. 1; Ulrich, 1889, p. 46-47, fig. 2; Ulrich, 1890, p. 401, fig. 15; Whiteaves, 1895, p. 117; Bassler, 1911, p. 153, fig. 74; Bassler, 1928, p. 160; Bassler, 1953, p. G130, fig. 90, 3; Ross, 1957, p. 474-475, pl. 37, figs. 10, 11; Kiepura, 1962, p. 401-402, pl. 10, figs. 1-3; Ross, 1982, pl. 2, fig. 6; Blake, 1983, p. 566, fig. 279; Bolton and Ross, 1985, p. 30-31, pl. 5.1 pl. 5.2, figs. 2-6, 8, 9, pls. 5.3-5.6, pl. 5.7, figs. 3, 4, 6, 8; Goryunova, 1985, p. 106, pl. 4, fig. 4.

Sceptropora estoniensis Brood, 1980, p. 166-168, fig. 3.

Diagnosis.--Articulated arthrostylids having short segments with widely flaring distal ends.

Description.--Zoarium dendroid, bifurcating occasionally; segments usually straight, some slightly curved, slightly less than 1 mm to a little more than 2 mm long; segments club-, bell-, or mushroom-shaped, and having a continuous range of shapes between these forms; proximal end slender, usually forming a bulbous expansion with diameter less than 0.2 mm to more than 0.8 mm in exceptionally robust forms; distal end ranges from only slight swelling (diameter less than 0.6 mm) to broad expansions (more than 2 mm), with intermediate values being more common; zooecia aligned between vertical ridges, circular to oval, about 0.1 mm in diameter; zooecia commonly in 2 to 3 rows both below and above margin of distal expansion, the proximal portion of segment consisting of extrazooecial skeleton; center of distal surface bears a socket of about same diameter as proximal end of segment.

Material and Occurrence.--More than 4000 segments have been collected. Of these, slightly fewer than 300 came from outcrop. Almost 3700 came from subsurface locality 2, with additional collections from localities 3, 4, and 6; a single specimen was recovered from locality 7. Most of these specimens are entire and many are quite well preserved.

Discussion.--The range of variation present in this species has been well documented by Bolton and Ross (1985), although there is a possibility that some of their "bell-shaped" forms may be assignable to *Sceptropora florida* Kiepura, 1962 (see discussion under that species, below).

I have included *S. estoniensis* Brood, 1980, in the synonymy above. Brood distinguished his species on size and shape, but the range of variation in *S. facula* encompasses the forms assigned to *S. estoniensis*, as noted by Bolton and Ross (1985, p. 31).

With respect to other species of *Sceptropora*, *S.* florida is discussed below under that species. *Sceptropora spinosa* Kiepura, 1962, is a very spinose form that resembles *S. facula* with the addition of large, blunt projections on the zoarial surface. *Sceptropora* fustiformis Ulrich, 1889, is very poorly known, having been described rather cursorily and never having been illustrated. *Sceptropora? obscura* Astrova, 1965, is not, according to Bolton and Ross (1985, p. 30), a *Sceptropora*.

Sceptropora florida Kiepura, 1962
Plate 2, figs. 6-12

Sceptropora florida Kiepura, 1962, p. 403, pl. 10, figs. 4,5.

Diagnosis.--*Sceptropora* having a rounded but not expanded distal termination, a flat attachment surface on the distal end, and a slender shaft with a relatively large distal expansion.

Description.--Zoarial shape unknown, but some segments show two attachment surfaces indicating that the colony bifurcated; segments straight, umbrella-shaped to bell-shaped; length about 1.3 to 1.8 mm; proximal end slender, cylindrical, almost flat to gently rounded to almost pointed, and about 0.1 mm in diameter; distal end moderately to markedly expanded, subcircular except for segments having two attachment surfaces, which may be strongly elliptical; diameter of distal expansion from slightly less than 0.4 mm to slightly more than 1 mm, with unusual specimens exceeding 1.5 mm in diameter; 2 or 3 rows of zooecia usually both on distal expansion and just below edge of expansion; center of distal surface with attachment area that is from slightly less than 0.03 mm to slightly more than 0.1 mm in diameter.

Material and Occurrence.--More than 1000 segments have been collected, mostly from locality 2. The outcrop contributed only 16 segments. The remainder have come from localities 3, 4, and 6. The great majority of the specimens have had their proximal ends broken off; otherwise, preservation is fairly good.

Discussion.--Bolton and Ross (1985) documented a wide range of variability within *Sceptropora facula*, and, for the most part, I agree with them. However, with respect to the articulation surfaces of the segments, there seems to be an either-or condition, and I feel that this can be used to discriminate *S. facula* and *S. florida*. *Sceptropora facula* has a socket (or two sockets) at the distal end, and, commonly, a bulbous expansion at the proximal end. *Sceptropora florida*, in contrast, has a planar attachment surface, rather than a socket, at the distal end, and a proximal end that is usually rounded, but not expanded. In almost all specimens where the distal end is adequately preserved and relatively free of matrix, these two species may be distinguished almost instantly. Other differences are that *S. florida* is more delicate than most segments of *S. facula*, has a greater distal expansion relative to the thickness of the shaft, and has a distal expansion that is usually planar or slightly rounded compared to the classic "club" shape of the distal termination of the majority of *S. facula* segments.

There seem to be some slight differences between these Stony Mountain specimens of *Sceptropora florida* and those from the Baltic area. The specimens in my collection seem to have a more delicate central shaft and a greater distal expansion than do those described by Kiepura (1962). The distal attachment surface in the former specimens is usually a small circular planar area, sometimes quite small in diameter; in the float specimens described from Poland, it is "slightly concave to nearly flat, occasionally with a central slit" (Kiepura, 1962, p. 403). The longitudinal ridges in the North American specimens do not seem to be as pronounced as those on the Baltic specimens. In my opinion, these minor differences do not warrant the erection of a new species for the Stony Mountain forms at this time.

Genus *Ulrichostylus* Bassler, 1952 (emended herein)

Type species.--*Helopora divaricatus* Ulrich, 1886 (by original designation).

Diagnosis.--Arthrostylids having articulated zoaria but lacking lateral articulation; peristomes usually prominent and commonly spinose.

Description.--Zoarium articulated, jointed longitudinally, lateral articulation unknown; bifurcation may occur at ends of segments; proximal articulation surfaces commonly weakly concave to accommodate weakly convex distal articulation surface of preceding segment; segments straight to slightly curved, 1 mm or less thick, 2 to 10 mm long, and weakly flared at ends; zooecial apertures usually in 4 to 8 longitudinal ranges; prominent longitudinal ridges separate ranges; peristome commonly developed proximally into spinose projection; metapores and acanthopores unknown.

Discussion.--Bassler's (1952, p. 384) original description of *Ulrichostylus* was: "Narrow, cylindrical stems bearing eight or more longitudinally arranged zooecial rows. Base articulated, circular sockets on sides for new branches." The genus is not recognizable from this description. Of the four characters given by Bassler, two (narrow, cylindrical stems and articulated bases) are family characters. The remaining two characters are, as far as I can determine, simply incorrect. The type species (*Helopora divaricatus* Ulrich, 1886) has 6 to 8 longitudinal rows of zooecia. Other species assignable to the genus make the generic range 4 to 8 rows; no included species has more than 8 rows.

As for the lateral articulation sockets, none of the included species has been described as possessing them. Bassler (1953, p. G130, fig. 90, 4) gives four pen and ink drawings, purportedly of the type species of *Ulrichostylus*, *U. divaricatus*. Three of these (4b, 4c, and 4d) were redrawn from Ulrich (1893, pl. 3, figs, 4, 5, and 3, respectively) and two of the three are actually of *U. spiniformis* and not of *U. divaricatus*. It is the fourth illustration that is of concern; it constitutes the only "evidence" for lateral articulation in *Ulrichostylus*.

I have been unable to find Bassler's source for this drawing. However, if it is indeed done to the same scale as the others in Bassler's figure 4, then several points may be made about the specimen that it represents. First, it is somewhat thinner than the type species; second, the zooecial apertures are more than twice the size of those of the type species; third, the apertures have a rhombic arrangement, rather than a gentle spiral arrangement, fourth, the apertures are strongly elongate, whereas those of Ulrich's illustration are weakly ovate; and fifth, the apertures are much closer and there is much less extra-zooecial skeleton in Bassler's illustration than in the type species. Given these differences, I do not believe the specimen illustrated by Bassler (1953, p. G130, fig. 90, 4a) to be referable to *Ulrichostylus* at all. If that is so, then no evidence remains for the existence of lateral articulation sockets in *Ulrichostylus*. Until some reliable evidence is adduced, I must regard *Ulrichostylus* as lacking lateral articulation and as having only longitudinal jointing.

Fortunately, Bassler (1952) designated a type species, and from Ulrich's (1886, 1893) description and illustration of this species, together with Ulrich's (1893, p. 189-191) excellent discussion of the group to which this species belongs, the generic characters may be deduced. Particularly, Ulrich (1893, p. 190), in his discussion of *Helopora*, elucidated the differences distinguishing his "group b" (containing Ordovician species referred to *Helopora*) from his "group a" (Silurian species of *Helopora*). Included in group b was *H. divaricatus*, now the type species of *Ulrichostylus*, together with seven other Middle and Upper Ordovician species (Ulrich, 1893). Of these eight species, I am referring *Helopora harrisi* James, 1883 to *Arthrotrypa* n. gen.; it differs from the remainder of the species of *Ulrichostylus* in characters that I regard as being of generic significance. The remaining seven species form the group from which the generic characters of *Ulrichostylus* may be determined.

Ulrichostylus costatus n. sp.
Plate 2, figs. 18-22

Etymology.--From the Latin *costa*, rib, referring to the strong longitudinal ridges possessed by this species.

Diagnosis.--*Ulrichostylus* having 7 to 8 ranges of zooecia, strong longitudinal ridges, and weakly developed peristomes.

Description.--Zoarial segments about 0.5 to 0.6 mm thick and 2.5 to 3.5 mm long; zooecial apertures in 7 or 8 longitudinal ranges, the faces of the segments separated by strong longitudinal ridges; proximal ends of segments slightly tapered and broadly rounded; distal end somewhat flared, with inter-facial ridges produced into projections; distal surface containing zooecial apertures and central attachment surface that may be produced into central boss; zooecial apertures elongate-ovate, about 0.1 by 0.2 mm, separated by about their own length, 5 or 6 in 2 mm longitudinally; zooecial apertures bordered by sinuous ridges that serve as lateral margins of peristomes, continuous from aperture to aperture; proximal margin of peristome commonly weakly produced into low rounded projection from which a ridge extends to distal margin of next proximal aperture.

Material and Occurrence.--Sixteen specimens have been assigned to this species. All are from the subsurface of North Dakota. One is from locality 6, seven from locality 4, and the remaining eight are from locality 2. Preservation is fair to good.

Specimen USNM 449170 is here designated the holotype, and locality 2, at a height of 37.8 ft (11.5 m) to 38 ft (11.6 m) above the base of the Gunn Member, is designated the type locality and horizon. Specimens USNM 449171 through 449174 are designated paratypes.

Discussion.--Although this species closely resembles *Ulrichostylus imbricata* (Ulrich, 1890), there are consistent major differences between *U. costatus* and *U. imbricata* in their ornamentation. Ulrich's (1890, p. 644) description of the latter species included these characters: "Zooecia in seven or eight vertical sets around the segment, the rows being separated by rather inconspicuous carinae; . . . the lower margin [of the peristome] strongly elevated and produced posteriorly into three small ridges." In contrast, *U. costatus* possesses strongly raised longitudinal ridges between the faces and only weakly produced proximal peristome margins. These differences are so pronounced that, at first glance, the two species do not appear as similar as they apparently are. Further examination, however, reveals that they are the only significant differences. As these differences are evidently persistent in the two populations on the oppostie sides of the Late Ordovician Transcontinental Arch, I think they are sufficient to differentiate the species.

Ulrichostylus dakotensis n. sp.
Plate 2, figs. 13-17

Etymology.--From the state of North Dakota, where the material was collected.

Diagnosis.--Slender, five-sided *Ulrichostylus* and having two sets of longitudinal ridges.

Description.--Segments five-sided, slender, about 0.3 mm thick, length unknown; branching at segment ends uncommon; angles between faces marked by longitudinal ridges; second set of ridges outlines sides of apertures and approach, but do not touch, each other in interzooecial spaces; proximal end of zooecial apertures in some cases marked by low, rounded projection; apertures elongate-ovate, about 0.1 by 0.2 mm, separated by about their own length, 5 in 2 mm longitudinally.

Material and Occurrence.--About 40 specimens from locality 2 have been assigned here, and an additional 30 from locality 4; many of the latter are only tentatively assigned here. Preservation is poor to moderately good.

Specimen USNM 449175 is here designated the holotype, and specimens USNM 449176 through 449179 are designated paratypes. Locality 2 is designated the type locality, and the horizon from 8 ft (2.4 m) to 10 ft (3.0) above the base of the Gunn Member is designated the type horizon.

Discussion.--This species is similar to *Ulrichostylus elegans* (Ulrich, 1893) but differs in being five-sided, rather than six-sided. *U. elegans* also has stronger ornamentation. *U. dakotensis* is also similar to tertiary segments of *Arthroclema pentagonalis* n. sp., but lacks the latter's spinose projections at the proximal margins of the zooecial apertures. The two species also differ in that *U. dakotensis* has tapering segment terminations, whereas *A. pentagonalis* has proximal ends that are rounded without tapering, as is characteristic of *Arthroclema*.

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APPENDIX

LOCALITY REGISTER

1. Municipality of Winnipeg Aggregate Plant, sec. 14, T. 13 N., R. 2 E., approximately 1 km NNW of the center of Stony Mountain, Manitoba, Canada. Approximately 5 m of Gunn Member is exposed at this location, overlain by about 3 m of Penitentiary Member, which in turn is overlain by about 5 m of Gunton Member.

2. Union Oil Co. of California Aanstad #1 (North Dakota Geological Survey [NDGS] Well #20), NE 1/4 NE 1/4 sec. 29, T. 158 N., R. 62 W., Ramsey Co., N.D. The full thickness (91 ft [27.7 m]) of the Gunn Member was cored in this well, from 2389 ft (728.2 m) below Kelly Bushing (KB) to 2480 ft (755.9 m) below KB.

3. Union Oil Co. of California Restad #1 (NDGS Well #37), SW 1/4 NW 1/4 sec. 26, T. 162 N., R. 64 W., Cavalier Co., N.D. The lowermost 19 ft (5.8 m) of the Gunn Member was cored, between depths of 2845 ft (867.2 m) below KB and 2864 ft (872.9 m) below KB.

4. Arco Wunderlich #1 (NDGS Well #8803), NE 1/4 NE 1/4 sec. 22, T. 151 N., R. 80 W., McHenry Co., N.D. The entire thickness of the Gunn Member (86 ft [26.2 m]) was cored, between depths of 7602 ft (2317.1 m) and 7688 ft (2343.3 m) below KB.

5. Sun Oil Co. Flemmer #1 (NDGS Well #8711), SE 1/4 SE 1/4 sec. 31, T. 146 N., R. 80 W., McLean Co., N.D. The lowest six feet (1.8 m) of the Gunn was cored, between 7715 ft (2351.5 m) and 7721 ft (2353.4 m) below KB.

6. Amoco Production Co. Richter #1 (NDGS Well #7340), NW 1/4 SE 1/4 sec. 26, T. 140 N., R. 88 W., Morton Co., N.D. The lowest 56 ft (17.1 m) of the Gunn was cored, between depths of 9770 ft (2977.9 m) and 9826 ft (2995.0 m) below KB.

7. Socony Vacuum Oil Co. Dvorak #F-42-6-P (NDGS Well #505), SE 1/4 NE 1/4 sec. 6, T. 141 N., R. 94 W., Dunn Co., N.D. All 89 ft (27.1 m) of the Gunn Member, between depths of 12224 ft (3725. 9 m) and 12313 ft (3753.0 m) below KB, was apparently cored in this well, but almost 50 ft (15 m) is missing in the middle.

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PLATE 1. Arthrostylid Bryozoans from the Gunn Member, Stony Mountain Formation: *Arthroclema* and *Arthrotrypa*

All figures are oriented with their proximal ends down except for transverse sections. Figures 10, 11, 13, 22-24, 26, 28, 29, and 31 are photomicrographs; all others are scanning electron microscope (SEM) photographs.

Figs. **1-14, 24.** *Arthroclema brevis* n. sp. All illustrated specimens are from locality 4; all figures X24 unless otherwise noted. **1-4.** Primary segments. **1.** USNM 449127, holotype. **2.** USNM 449129, paratype. **3.** USNM 449128, paratype. **4.** USNM 449133, paratype. **5-7.** Secondary segments. **5.** An exceptionally long segment. USNM 449132, paratype. **6.** USNM 449136, paratype. **7.** USNM 449134, paratype. **8, 9.** Tertiary segments. **8.** USNM 449137, paratype. **9.** USNM 449135, paratype. **10.** Longitudinal section, secondary segment. USNM 449141, paratype. **11.** Longitudinal section, primary segment. Black areas are pyrite filling zooecial cavities. USNM 449139, paratype. **12, 14.** Unusually short, stubby segments, interpreted to be aberrant primary segments. **12.** USNM 449131, paratype. **14.** USNM 449130, paratype. **13.** Transverse section, primary segment; note large proportion of extrazooecial skeleton (light areas) to zooecial volume (dark areas), characteristic of primary segments of *Arthroclema*. USNM 449140, paratype. **24.** Transverse section, secondary segment. USNM 449138, paratype, X33.

Figs. **15-23, 25-28.** *Arthroclema pentagonalis* n. sp. All illustrated specimens are from locality 2, and all figures are X24 unless otherwise indicated. **15.** Primary segment showing distal end and lateral articulation socket. USNM 449145, paratype. **16.** Primary segment showing proximal end and indistinct lateral socket on left side just above middle. USNM 449146, paratype. **17.** Secondary segment showing slightly flaring distal end and zooecial apertures with the proximal portion of their peristomes produced into spine-like processes, characteristic of this species. USNM 449147, paratype. **18.** Secondary (?) segment with two lateral sockets. USNM 449142, holotype. **19.** Fragments of two secondary segments, joined at their ends. USNM 449143, paratype. **20.** Secondary (?) segment, with lateral socket near top. USNM 449148, paratype. **21.** Tertiary (?) segment. USNM 449150, paratype. **22.** Transverse section, primary segment. USNM 449151, paratype, X33. **23.** Transverse section, secondary segment, showing five ranges of zooecia. USNM 449152, paratype, X33. **25.** Secondary segment preserving flared distal end. USNM 449149, paratype. **26.** Longitudinal section, primary segment. USNM 449155, paratype. **27.** Secondary segment. USNM 449144, paratype. **28.** Longitudinal section, secondary segment. USNM 449154, paratype.

Figs. **29-35.** *Arthrotrypa ovata* n. gen., n. sp. All figures X33. **29.** Transverse section showing six ranges of zooecia. USNM 449163, paratype, locality 2. **30.** Fragment showing distal end. USNM 449161, paratype, locality 2. **31.** Longitudinal section. USNM 449162, paratype, locality 2. **32.** Fragment showing longitudinal ridges and zooecial apertures. USNM 449158, paratype, locality 2. **33.** Fragment showing proximal end. USNM 449159, paratype, locality 3. **34.** Fragment preserving distal end. USNM 449157, paratype, locality 2. **35.** Fragment preserving distal end and displaying sharp longitudinal ridges and low but sharp peristomes. USNM 449156, holotype, locality 3.

Plate 1

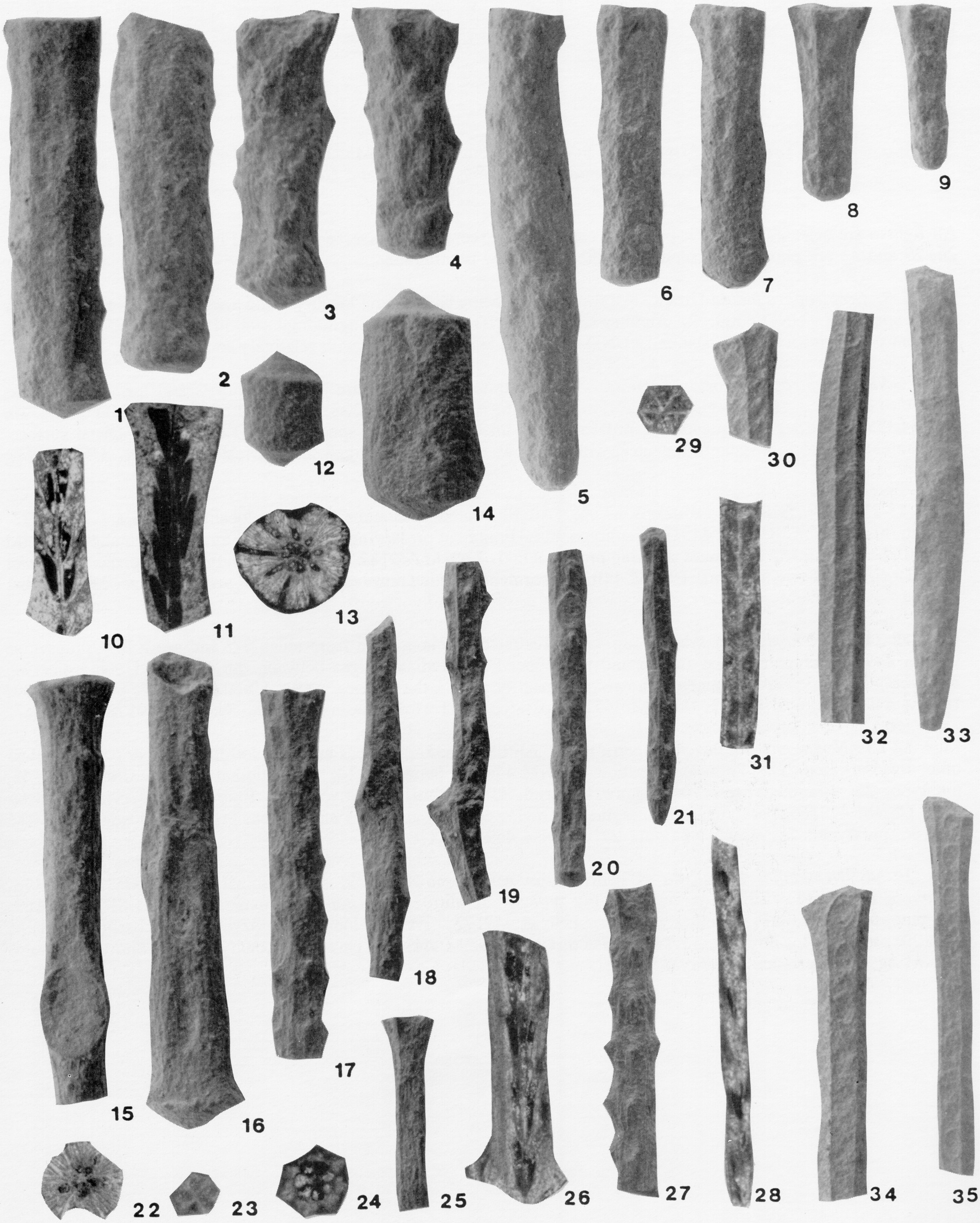


PLATE 2. Arthrostylid Bryozoans from the Gunn Member, Stony Mountain Formation: *Nematoporella*, *Sceptropora*, and *Ulrichostylus*

All figures are oriented with their proximal ends down, except for transverse sections. Figures 3, 6, 13, 17, 18, 22-24, 29 and 33 are photomicrographs; all others are SEM photographs.

Figs. **1-5.** *Sceptropora facula* Ulrich. All illustrated specimens are from locality 2 and are X28.7. **1.** Exceptionally robust specimen. UND 6309. **2.** Another segment, UND 6317. **3.** Longitudinal section. UND 6385. **4.** Robust segment with two sockets at distal end. UND 6315. **5.** Smaller segment with relatively smaller socket. UND 6319.

Figs. **6-12.** *Sceptropora florida* Kiepura. All illustrated specimens are from locality 2 and are X28.7 unless otherwise indicated. **6.** Longitudinal section. UND 6370. **7.** UND 6328. **8.** UND 6323. **9.** UND 6330. **10.** UND 6329. **11.** Segment preserving proximal end, uncommon in this species. UND 6327. **12.** Distal surface. Attachment surface (not socket) in center, with two rows of zooecia arranged concentrically around it. UND 6324., X66.7.

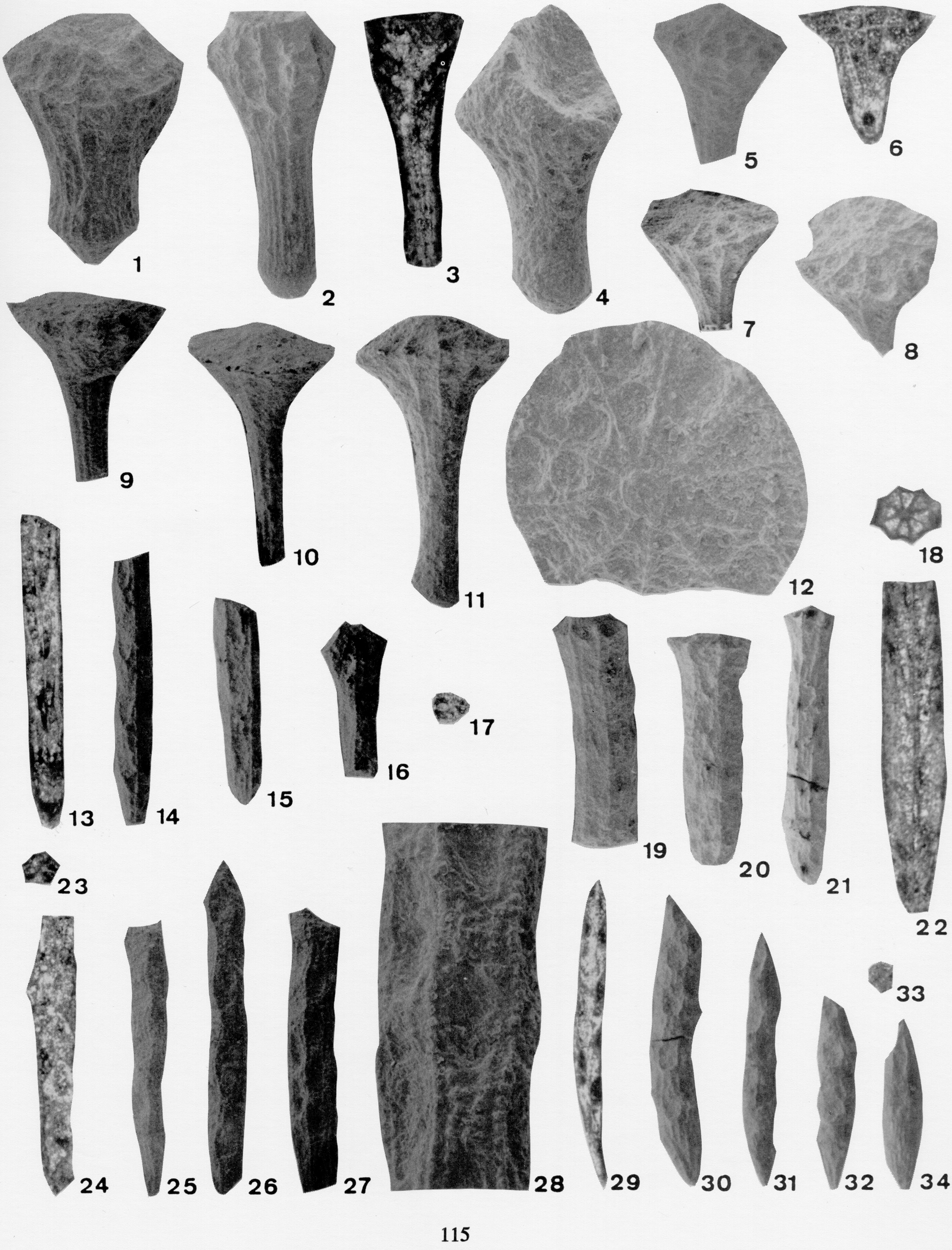
Figs. **13-17.** *Ulrichostylus dakotensis* n. sp. All illustrated specimens are from locality 2 and are X26. **13.** Longitudinal section. USNM 449184, paratype. **14.** Fragment preserving proximal end and ornamentation. USNM 449180, holotype. **15.** Fragment showing proximal end. USNM 449182, paratype. **16.** Fragment preserving distal end, consisting of two sockets. USNM 449181, paratype. **17.** Transverse section, showing five zooecial ranges. USNM 449185, paratype.

Figs. **18-22.** *Ulrichostylus costatus* n. sp. All illustrated specimens are from locality 2 and are X18. Transverse section showing eight zooecial ranges and pronounced longitudinal ridges between the ridges. USNM 449179, paratype. **19-21.** Three segments showing variability within the species. **19.** USNM 449177, paratype. **20.** USNM 449175, holotype. **21.** USNM 449176, paratype. **22.** Longitudinal section. USNM 449178, paratype.

Figs. **23-28.** *Nematoporella ulrichi* n. gen., n. sp. All illustrated specimens are from locality 2 and are X28.7 unless otherwise indicated. **23.** Transverse section. USNM 449167, paratype. **24.** Longitudinal section. USNM 449168, paratype. **25.** Fragment preserving the proximal end. USNM 449164, holtype. **26.** Fragment preserving the distal end. USNM 449165, paratype. **27.** Fragment showing zooecial apertures and sinuous longitudinal ridges. USNM 449166, paratype. **28.** Detail of figure 27. USNM 449166, X100.

Figs. **29-34.** *Nematoporella falcata* n. gen., n. sp. All figures X26. **29.** Longitudinal section. USNM 449173, paratype, locality 2. **30.** Zoarium showing typical curvature and details of ornamentation. USNM 449169, holotype, locality 2. **31.** Another zoarium. USNM 449172, paratype, locality 3. **32.** Shorter zoarium. USNM 449170, paratype, locality 2. **33.** Transverse section. USNM 449174, paratype, locality 2. **34.** Shorter zoarium. USNM 449171, paratype, locality 2.

Plate 2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CYANOBACTERIAL FILAMENTS AND ALGAE IN THE WINNIPEGOSIS FORMATION (MIDDLE DEVONIAN), WILLISTON BASIN, NORTH DAKOTA

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ABSTRACT

The Winnipegosis Formation was deposited in the Williston-Elk Point Basin during the Middle Devonian (upper Eifelian - lower Givetian). It is composed of limestone, dolostone and anhydrite in a "shallowing-upward" sequence. During initial deposition of the Winnipegosis, a uniform, shallow marine environment covered the entire basin. Then, associated with a rapid rise in sea level, the basin differentiated into a deep basin that received limited sediment and an encompassing shallow marine shelf. A variety of depositional environments developed at this time including deep-basin, deep-shelf, shallow-shelf, reef, lagoon, and tidal-flat environments. Pinnacle reefs developed in the deep basin; and patch reefs grew at both the shelf margin and at shoaling areas on the shelf. The reef rims that developed at the windward edge of pinnacle reefs sheltered back-reef lagoons. Shelf lagoons were associated with patch reefs.

In North Dakota, algae and cyanobacteria (photosynthesizing bacteria previously known as blue-green algae) thrived in many of these shallow-water environments. Cyanobacterial filaments contributed to the binding of the pinnacle reef rims and the patch reefs. They also encrusted a variety of organisms, thriving especially in association with stromatoporoids in the reef environment. Codiacean algae (*Lanicula, Litanaia*) and calcispheres (?dasycladacean algae) were dominant in pinnacle reef lagoons. Whereas, rare, small, dendroid stromatoporoids (*Amphipora*) and abundant, segmented, red algae (*Parachaetetes*) and calcispheres have been found in shelf-lagoon rocks.

The Elk Point Basin extended from northwestern North Dakota/northeastern Montana northwestward into Manitoba and across Saskatchewan to northern Alberta. The distribution of the various types of algae in the Winnipegosis in North Dakota is in some ways unlike the distribution of these types of algae in the Winnipegosis and its correlative Keg River Formation of Alberta. The lagoons in western Canada were dominated by dasycladacean algae (*Vermiporella*) and dendroid stromatoporoids (*Amphipora*), with minor occurrences of codiacean algae, red algae, and calcispheres. The western Canadian lagoons apparently were more restricted than the lagoons in North Dakota. Although cyanobacterial filaments have seldom been reported from Canada, they were probably distributed in reef rocks there as extensively as in North Dakota.

INTRODUCTION

The Elk Point Basin (Fig. 1) was a large basin in the north-central United States and south-central Canada that existed as a prominent feature during early and middle Devonian time. The Williston Basin was essentially the southern part of this much more extensive, elongate, northwest-southeast trending basin at that time. The Presqu'ile barrier-reef complex extended across the mouth of the basin from northeastern British Columbia across northwestern Alberta to southwestern Northwest Territories.

In the north-central United States, the Winnipe-

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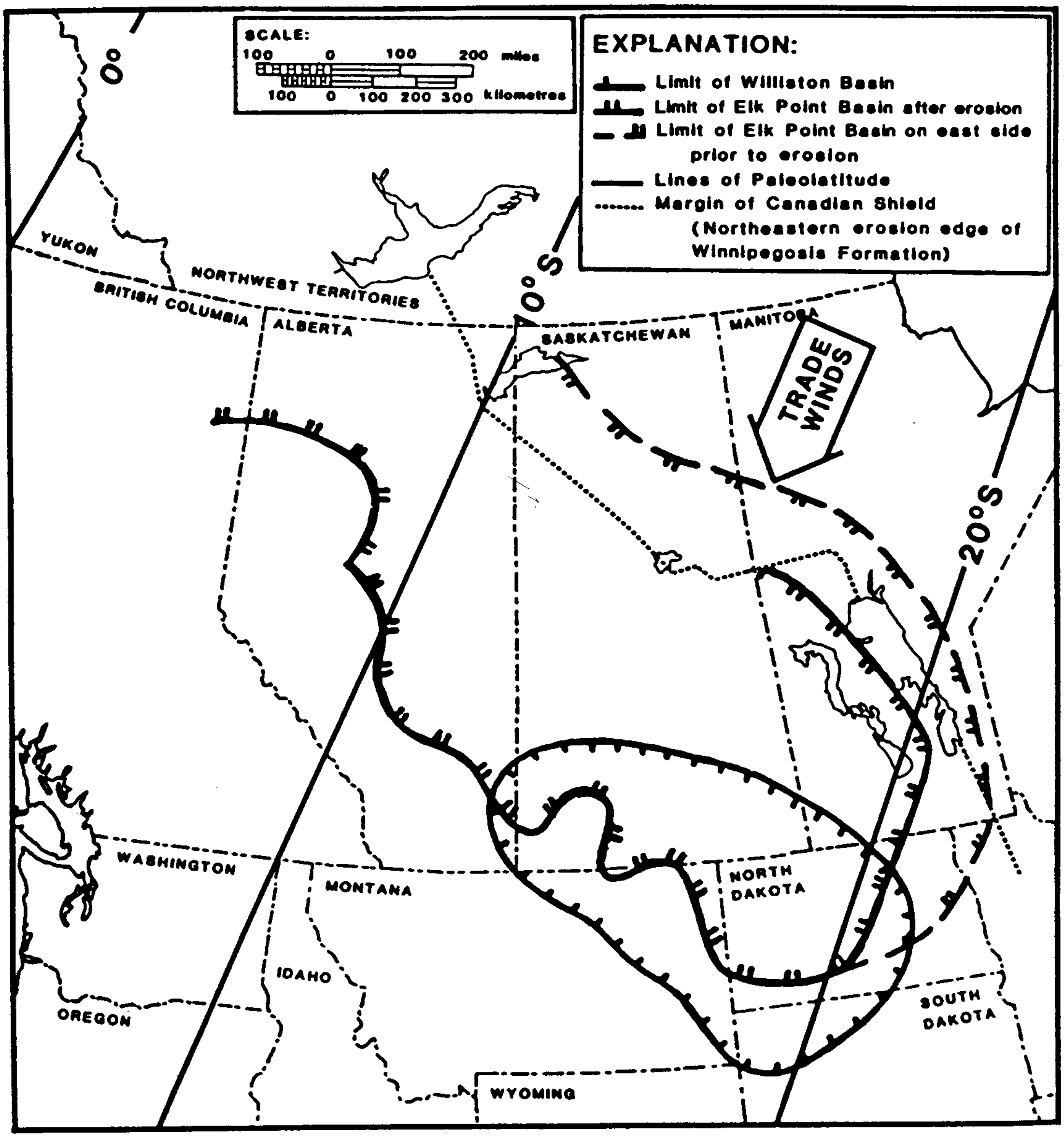

Figure 1-Index map showing the location of the Williston Basin and the Elk Point Basin in the United States and Canada (Grayston et al., 1964; Worsley and Fuzesy, 1978). Paleolatitude lines and trade wind direction (Heckel and Witzke, 1979) for the Middle Devonian and the postulated pre-erosional, eastern limit of the Elk Point Basin (Maiklem, 1971) are indicated.

gosis Formation was deposited during the Middle Devonian (upper Eifelian to middle Givetian). It is present in the subsurface in northwestern North Dakota and northeastern Montana. The Winnipegosis Formation overlies the Ashern Formation and is overlain in the center of the basin by evaporites of the Prairie Formation (Fig. 2). These formations are recognized on well logs throughout much of the state. The general characteristics of the Ashern, Winnipegosis and Prairie Formations are shown on the west-east cross section (Fig. 3). In Canada, the Winnipegosis occurs in southeastern Manitoba, southern and central Saskatchewan, and south-central Alberta. The Winnipegosis is correlated with the Keg River Formation of northern Alberta (Craig et al., 1967) and northeastern British Columbia (Grayston et al., 1964).

Depositional environments (Perrin, 1982a) and major diagenetic features (Perrin, 1982b; 1987) of the Winnipegosis Formation were summarized for North Dakota. Data analysis and interpretation for these studies were based on 732 mechanical well logs, 39 cores, 625 representative core slabs, and 1043 petrographic thin sections. The cores are from wells located in northwestern North Dakota (Fig. 4). Table 1 lists the cored wells by North Dakota Geological Survey

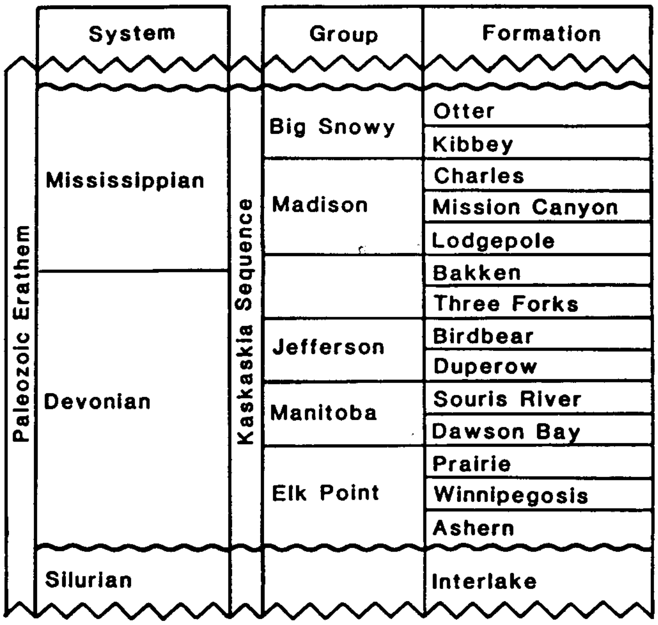

Figure 2-Stratigraphic column of the Kaskaskia Sequence showing the Winnipegosis Formation overlying the Ashern Formation and underlying the Prairie Formation in the subsurface of North Dakota.

Well Number (NDGS Well No.).

The Winnipegosis Formation is composed of limestone, dolostone and anhydrite in a "shallowing-upward" sequence (Fig. 5A). Rocks of the Winnipegosis and Prairie Formations in North Dakota were formed during six episodes of deposition (Fig. 5B). The application of the names "Winnipegosis" and "Prairie" to these diverse rock types and to the inferred episodes of deposition is shown on Figure 5C. During initial deposition (first episode) of the Winnipegosis, a uniform, shallow marine sea covered the entire basin (Fig. 6A). Then, associated with a rise in sea level and an increased rate of subsidence, the basin differentiated into a deep basin that received little sediment and an encompassing shallow marine shelf. During this second episode of deposition, a variety of depositional environments (Fig. 6B) developed that included deep-basin, deep-shelf, shallow-shelf, reef, lagoon, and tidal-flat. Pinnacle reefs developed in the deep basin. The reef rims that formed at the windward edge of pinnacle reefs sheltered back-reef lagoons. Patch reefs grew both at the shelf margin and on shoaling areas on the shelf; shelf lagoons were associated with the patch reefs.

In North Dakota, red and green algae and cyanobacteria thrived in many of the shallow-water environments that developed during the second episode of deposition. In rocks deposited in the shallow-shelf environment, cyanobacterial filaments were found within oncolites and intracrasts, and in the matrix as remnant "algal mats"; and endolithic algae and fungi contributed both to micrite-rimmed grains and to completely micritized grains. Cyanobacterial filaments were involved in the binding of the pinnacle reef rims and the patch reefs. These kinds of filaments encrusted a variety of different organisms, thriving especially in association with corals and stromatoporoids in the reef environment. Codiacean green algae (*Litanaia, Lanicula*) and calcispheres lagoons; whereas, segmented red algae (*Parachaetetes*), (?dasycladacean green algae) dominated pinnacle-reef dendroid stromatoporoids (*Amphipora*), and calcispheres (?dasycladacean green algae) dominated shelf lagoons.

ALGAE AND CYANOBACTERIAL FILAMENTS IN THE WINNIPEGOSIS FORMATION IN NORTH DAKOTA

Cyanobacterial filaments and endolithic algae

Description.--Filaments of cyanobacteria (photosynthesizing bacteria, previously known as blue-green algae) have been identified from four Winnipegosis environments of deposition: the shallow-shelf, shelf-lagoon, reef, and reef-lagoon environments. Two form-genera are recognized: (1) entwined filaments or *Girvanella* (Fig. 7A) and (2) "beads" or *Sphaerocodium* (Fig. 7B).

Both of these form-genera have been identified within oncolites formed in the shallow-shelf environment (Fig. 7C). In addition, some solitary rugosan and tabulate corals are "oncolitically-coated" with cyanobacterial filaments; both *Girvanella* and *Sphaerocodium* have been recognized. Several unusual intraclasts (Fig. 7D) are composed of micrite criss-crossed by tubular cyanobacterial filaments. These intraclasts are probably rip-up clasts of an "algal mat." Micrite-rimmed grains (Fig. 7E) and large, irregularly-shaped peloids (Fig. 7F) were formed in the shallow-shelf environment by endolithic algae (Winland, 1968; Kendall and Skipwith, 1969; Gebelein and Hoffman, 1971; Bathurst, 1966).

In the pinnacle-reef rim and shelf-patch reef rocks, stromatoporoids and tabulate corals are the dominant megascopic allochems. However, of equal dominance although seen only microscopically, cyanobacterial filaments are common to abundant in well-preserved reef rocks and appear as ghost filaments in mildly recrystallized and mildly dolomitized reef rocks. Cyanobacterial filaments were probably present in many of the more strongly altered rocks, but are unidentifiable now. Stromatoporoids in the reef environment typically encrusted tabulate corals (*Thamnopora, Alveolites, Favosites, Aulopora,* and

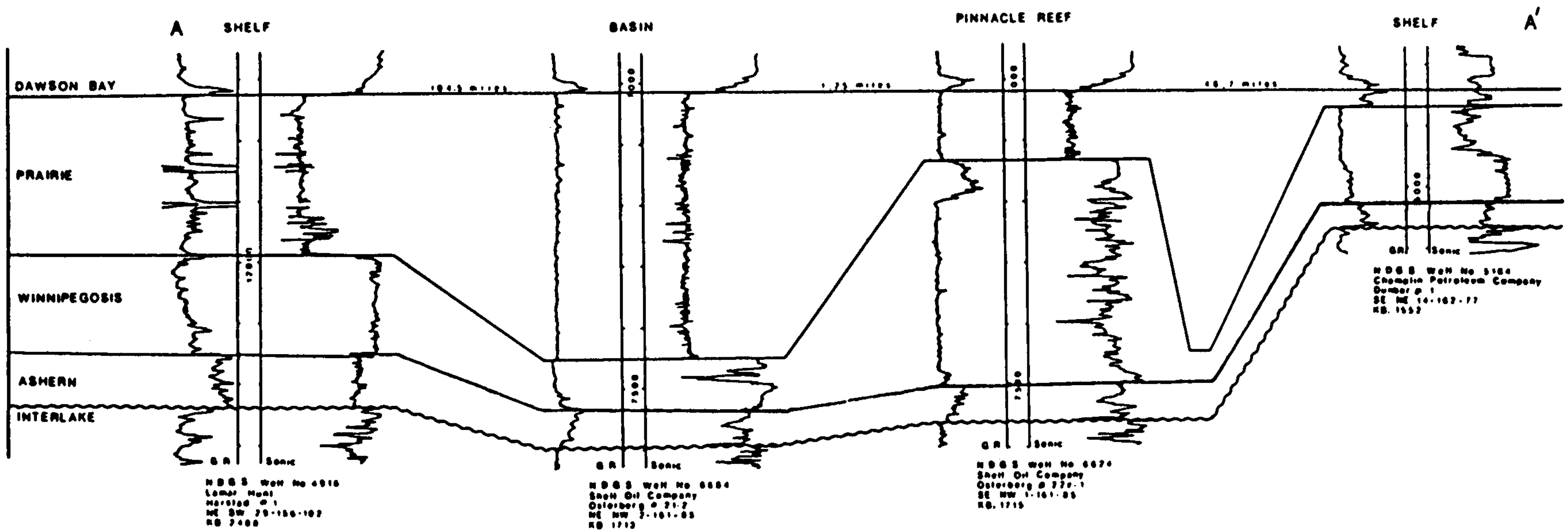

Figure 3-West-east cross section showing mechanical well log characteristics of the Ashern, Winnipegosis and Prairie Formations in different parts of the Williston Basin in North Dakota. Location of cross section is indicated on Figure 4.

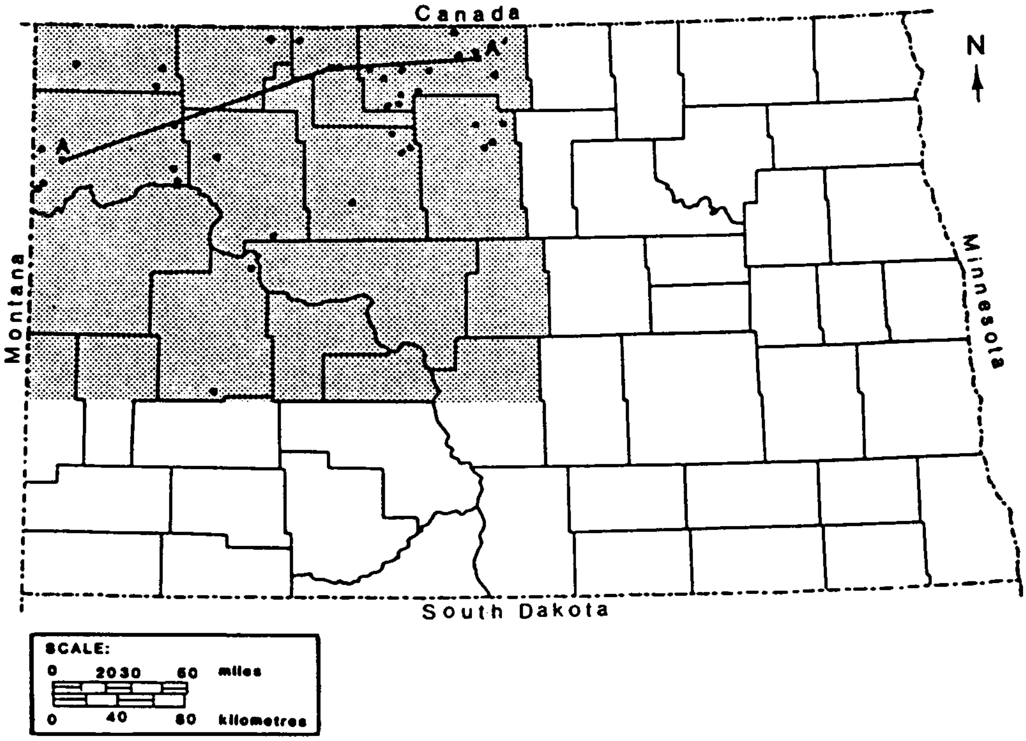

Figure 4-Index map of North Dakota showing position of west-east cross section (Figure 3) and the location of the 39 wells from which cores were examined for this study.

Syringopora) (Fig. 8A, 8B), and solitary and colonial rugose corals (*Hexagonaria*), with mutual encrustation between stromatoporoids and other corals (*Alveolites*) (Fig. 8C). Cyanobacteria are of special importance in these rocks. Both form-genera are recognized; however, they are not equally distributed. *Sphaerocodium* (Fig. 7B) rarely encrusted tabulate corals or stromatoporoids. Cyanobacterial filaments (*Girvanella*) seem to have encrusted almost everything. Of special interest is their association with stromatoporoids where they are commonly found between the laminae of the stromatoporoid (Fig. 8D), especially upon the sides of bulbous and hemispherical growth forms, and, in rare cases, across the tops. In hand sample and at low magnifications under the microscope, these areas appear to be "muddy" (Fig. 8A). However, upon closer examination such as at 40 or 100 times magnification, the tubular filaments are recognizable (Fig. 8E).

Environmental Interpretation.--Modernhermatypic hexacorals possess unicellular symbiotic algae (zooxanthellae) in their tissue. This relationship provides the coral with an excellent excretory mechanism (Heckel, 1974). The close association of cyanobacterial filaments with corals and stromatoporoids in the Winnipegosis Formation suggests that these organisms may also have had a symbiotic relationship with cyanobacteria. Regardless of whether there was a symbiotic relationship or not, stromatoporoids are considered to have had shallow depth restrictions where closely associated with cyanobacteria (Heckel, 1972).

Cyanobacterial mats ("algal mats") are rare in the matrix of reef-lagoon rocks. However, they may have been much more common than presently recognized, but destroyed by grazing organisms or by diagenesis. Cyanobacterial mats were normally ephemeral features; but, while in place, they had considerable influence on the sediment that they were binding. They protected sediment from erosion, and trapped fine material that normally would have remained in suspension (Neuman et al., 1970). Recognition of cyanobacterial mats in the geologic record is difficult. Criteria used to recognize mats in the Winnipegosis Formation include the remains or traces of cyanobacterial filaments on or between sediment particles, non-uniform packing of particles resulting in a clotted texture, and irregular patches of coarse and fine grains. Cyanobacterial filaments have been found within the matrix as remnants of former mats (Fig. 8F). There was special competition among cyanobacteria, stromatoporoids and corals in the reef environment (Meyer, 1978). Very rapid growth of cyanobacteria permitted the mat to encrust both stromatoporoids and corals and prevented

TABLE 1
SUMMARY OF CORED WELL INFORMATION: NORTH DAKOTA GEOLOGICAL SURVEY WELL NUMBER, WELL NAME, LOCATION, SLAB AND THIN SECTION STORAGE NUMBERS

NDGS WELL NO.	WELL NAME	LOCATION	SLAB STORAGE TRAY NUMBERS	THIN SECTION STORAGE BOX NUMBER/SLOTS
	BOTTINEAU COUNTY			
38	California—Thompson # 1	SW SE 31-160-81	8	-
286	Lion—Erickson # 1	SW NE 32-164-78	7A	2/32-40
2219	California—Henry # 4	SE SW 6-161-79	7D	1/99-100
2596	Phillips—Brandt # 1	SE NW 19-160-80	7B	2/41-47
2638	Phillips—Brandvold # 1	SW SE 12-162-78	7C	2/48-50
4790	Union—Steen # 1	SE SE 20-159-81	22D	-
4918	Marathon—Adams # 1	NW SW 33-161-82	11, 12	3/1-99; L/4
4924	Union—Huber # 1-A-2	NE NE 2-161-81	5B	5/20-54; L/5-8
5184	Champlin—Dunbar # 1-42-14	SE NE 14-162-77	1B	1/12-16
5277	McMoran—Tonneson # 1	SW SW 11-162-77	1A	1/1-10
5280	McMoran—Deraas # 1	SW SW 24-161-76	2, 3A	1/18-64; L/15-17
5692	Kirby—Brooks # 1	NE NW 32-159-82	25B	-
6535	Shell—Greek # 41-2	NE NE 2-161-83	13, 14, 15A	4/1-100; 5/1-9
	BURKE COUNTY			
2800	Sunray Dx—Gagnum # 1	SW NW 13-163-89	17A	8/24-39
	DIVIDE COUNTY			
4423	Pan American—Raaum # 1	NW SW 26-162-101	25C	-
5246	Shell—Tanberg # 1	NE NE 5-161-95	18, 19A	10/1-64
6603	Chapman—State # 1-A	SW SW 36-160-96	22B	-
	DUNN COUNTY			
505	Socony-Vacuum—Dvorak # F-42-G-P	SE NE 6-141-94	23B	7/38-47
793	Mobil—Birdbear # F-22-22-1	SE NW 22-149-91	23A	6/1-100; 7/1-37
	McHENRY COUNTY			
5185	Champlin—Best # 14-1	SW SW 1-156-77	10B	-
5279	McMoran—State # 1	NE SW 34-157-76	6	2/1-31; L/14
5281	McMoran—State # 2	SW SW 16-158-75	3B	1/66-79
5283	McMoran—Fairbrother # 1	NE NE 34-158-77	4, 5A	1/81-97; L/18-19
	MOUNTRAIL COUNTY			
5088	Shell—Texel # 21-35	NE NW 35-156-93	21, 22A	7/54-100; 8/1-23; L/9-12
5257	McCulloch—Wahner # 1-34	NW SW 34-151-90	22C	7/48-53
	RENVILLE COUNTY			
6296	Shell—Larson # 23x-9	NE SW 9-163-87	17B	8/40-56
6624	Shell—Osterberg # 22x-1	SE NW 1-161-85	15B	5/10-19; L/20
6684	Shell—Osterberg # 21-2	NE NW 2-161-85	16	8/57-93; L/21
	WARD COUNTY			
4923	Union—Olson # 1-B-5	NW NE 5-156-81	9B, 10A	2/51-62
4992	Union—Anderson # 1-I-2	NE SE 2-156-82	9A	2/63-70
5158	Union—Hanson # 1-C-13	NE NW 13-153-85	-	2/71-100; L/13
5498	Marathon—Gowin # 1	NW SE 1-157-82	3C	-
	WILLIAMS COUNTY			
25	Amerada—Iverson # 1	SW SW 6-155-95	26B	-
4340	Pan American—Marmon # 1	SW SW 2-154-95	20B	8/94-100; 9/1-52; L/1
4379	Amerada—Ives # 3	NW SW 25-158-95	20A	10/65-97
4510	Hunt—Oyloe # 1	SW NE 7-154-103	19B	-
4597	Hunt—Voll # 1	SW NE 5-154-103	26A	-
4618	Amerada—Trogstad # 1	NE NW 17-156-103	24	5/55-100
4916	Hunt—Harstad # 1	NE SW 29-156-102	25A	9/33-97; L/2-3
	MONTANA			
	Rainbow # 1-28	See Appendix F-2	-	11/1-23
	Rainbow # 1-33	See Appendix F-2	-	11/24-44
	MANITOBA, CANADA			
	Quarry outcrops	See Appendix F-1	27	11/53-90

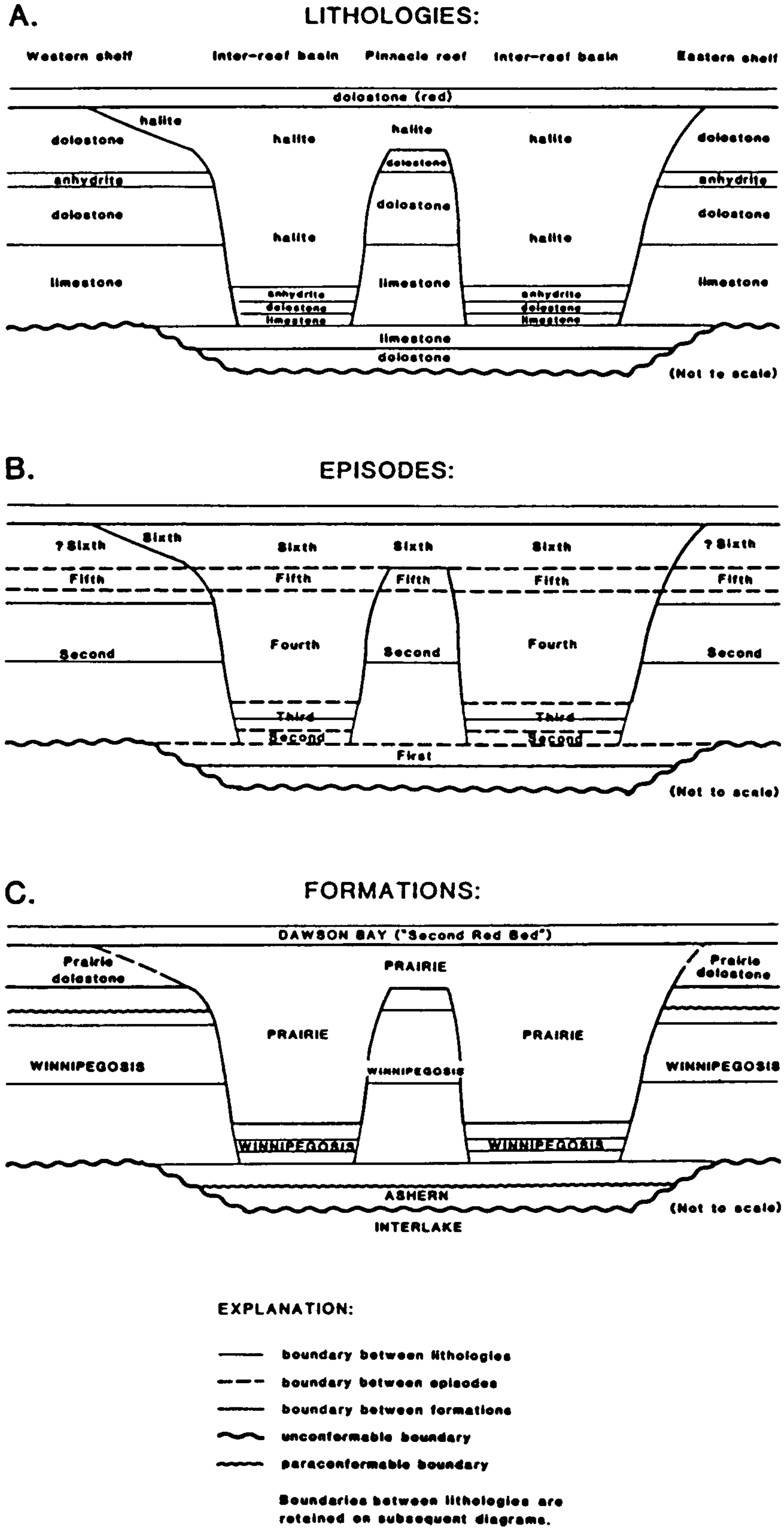

Figure 5-Diagrams illustrating relationship of lithologies, episodes, and formation names--Winnipegosis and Prairie Formations. **A.** Idealized cross section illustrating the sequence of lithologies found in various parts of the Williston Basin in North Dakota. **B.** Distribution of rocks formed during each episode of deposition. **C.** Formation names applied to these rocks.

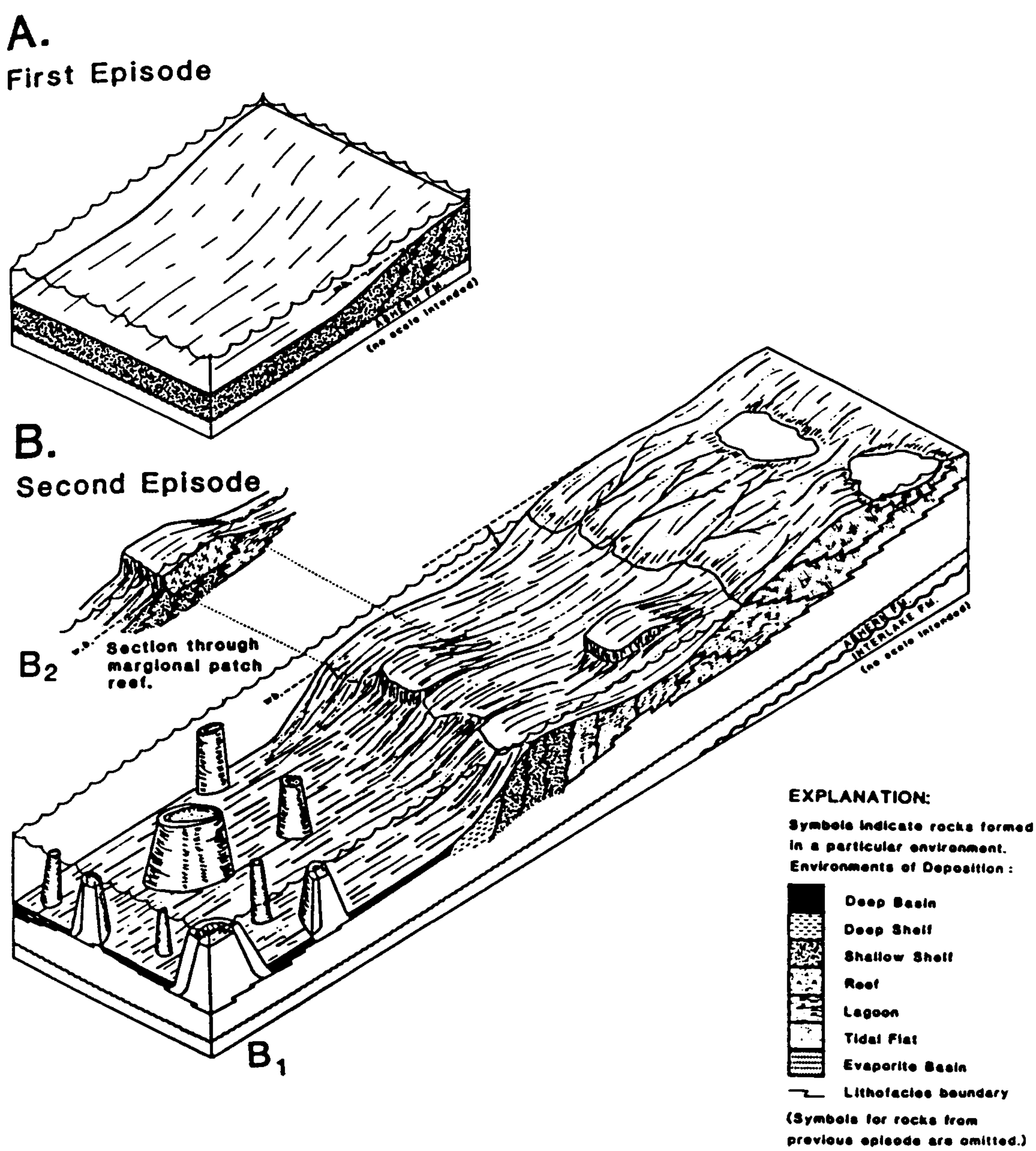

Figure 6-Diagrams illustrating the first and second episodes of Winnipegosis deposition. **A**. First episode of deposition illustrating a uniform, shallow marine environment that covered the entire basin. **B**. Second episode of deposition illustrating the following ideas: 1. At this time, differentiation of the Elk Point Basin into a deep basin and an encompassing shallow marine shelf. 2. A variety of environments of deposition including deep basin, deep-shelf, shallow-shelf, reef (patch and pinnacle), lagoon (shelf and pinnacle), and tidal flat environments.

these organisms from successfully colonizing areas where the algal mats were thriving.

Tubular filaments of cyanobacteria (*Girvanella*) are recognizable also in the matrix of some shelf-lagoon rocks (Fig. 9A) and appear as ghosts in other samples. They can even be recognized in mildly dolomitized rocks (Fig. 9B). The presence of these filaments tends to produce a clotted fabric (Fig. 9C) and to coincide with a packstone texture. Other areas of the same sample, with no evidence of cyanobacterial filaments, may have a grainstone texture (Fig. 9D). The mud of the packstone is patchily recrystallized to microspar, increasingly altered away from areas of cyanobacterial-

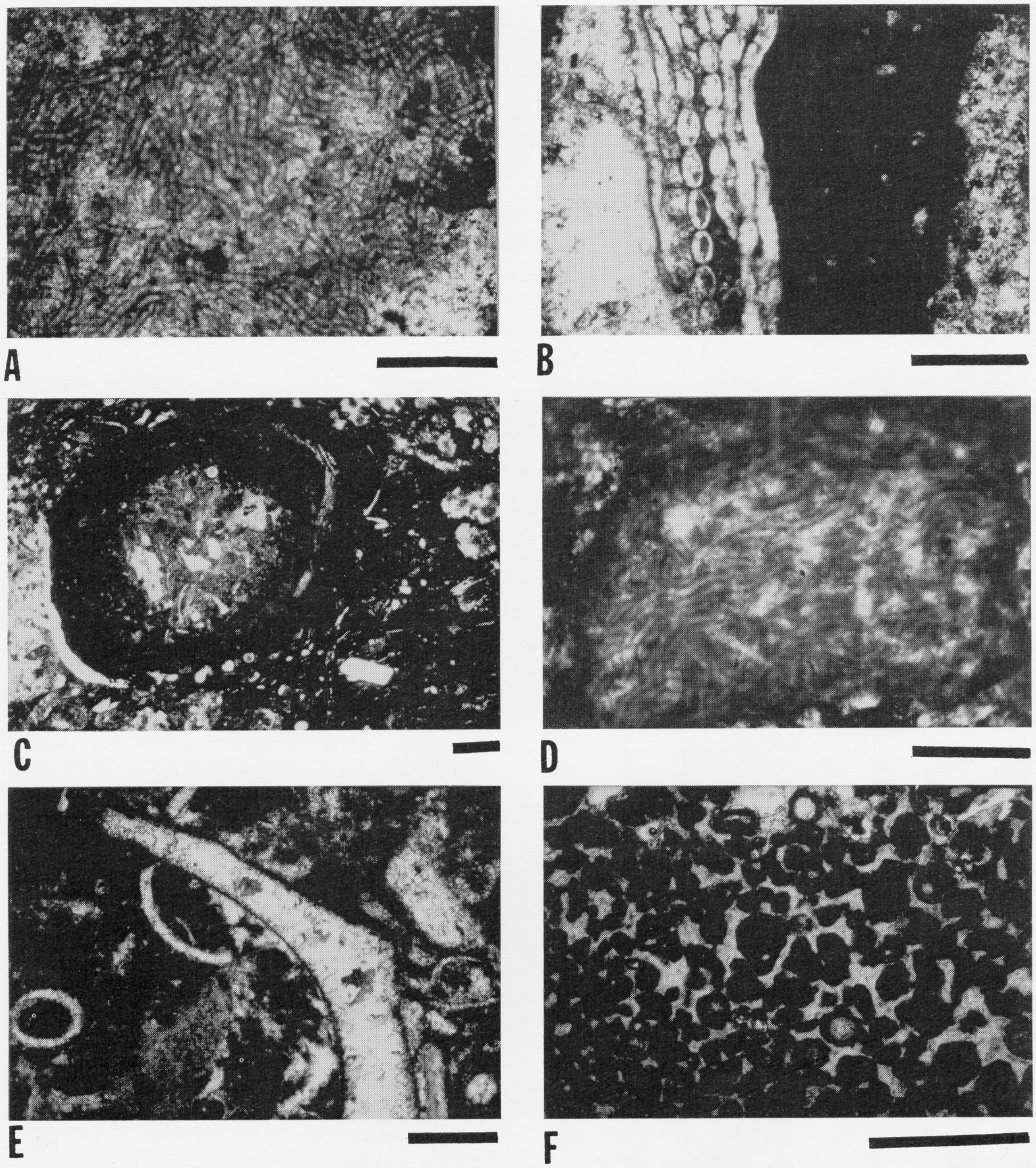

Figure 7-A. Photomicrograph of entwined filaments of the cyanobacteria *Girvanella*. Thin section: NDGS Well No. 793-11455.5*. Polarized light. Bar scale 0.25 mm. **B**. Photomicrograph of filaments of the cyanobacteria *Sphaerocodium* in the form of "beads on a string". Thin section: NDGS Well No. 793-11486.6. Polarized light. Up direction to the left. Bar scale 0.25 mm. **C**. Photomicrograph of an oncolite containing *Sphaerocodium*. Thin section: NDGS well No. 5246-10280.0. Bar scale 1.0 mm. **D**. Photomicrograph of an intraclast exhibiting micrite criss-crossed by tubular cyanobacterial filaments, probably a rip-up clast of an "algal mat". Thin section: NDGS well No. 5246-10280.0. Polarized light. Bar scale 0.25 mm. **E**. Photomicrograph of micrite-rimmed grains formed by endolithic algae. Thin section: NDGS Well No. 793-11477.8. Polarized light. Bar scale 0.5 mm. **F**. Photomicrograph of large, irregularly-shaped peloids formed by endolithic algae that bored an entire skeletal grain. Thin section: NDGS Well No. 5088-12028.9. Bar scale 1.0 mm.

*The number in front of the dash is the North Dakota Geological Survey well number. The depth from the kelly bushing to the sample is given after the dash to tenths of a foot (11455.4). A table that converts NDGS Well Numbers to formal well names and their locations is included in Table 1.

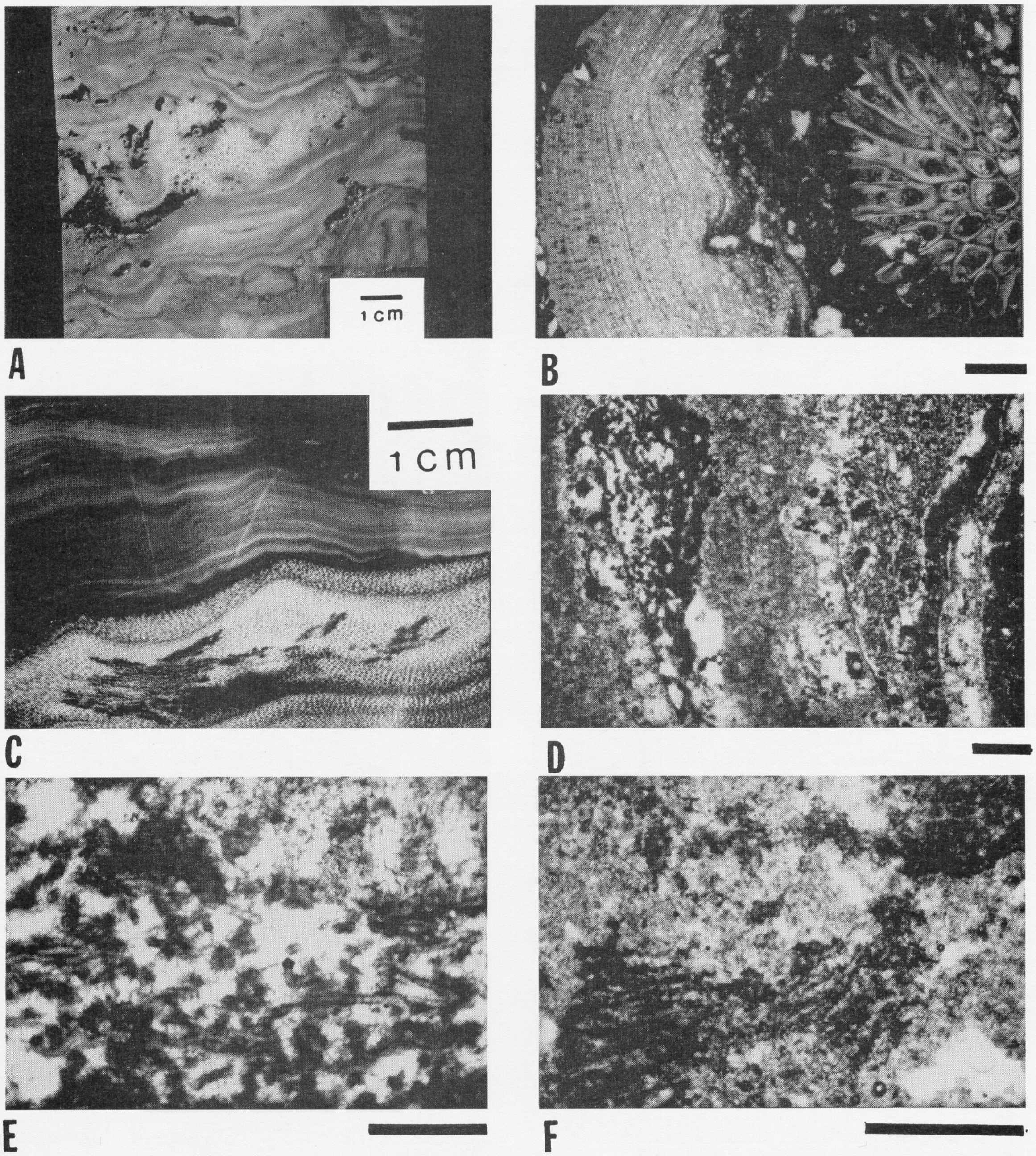

Figure 8-A. Photograph of stromatoporoids in reef rock encrusted by tabulate coral (*Thamnopora*), which is, in turn, encrusted by stromatoporoid. Slab: NDGS Well No. 5280-4819. **B**. Photomicrograph of *Thamnopora*, at right, encrusted by muddy area containing cyanobacterial filaments (visible at 40X magnification), encrusted by stromatoporoid. Thin section: NDGS Well No. 5280-4739.9. Up direction to the left. Bar scale 2.0 mm. **C**. Photograph of stromatoporoids in the reef environment rocks encrusting the tabulate, coral *Alveolites*. Slab: NDGS Well No. 505-11167. **D**. Photomicrograph of stromatoporoid laminae that are separated by muddy areas (dark) that contain cyanobacterial filaments, seen upon closer examination (40X - 100X). Thin section: NDGS Well No. 4916-12046.4. Polarized light. Up direction to the left. Bar scale 0.5 mm. **E**. Photomicrograph of muddy area (lower 2/3 of picture) that occurs between stromatoporoid laminae (one lamina seen in upper part of picture) containing cyanobacterial filaments. Thin section: NDGS Well No. 4916-12046.4. Polarized light. Bar scale 0.25 mm. **F**. Photomicrograph of ghosts of cyanobacterial filaments within matrix as remnants of a former "algal mat". Thin section: NDGS Well No. 4918-6530.8. Bar scale 0.5 mm.

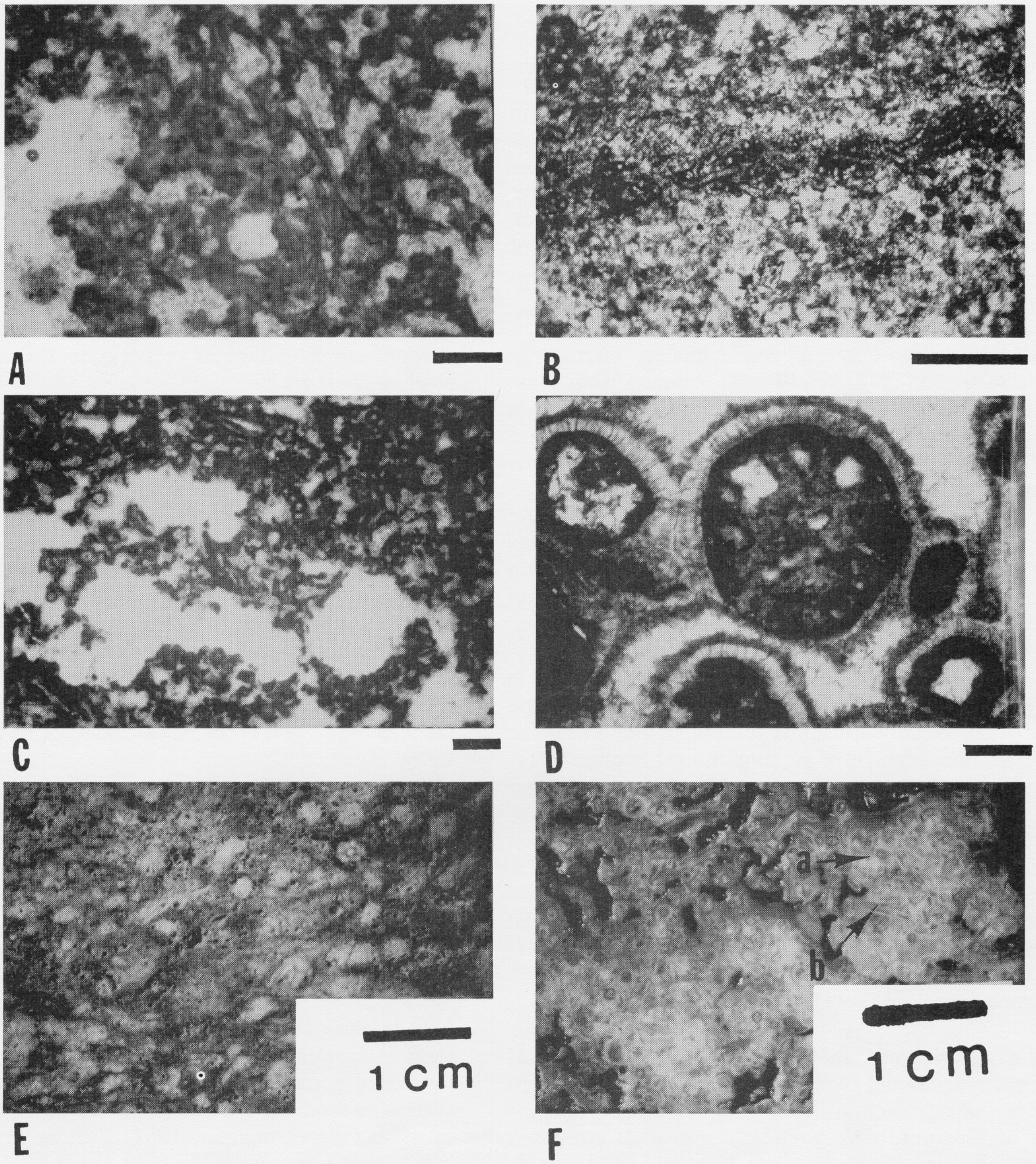

Figure 9-A. Photomicrograph of tubular filaments of cyanobacteria (*Girvanella*) in the matrix of shelf-lagoon rocks. Thin section: NDGS Well No. 5280-4713.9. Bar scale 0.5 mm. **B**. Photomicrograph of filaments of cyanobacteria (*Girvanella*) as ghosts in mildly dolomitized rocks. Thin section: NDGS Well No. 793-11453.7. Polarized light. Bar scale 0.25 mm. **C**. Photomicrograph illustrating that the presence of cyanobacterial filaments in the sediment tends to produce a clotted fabric. Thin section: NDGS Well No. 5280-4713.9. Bar scale 1.0 mm. **D**. Photomicrograph illustrating a grainstone texture, without cyanobacterial filaments in the matrix. Thin section: NDGS Well No. 5280-4711.2. Bar scale 0.5 mm. **E**. Photograph of partly dolomitized limestone exhibiting *Lanicula*, the more common codiacean green alga genus found in the Winnipegosis Formation in North Dakota. Slab: NDGS Well No. 4918-6671. **F**. Photograph of *Lanicula* in limestone; arrows point to transverse view (a) and longitudinal view (b). Slab: NDGS Well No. 4918-6710.

filament concentration.

GREEN CODIACEAN ALGAE

Description.--Devonian green codiacean algae were erect, rooted, segmented plants (Johnson and Konishi, 1958; Johnson, 1964). They have been identified in rocks from both the pinnacle reef lagoon and the shallow-shelf environments. Codiacean algae in the Winnipegosis Formation are represented by two genera: *Lanicula* and *Litanaia*. *Litanaia* is abundant when encountered, but is generally rare in the Winnipegosis of North Dakota. *Lanicula*, on the otherhand, varies from common to abundant in most reef-lagoon samples.

Lanicula segments are approximately circular in transverse section (Fig. 9E, 9F). It commonly has from three to six circular, internal tubes (Fig. 10A, 10B). In longitudinal section, this codiacean alga has a spiny, wave-like outline (Fig. 10C), and has long internal tubes that may appear parallel, or *en chelon* at an angle, with the exterior beginning near the margin of the wall and ending near the center of the sheath. Segment lengths vary greatly (Fig. 10D, 10E). In general, *Litanaia* segments are larger than those of *Lanicula*. *Litanaia* segments are circular to somewhat irregular in transverse section (Fig. 10F, 11A). They show variable arrangement of many more, smaller tubes than those found in *Lanicula*. *Litanaia* tubes are typically grouped in the center of the sheath with some, in oblique view, near the margin of the segment. In longitudinal section (Fig. 11B), *Litanaia* has a straight to wavy outline and internal tubes are mostly observed in longitudinal profile. Only one sample (NDGS Well No. 6535-6700.6) encountered in this study contained both codiacean genera. The codiacean algae were not found in growth position and the segments were separated. In several cases, the segments were aligned parallel to each other and to bedding. *Lanicula* can be identified even in slightly dolomitized rocks (Fig. 11C, 11D).

Environmental interpretation.--The ecological niche of *Lanicula* and *Litanaia* appear similar to modern codiacean algae, such as *Halimeda*. *Halimeda* is composed of aragonite (Wray 1971a) with high strontium content (Hoskin, 1968), has a fast but irregular growth rate (Wray, 1977a) which produces prodigious, sand-sized sediment, and is found in and around reefs, particularly in lagoonal habitats (Johnson, 1971; Wray, 1971b; Rezak and Ginsburg, 1971). *Halimeda* lives below intense wave agitation, just below low tide, to depths of 100 metres; but it is most common and diverse at shallow-water depths (Moore et al., 1976; Wray, 1977a) usually no greater than 10 to 20 metres (Milliman, 1974). A similar shallow-water depth is interpreted for the codiacean algae in the Winnipegosis Formation.

GREEN DASYCLADACEAN ALGAE (CALCISPHERES)

Description.--Green dasycladacean algae have been recognized from a few shelf lagoon rocks. *Vermiporella* is the genus represented. Although dasycladacean algal segments in the Winnipegosis in North Dakota are very rare, calcispheres are abundant in both reef-lagoon and shelf-lagoon rocks. Calcispheres are thought to be reproductive bodies (Stanton, 1963) probably of dasycladacean algae (Rupp, 1968). Calcispheres found in the Winnipegosis are of two types. One type is a hollow spherical body, with radially arranged spines on the outer surface (Fig. 11E, 11F). These spined-calcispheres are abundant in reef-lagoon and are rare in shallow-shelf rocks.

The second type of calcisphere found in Winnipegosis rocks has a smooth, spherical body. This calcisphere is also larger, more uniform in size (Fig. 12A), and has very thick walls that are usually divided into an inner dark layer and an outer radiating-calcite layer (Fig. 12B). It has a smooth to scalloped outer margin without spines and an equant, spar-filled center. Although calcispheres are usually intact with circular outlines, they have been found compacted and broken in some samples. This type of calcisphere is found in rocks deposited in restricted parts of shelf lagoons. The two types of calcispheres have not been found together.

Environmental Interpretation.--Calcispheres dominate lagoonal rocks in the Devonian. However, the two types of calcispheres found in the Winnipegosis in North Dakota are found in two different kinds of lagoons. The spined-calcispheres are found in pinnacle reef lagoons and the thick-walled calcispheres are found in shelf-lagoons.

In the "back-reef" lagoons located on pinnacle reefs where spined-calcispheres are found, wave energy decreased across the reef tract to a point where only carbonate sand and mud accumulated in the central part of the lagoon (Longman, 1981). Water in the "back-reef" lagoon was probably 1 to 5 metres deep, but in places perhaps reached depths of as much as 10 metres. The muddy sand of this lithofacies represents deposition under relatively quiet conditions, with low wave energy and limited water circulation, except during storms which aligned codiacean algal segments. The spined-calcispheres are interpreted to have accumulated in sediments deposited in central "back-reef" lagoon areas sheltered by the pinnacle reef rim and rarely in back-reef lagoons on the shelves.

The second type of calcisphere is interpreted to

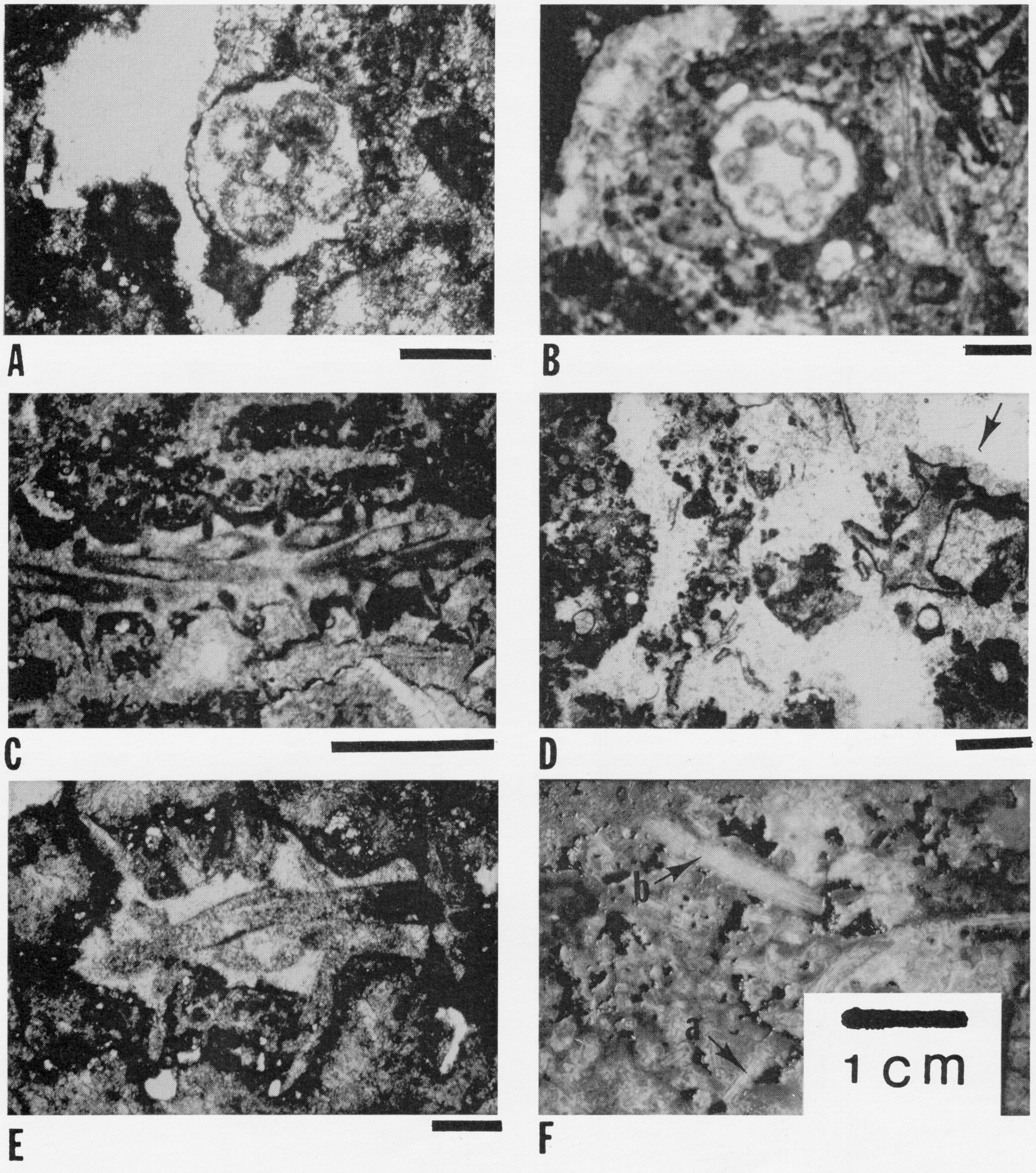

Figure 10-A. Photomicrograph of transverse view of *Lanicula* with four internal tubes. Thin section: NDGS Well No. 6535-6643.7. Bar scale 0.5 mm. **B**. Photomicrograph of transverse view of *Lanicula* with six internal tubes and roughly circular external shape. Thin section: NDGS Well No. 6535-6726.9. Bar scale 0.5 mm. **C**. Photomicrograph of longitudinal view of a long segment of *Lanicula* with *en echelon* internal tubes and slightly scalloped outer edge. Thin section: NDGS Well No. 6535-6675.7. Bar scale 1.0 mm. **D**. Photomicrograph of the longitudinal view of a tip segment (arrow) from *Lanicula*. Thin section: NDGS Well No. 6535-6670.3. Bar scale 1.0 mm. **E**. Photomicrograph of the longitudinal view of a short segment of *Lanicula* with an extremely scalloped outer edge. Thin section: NDGS Well No. 6535-6661.5. Bar scale 0.5 mm. **F**. Photograph of the two genera of green codiacean algae: *Lanicula* (smaller grains, arrow with 'a') and *Litanaia* (larger grains, arrow with 'b'); both longitudinal views. Slab: NDGS Well No. 4918-6710.

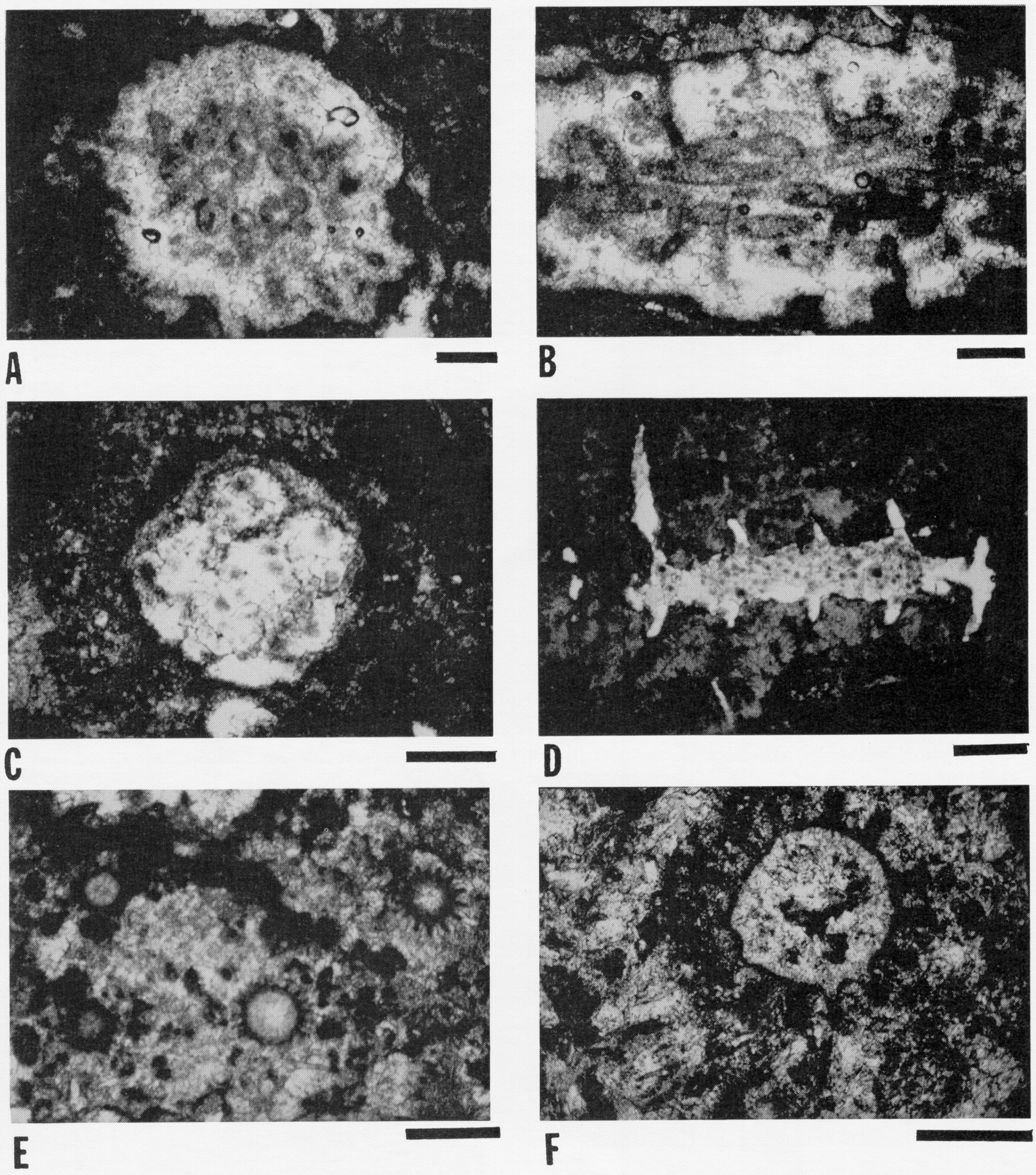

Figure 11-A. Photomicrograph of a transverse view of *Litanaia* illustrating large number of internal tubes and the roughly circular outer margin, both characteristics of this genus. Thin section: NDGS Well No. 4918-6700.6. Bar scale 0.5 mm. **B**. Photomicrograph of a longitudinal view of *Litanaia* showing both the large number of internal tubes and the less-scalloped outer margin (as compared to *Lanicula*), both characteristics of this genus. Thin section: NDGS Well No. 4918-6700.6. Bar scale 0.5 mm. **C**. Photomicrograph illustrating transverse view of codiacean algae (*Lanicula*) when rock is slightly dolomitized. Thin section: NDGS Well No. 6535-6643.7. Bar scale 0.5 mm. **D**. Photomicrograph showing longitudinal view of codiacean algae (*Lanicula*) when slightly dolomitized. Thin section: NDGS Well No. 6535-6709.8. Bar scale 1.0 mm. **E**. Photomicrograph of calcispheres (algal spores) with outer spines. Thin section: NDGS Well No. 6535-6716.1. Bar scale 0.5 mm. **F**. Photomicrograph of calcisphere with spines typically found in back-reef lagoons on pinnacle reefs in the Winnipegosis Formation in North Dakota. Thin section: NDGS Well No. 6535-6711.6. Polarized light. Bar scale 0.25 mm.

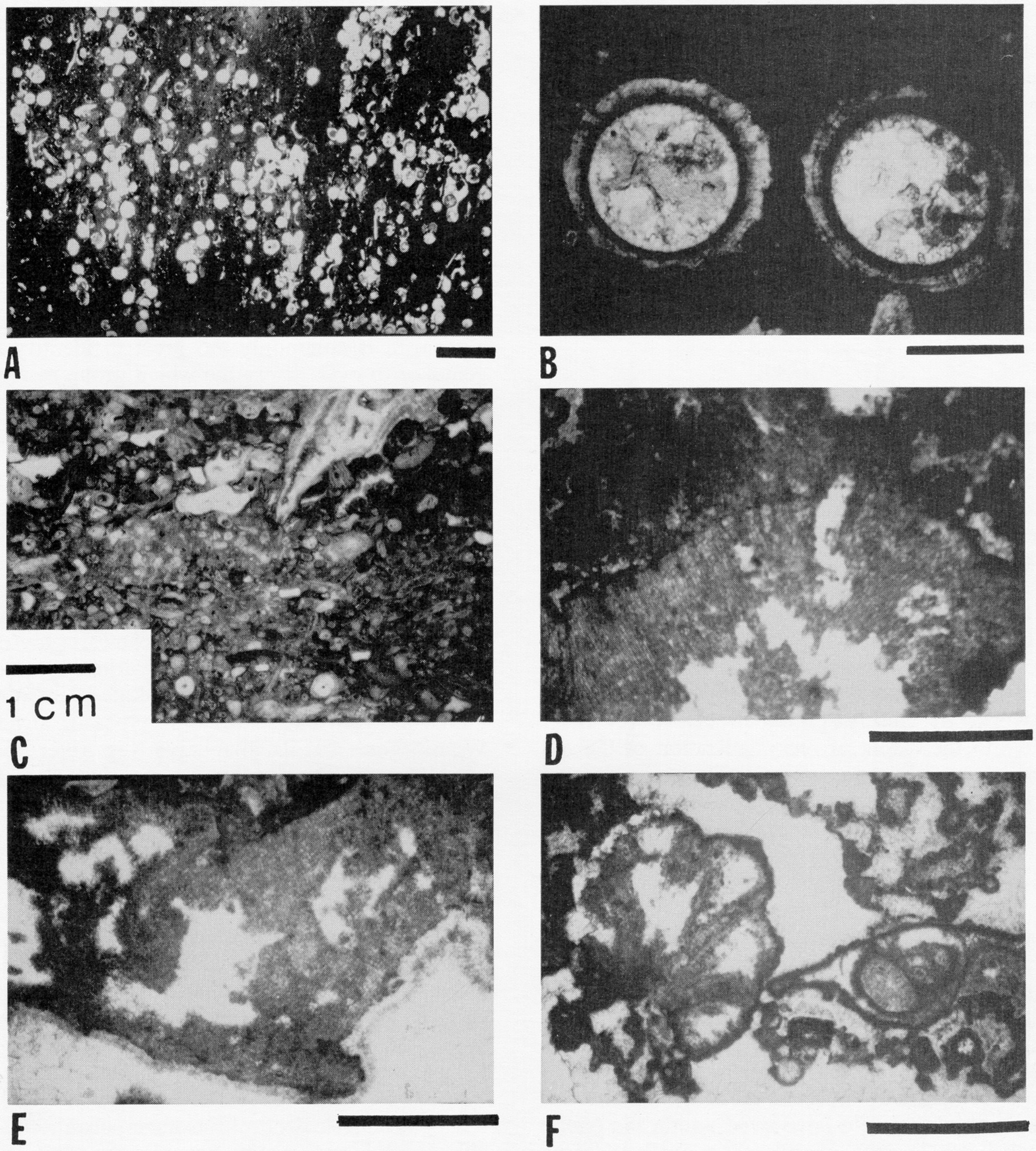

Figure 12-A. Photomicrograph of a second type of calcisphere exhibiting a thick-walled, slightly recrystallized smooth sphere. Thin section: NDGS Well No. 5158-8852.1. Up direction to the left. Bar scale 2.0 mm. **B**. Photomicrograph of typical thick-walled calcispheres from restricted shelf lagoon in the Winnipegosis Formation in North Dakota. Thin section: NDGS Well No. 5158-8852.1. Polarized light. Bar scale 0.25 mm. **C**. Photograph illustrating red algal grains (small circular grains). Slab: NDGS Well No. 5280-4711. **D**. Photomicrograph of *Parachaetetes*, red algae, recognized in longitudinal view by parallel to radiating boxwork and cross partitions at regular intervals. Grains are commonly partly recrystallized. Thin section: NDGS Well No. 5280-4731.8. Bar scale 1.0 mm. **E**. Photomicrograph of *Parachaetetes*, red algae, recognized in transverse view by the network of closely-spaced circular pores. Grains are commonly partly recrystallized. Thin section: NDGS Well No. 5280-4715.3. Bar scale 1.0 mm. **F**. Photomicrograph illustrating fan- or bushy-shaped grains of possible algal origin found in association with red algae in shelf lagoons and with green algae in reef lagoons. Grains with variably micritized outer margins and recrystallized centers. Thin section: NDGS Well No. 5280-4712.6. Bar scale 1.0 mm.

have been deposited in a restricted-marine shelf lagoon because these rocks lack faunal diversity, lack stenohaline organisms, and contain abundant fossils of euryhaline organisms (Heckel, 1974). The euryhaline organisms that are found in these rocks (i.e., ostracodes, calcispheres, gastropods, bivalves) are characteristic of a brackish or hypersaline fauna (schizohaline fauna). A depauperate fauna such as this is adapted for survival under extreme conditions such as abrupt salinity fluctuations and very shallow depths (Heckel, 1972). It is interpreted that the rocks containing thick-walled calcispheres were deposited in this type of environment.

RED ALGAE

Description.--*Parachaetetes* is represented by sand-sized fragments (Fig. 12C) of bushy-like, hemispheroidal-nodular to irregularly-shaped grains which commonly have outer margins composed of micrite and internal patches that have been recrystallized to microspar. Identifications are based on small areas of the algal grains that preserve ghosts of the internal red algal texture. Longitudinal sections through the grains (Fig. 12D) show cellular structures of minute radiating to parallel walls with cross partitions at regular intervals forming boxwork patterns, and the transverse sections have networks of closely-spaced circular pores (Fig. 12E). Due to the extent of recrystallization of the red algal grains, a second common Devonian genus, *Solenopora*, may be present, but not recognized. The latter genus is distinguished from *Parachaetetes* by the lack of, or rare, irregularly-spaced partitions seen in the longitudinal sections.

Environmental Interpretation.--Modern red algae are composed of Mg-calcite (Hoskin, 1968; Johnson, 1971), and if Devonian red algae had the same composition, this may have been an important factor in the early diagenetic recrystallization of the red algal grains (Wray, 1977b). If the ecologic niche of solenoporacean red algae is comparable to that of modern corallinacean red algae, then they would have lived within the photic zone (Heckel, 1972), most abundantly at shallow depths less than 10 metres, in the high energy intertidal zone (Wray, 1977a), or in the moderately agitated subtidal zone (Heckel, 1972). It is inferred by the erect habit of the red algae found in the Winnipegosis that they lived in moderately agitated waters of shelf lagoons in the shallow, subtidal zone.

OTHER ALGAL(?) GRAINS

Description.--Other common allochems in the Winnipegosis are fan- or bushy-shaped grains found in association with red algae in shelf lagoon rocks and with green algae in the reef lagoon rocks. These grains have variably micritized outer margins and recrystallized centers (Fig. 12F). Radiating from a possible stem, ghost structures are usually visible (Fig. 13A, 13B, 13C). They resemble both green and red algae; however, the internal ghost structures seem to be an order of magnitude larger than those of red algae. Diagenetic features found in these grains appear similar to diagenetic features in identifiable algae from the Winnipegosis.

Environmental Interpretation.--These grains are interpreted to be of probable algal origin, some may be related to red algae and some to green algae, but neomorphism is commonly too great to identify them to genus or to even determine which group of algae they belong. No environmental interpretation can be made at this time.

COMPARISON OF THE WINNIPEGOSIS FLORA IN NORTH DAKOTA TO THAT OF THE WINNIPEGOSIS, OR KEG RIVER, IN CANADA

The Elk Point Basin extended from northwestern North Dakota/northeastern Montana northwestward into Manitoba, across Saskatchewan to northern Alberta. The distribution of the various types of algae in the Winnipegosis in North Dakota is in some ways unlike the distribution of these types of algae in the Winnipegosis and its correlative Keg River Formation of Alberta. The lagoons in western Canada were dominated by dasycladacean green algae (*Vermiporella*) (e.g., Jamieson, 1971; Krebs, 1974; Coppold, 1976) and by dendroid stromatoporoids (*Amphipora*), (e.g., Wray, 1967; Streeton, 1971; Machielse, 1972; Riding, 1972; Tsien and Dricot, 1977), with minor occurrences of codiacean green algae, red algae, and calcispheres. The Winnipegosis in North Dakota, however, is dominated by red algae, codiacean green algae, and abundant calcispheres, and contains very rare dasycladacean green algae, and rare dendroid stromatoporoids (*Amphipora*).

The delicate dendroid stromatoporoid, *Amphipora*, although it is not an alga, occupies the same ecological niche as green algae, and will be briefly discussed in the context of the comparison of Canadian and North Dakota lagoons. *Amhipora* is rare to abundant in some shelf-lagoon rocks in North Dakota. In hand sample, dendroid stromatoporoid grains (Fig. 13D) can be confused with peloids, red algae, or transverse sections of green algae. In hand sample, the transverse view of dendroid stromatoporoids appears as small (0.6 mm or less in diameter) circular grains, in some cases with a central pore. In longitudinal view, dendroid stromatoporoids appear as small, rod-like grains approximately 2.5 mm long. However, in thin section, *Amphipora* can easily be recognized. In transverse

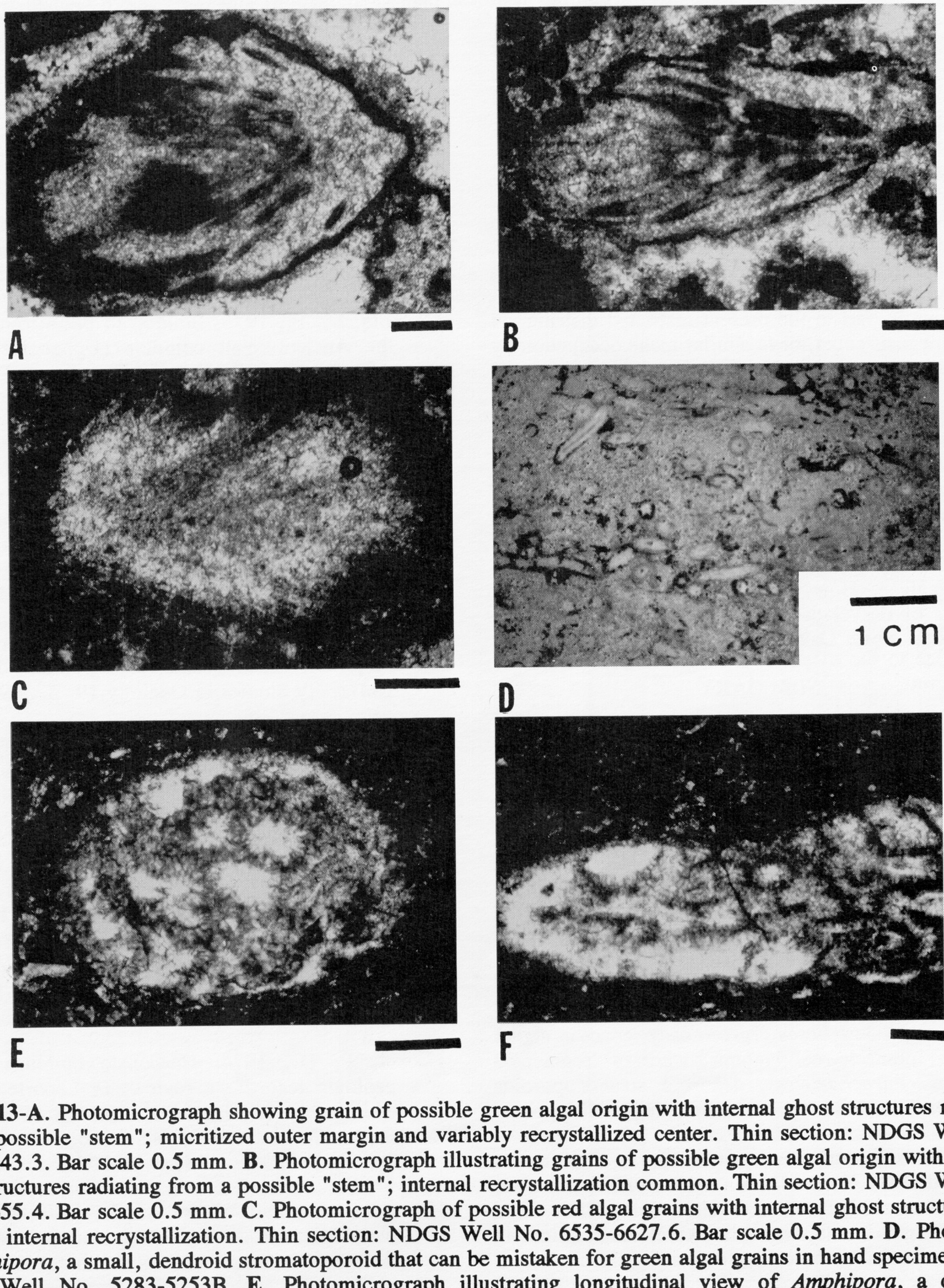

Figure 13-A. Photomicrograph showing grain of possible green algal origin with internal ghost structures radiating from a possible "stem"; micritized outer margin and variably recrystallized center. Thin section: NDGS Well No. 6535-6643.3. Bar scale 0.5 mm. **B**. Photomicrograph illustrating grains of possible green algal origin with internal ghost structures radiating from a possible "stem"; internal recrystallization common. Thin section: NDGS Well No. 6535-6655.4. Bar scale 0.5 mm. **C**. Photomicrograph of possible red algal grains with internal ghost structures and variable internal recrystallization. Thin section: NDGS Well No. 6535-6627.6. Bar scale 0.5 mm. **D**. Photograph of *Amphipora*, a small, dendroid stromatoporoid that can be mistaken for green algal grains in hand specimen. Slab: NDGS Well No. 5283-5253B. **E**. Photomicrograph illustrating longitudinal view of *Amphipora*, a dendroid stromatoporoid. Thin section: NDGS Well No. 4379-11200.8. Polarized light. Bar scale 0.5 mm. **F**. Photomicrographshowing transverse view of *Amphipora*, a dendroid stromatoporoid. Thin section: NDGS Well No. 4379-11200.8. Polarized light. Bar scale 0.5 mm.

view, it occurs as circular- to ecliptical-shaped grains (Fig. 13E), with characteristic stromatoporoid wall texture, and with circular pores aligned along the circumference of the wall and within the central part of the grain. In longitudinal view (Fig. 13F), the grains appear to have a variable pattern of circular or elliptical pores within a tabular to thin, ellipsoidally-shaped grain.

In general, *Amphipora* was rare in North Dakota. However, it has been reported as dominant, abundant, and ubiquitous in back-reef lagoons in Canadian Devonian rocks (Klovan, 1964; Kobluk, 1975; Murry, 1966; Nelson, 1975). This apparent difference in widespread occurrence and abundance of *Amphipora* may be due in part to the present restricted distribution of Winnipegosis cores, or to similar niche occupation by green codiacean algae in North Dakota.

It is possible that the reef lagoons represented in North Dakota Winnipegosis core were less restricted than those found in Canada because of the abundance of codiacean algae and calcispheres and sparcity of dasycladacean algae. Dasycladacean algae are believed to have lived under somewhat more restricted conditions (Wray, 1971c; Jamieson, 1971; Coppold, 1976) than codiacean algae. However, if calcispheres are reproductive cysts of dasycladacean algae, that alga may have also lived in North Dakota reef lagoons.

SUMMARY

In North Dakota, algae and cyanobacteria thrived in many of the shallow-water environments that developed during the second episode of deposition of the Winnipegosis Formation. Cyanobacterial filaments were found in oncolites, intraclasts, in the matrix as remnant "algal mats," and as endolithic algae that contributed both to micrite-rimmed grains and to completely micritized grains. Cyanobacterial filaments contributed to the binding of the pinnacle-reef rims and the patch reefs. They encrusted a variety of organisms, thriving especially in association with corals and stromatoporoids in reef environments. Green codiacean algae (*Lanicula, Litanaia*) and calcispheres (?green dasycladacean algae) dominated pinnacle-reef lagoons; whereas, segmented red algae (*Parachaetetes*), dendroid stromatoporoids (*Amphipora*), and calcispheres dominated shelf lagoons.

In North Dakota, *Amphipora* is rare in shelf lagoon rocks, and pinnacle reef lagoon rocks contain abundant *Lanicula*. Apparently the ecological nich usually filled by branching stromatoporoids or dasycladacean algae in Canada was filled by branching codiacean algae in North Dakota.

Based upon this floral analysis, it is inferred that the reef lagoons in North Dakota were less restricted than shelf lagoons and the western Canadian lagoons apparently were more restricted than North Dakota lagoons. Although cyanobacterial filaments have seldom been reported from Canada, they were probably distributed as extensively in reef environments there as they were in North Dakota.

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THE PALEOECOLOGY OF *ECHINOCARIS RANDALLII* BEECHER FROM DRAKE WELL, TITUSVILLE, PENNSYLVANIA

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ABSTRACT

***Echinocaris randallii* Beecher is reported, for the first time, in interbedded coarse to fine clastic rocks cropping out at Drake Well, Titusville, Pennsylvania. The rocks have been identified as belonging to the Corry Sandstone, a unit presumed to be Mississippian, by recent workers. However, the presence of *Cyrtospirifer* Nalivkin in these rocks and the absence of *Paraphorhynchus* Weller firmly establishes the age of the rocks as Late Devonian -- not Mississippian. There are no unequivocal Mississippian occurrences of *Echinocaris randallii*. By contrast with "typical" occurrences of species of *Echinocaris*, *E. randallii* occurs at this locality in association with a diverse assemblage of megainvertebrates including sponges, brachiopods, pelecypods, gastropods, cephalopods, and pelmatozoans as well as trace fossils, including *Teichichnus* Seilacher and *Palaeophycus* Hall. This association probably represents a benthic community developed on medium to fine clastic, inner shelf substrata which were periodically interrupted by rapid influxes of coarser sediments.**

INTRODUCTION

Echinocaris randallii Beecher, 1902 has been collected from rocks of the Corry Sandstone, near Titusville, Pennsylvania, for the first time. Prior to this, *E. randallii* along with *E. clarkii* Beecher, 1902 were reported from the Mississippian Waverly Group near Warren, Pennsylvania (Beecher, 1902, p. 443-444). Caster (1934, p. 75) listed this taxon as occurring, questionably, in the Oswayo-lower Riceville Member and Cussewago series (Knapp suite and Kushequa shale). Later, Rolfe (1969, p. R305) illustrated a specimen of *E. randallii*? which had been collected by Caster from Warren. *Echinocaris randallii* has been thought to be one of very few species of the genus to be known from the Mississippian. Subsequent work in the Warren area has not provided confirmation of this age determination. The only other occurrence of the genus reported to be Mississippian is that of *E. beecheri* Copeland, 1960 which was described from the Banff? Formation in Alberta, Canada (Copeland, 1960, p. 6-7).

This new occurrence of *E. randallii* is from an exposure of sandstone near Drake Well, Titusville, Pennsylvania (Fig. 1). The rocks have been referred to the Corry Sandstone by recent workers (Ward et al., 1976; Hoskins et al., 1983) and we follow this precedent here although we have not confirmed this correlation. The first six specimens of *Echinocaris* were collected by Scott McKenzie of Erie, Pennsylvania. Subsequent collecting has yielded one additional specimen definitely referable to *E. randallii* and one abdominal fragment and a portion of a mold of a carapace likely belonging to the same genus.

The purpose of this paper is to document the occurrence of *Echinocaris*, to determine the age of the beds, and to evaluate the environmental setting in which the rocks at this locality were deposited. This analysis will attempt to reconstruct the Corry Sandstone paleocommunity in the vicinity of Drake Well by assess-

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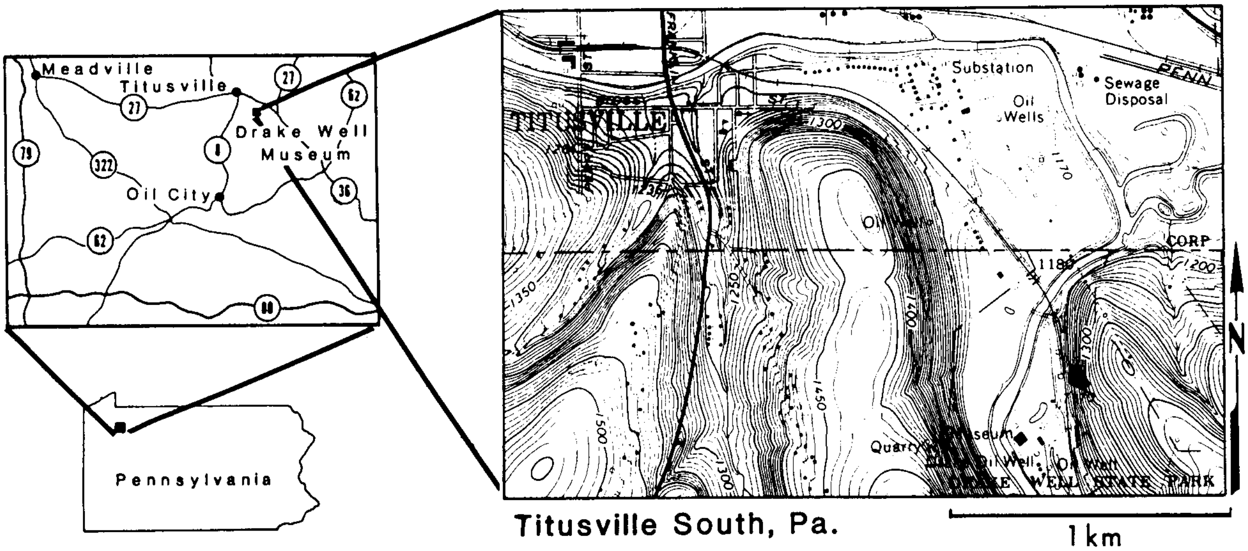


Figure 1-Maps showing the location of Drake Well, near Titusville, Pennsylvania. Arrow denotes the location of the exposure of Corry Sandstone which was studied.

ing environmental tolerances of associated fauna. Additionally, trace fossil associations will be considered independently in order to establish the representative ichnofacies for the Corry Sandstone.

STRATIGRAPHY

The Corry Sandstone was named by I. C. White (1881, p. 92) who first correlated it with the Berea Sandstone. Girty (1939, p. 47) and Pepper et al. (1954, p. 39-40) also recognized this correlation. Pepper et al. (1954, p. 40) redescribed the Corry Sandstone at its type area. Subsequently, Ward et al. (1976, p. 33) identified the strata at the Drake Well locality to be within the lower Corry or, possibly, a sandstone of similar lithology just below the Corry. Edmunds (1981) mapped this exposure as the Corry Sandstone through the Riceville Formation, undivided. Hoskins et al. (1983, p. 177-178) considered the Drake Well outcrop to be the Corry Sandstone. The Corry Sandstone was considered to be Kinderhookian in age by Berg et al. (1986). Caster (1934, p. 123-124) listed a large number of taxa occurring in the Corry. The most detailed study of the paleontology of the Corry Sandstone, however, has been that of Sass (1960). Langdon (p. 33, *in* Ward et al., 1976) identified the sponge *Titusvillia drakei*, the brachiopods *Rugosochonetes*, *Schumardella*, *Spirifer*, and *Lingula*, the clams *Parallelodon* and *Leiopteria*, the snail *Straparollus*, nautiloids, crinoids, stelleroids, and trace fossils at the Drake Well locality. Hoskins et al. (1983, p. 178) listed essentially the same fauna at this site.

The Corry Sandstone is a sequence of clastic rocks which crop out in northeastern Pennsylvania from Corry, southward along Oil Creek, to the town of Oil Creek. The Corry has been subdivided into three members. Sass (1960, p. 274) described these subdivisions as follows: The lowest member is an irregularly bedded, grayish-white to buff sandstone which attains a maximum thickness of 3.0-3.6 m in the vicinity of Oil City, south of the study area. At some locations, calcareous concretions are evident at the basal contact and irregular lentils with high calcium carbonate concentrations and recrystallized shell material are preserved. The middle Corry section is characterized by flaggy, gray to greenish-gray siltstones and shales which attain a maximum thickness of 3.0 m near Oil City. This member contains abundant mica flakes oriented parallel to bedding and has generally been considered to be unfossiliferous. The upper member of the Corry is similar in lithology to the lowest member but is unfossiliferous and reaches a maximum thickness of 3.0 m in the Oil City area.

The exposure of alternating shales/mudstones, siltstones, and very fine sandstones measured near Drake Well is approximately 8 m thick (Fig. 2). The lower 1.0 m represents the uppermost Riceville Shale. The base of the Corry is described as calcareous and fossiliferous. These criteria may be used to recognize the boundary of the Corry with the underlying strata (Sass, 1960). The three Corry members are interpreted to be present at Drake Well based upon fossil occurrences, sedimentary structures, thickness, and lithology.

The lower Corry (Fig. 3, 1.0-3.5 m) consists of thick beds of slabby to blocky siltstone which, in some places, coarsen to very fine sandstone, and a few inter-

Figure 2-Exposure of Corry Sandstone at Drake Well. Person in lower right corner of photo is examining the contact between the Riceville Shale and the Corry Sandstone.

vening laminated, fissile shales. Sedimentary features include hummocky crossbeds, clay rip-up clasts, ripple and scour marks, and soft sediment deformation. Trace fossils are concentrated at the bases of the siltstone beds and a few are preserved within the shales. The most abundant trace fossils are *Paleophycus* and *Teichichnus*. Body fossils, in order of abundance, include brachiopods, pelecypods, crinoids, bryozoans, and sponges.

The middle Corry (Fig. 3, 3.5-5.9 m) is dominated by blocky beds of mudstone and siltstone with thin, laminated, fissile shale interbeds. Many of the beds are highly micaceous. The mudstones and shales often contain siltstone lenses and concretions are present near the upper portion of the interval. The strata are typically flat bedded with minor cross laminations, ripple and sole marks. A diverse group of trace fossils are concentrated in the basal 60 cm and brachiopods are present in many of the siltstone beds.

The upper Corry (Fig. 3, 5.9-8.3 m) is composed of massive to blocky siltstone beds and thicker intervals of laminated shales with pods of siltstone. Concretions and iron staining are common in the shales and scours were identified in an upper siltstone bed. This member is devoid of body fossils and contains only a limited number of the trace fossils *Palaeophycus* and *Teichichnus* near the top of the section.

AGE

Although several invertebrate taxa are present in the Corry Sandstone at this locality, only the brachiopod *Cyrtospirifer* Nalivkin (*in* Fredericks) can be used to define an age for the unit. McKellar (1970) cited the occurrence of *Cyrtospirifer* in the Devonian of Australia, succeeded by *Tenticospirifer* at the very top of the Famennian. Carter (personal communication) asserted that in the United States, unlike Australia, *Cyrtospirifer* can be found throughout the Famennian, up to and including the top. This corresponds with the top of the *Wocklumeria* VI zone, which defines the top of the Famennian sequence in Germany. McKellar (1970) and Carter (personal communication) both considered *Cyrtospirifer* to be solely a Devonian taxon. Therefore, its presence in the section at Drake Well permits unequivocal assignment of a Devonian age to at least the lower 1.5-2.0 m of the measured section.

PALEONTOLOGY

Systematics of ***Echinocaris***
Subclass **PHYLLOCARIDA** Packard, 1879
Order **ARCHAEOSTRACA** Claus, 1888
Suborder **CERATIOCARINA** Clarke *in* Zittel, 1900
Family **ECHINOCARIDIDAE** Clarke *in* Zittel, 1900
Genus **ECHINOCARIS** Whitfield, 1880
Echinocaris randallii Beecher, 1902
Fig. 4

Echinocaris randallii BEECHER, 1902, p. 443, Pl. 18, Fig. 8;
Echinocaris randalli CASTER, 1930, p. 98, Pl. 55,

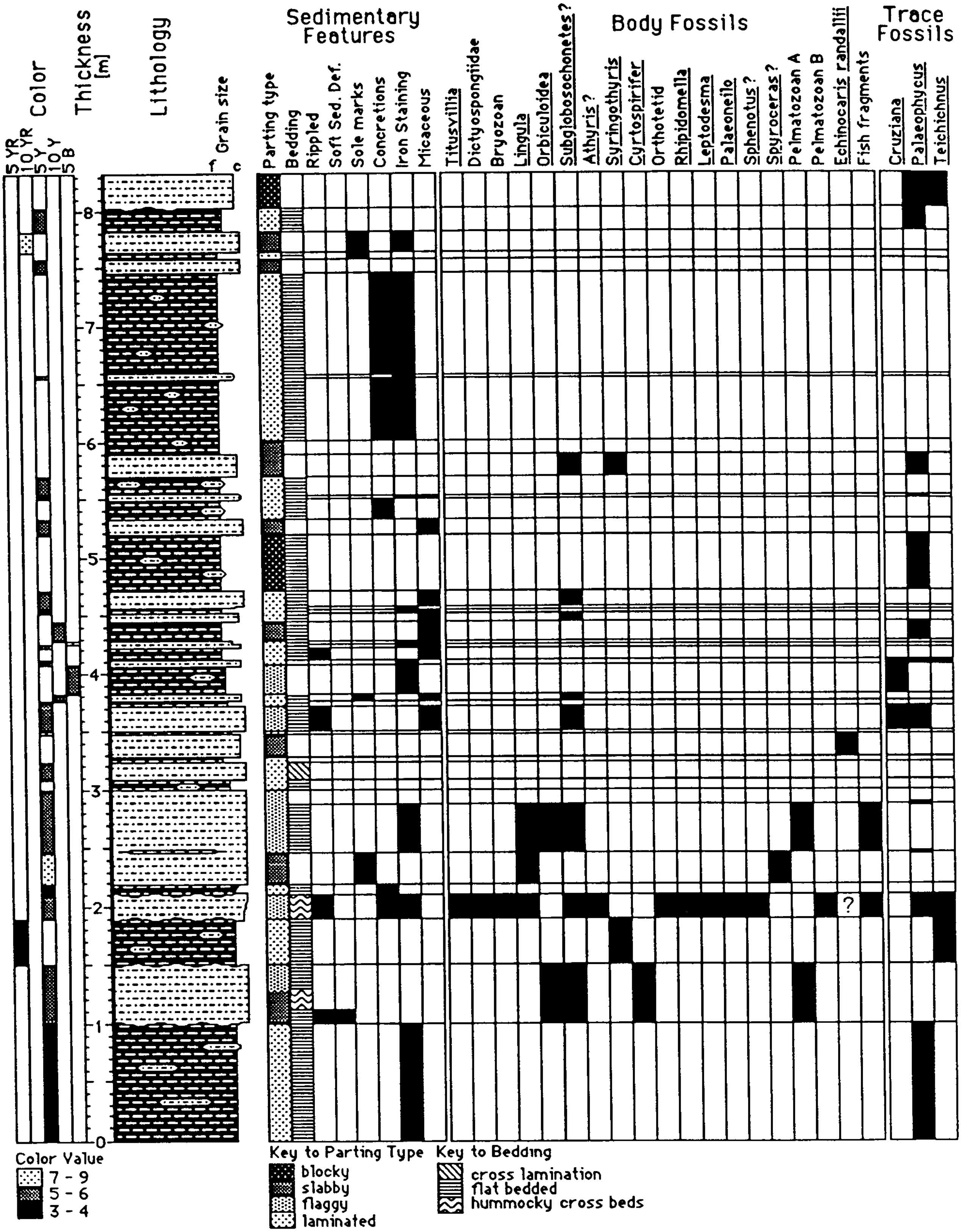


Figure 3-Stratigraphic section of a portion of the Riceville Shale and the Corry Sandstone measured at Drake Well. Fossils not otherwise indicated are deposited in the collections of the Kent State University Geology Department.

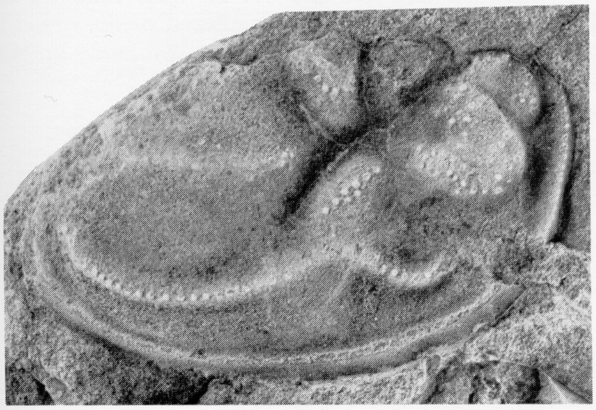


Figure 4-Right lateral view of the carapace of *Echinocaris randallii* Beecher, Cleveland Museum of Natural History (CMNH) 8296, collected from the Corry Sandstone at Drake Well. Bar scale equals 1 cm.

Fig. 5;
non Echinocaris randallii? ROLFE, 1969, Fig. 128. (for additional references see Hannibal and Feldmann, 1987).

Material studied.--Cleveland Museum of Natural History (CMNH) 8296; Carnegie Museum (CM) 35616, 35617, 35618, 35619, 35620, 35621.

Description.--Carapace small to large size for genus, length measured parallel to hinge line about 7.5 to 18 mm and, assuming that CM 35621 (a less well-preserved specimen) is a member of the species, up to about 40 mm. Outline of each valve of carapace subovoid, truncate anteriorly, posteriorly extended. Length to width ratio of valve approximately 3 to 2.

Hinge line located toward anterior. Well-defined, typically keeled, marginal ridge surrounds carapace on remaining sides, but is less well developed between the posterodorsal ridge and the hinge line. Anterior portion of this ridge with small, upright tubercles developed along axis and along anterior margin; tubercles or spines also developed on posterodorsal portion of this ridge. Marginal sulcus located interior of most of marginal ridge.

Centroventral ridge strongly sigmoidal, long, extending up to about 80% length of carapace; with single row of strongly developed tubercles closely and evenly distributed along its axis. Posterocentral ridge long, straight or curved; with tubercles, typically arrayed in about two rows. Posterodorsal ridge long, strongly tuberculate. This ridge intercepts posterodorsal lobe, but becomes less developed close to that lobe. Anterodorsal lobe large, subtriangular, convex, with more or less randomly distributed tubercles. An anterior groove often divides this lobe into two parts, a smaller, dorsal sublobe and a larger, ventral sublobe. Dorsal lobe subtriangular, convex, with more or less randomly distributed tubercles. Posterodorsal lobe subovate, dorso-ventrally elongate, strongly and smoothly convex, with more or less randomly distributed tubercles. Centroventral lobe subovate, obliquely elongate, strongly and smoothly convex, with two rows of tubercles. Sulci defining major lobes well defined.

Remarks.--*Echinocaris randallii* resembles, in some respects, several other species of *Echinocaris*, including *Echinocaris socialis* Beecher, 1884, *E. beecheri* Copeland, 1960, and *E. crosbyensis* Eller, 1937. It can be distinguished from *E. socialis* by the more strongly developed anterior portion of its centroventral ridge and other features. *Echinocaris beecheri* was originally differentiated from *E. randallii* by being larger and in having a dorsal carina presumed to be lacking in the latter (Copeland, 1960, p. 7). With the description of the Titusville material this is no longer true; however, *E. beecheri* can be distinguished from *E. randallii* by the former's generally more pustulose nature. *Echinocaris randallii* can be distinguished from *E. crosbyensis*, with which it shares a long, strongly sigmoidal, centroventral ridge, by the lack of a posterocentral ridge on the latter.

Echinocaris randallii was collected *in situ* in an outcrop about 33 m north of the measured section in a position equivalent to 3 m from the base of the section. This interpretation places the echinocaridid in a unit containing only body fossil fragments and one trace fossil. In addition, the species was collected as float from several samples of calcareous siltstone containing a diverse megafauna strongly suggesting that the blocks had been derived from the unit 2 m above the base of the section. It is from that position that an isolated abdominal segment, presumed to be an echinocaridid, was collected *in situ*.

Echinocaris remains are well preserved in siltstone. Typically they occur as molds of the exterior with cuticle adherent to at least one of these molds. It is not clear whether these individuals represent exuvia or carcasses. The specimens show no signs of predation or scavenging. The generally high quality of preservation of *Echinocaris* suggests that any other arthropods, such as trilobites, buried in the siltstones of the Corry should have been preserved. None was found.

This association of *Echinocaris* with a moderately diverse megainvertebrate fauna is not typical. More commonly, especially in the Upper Devonian, echinocaridids have been recognized in fine clastic units, greenish gray to dark shales, such as the Chagrin Shale interpreted (Schwimmer et al., 1987) to have been deposited in oxygen deficient habitats. In these settings, the associated fauna tends to be sparse.

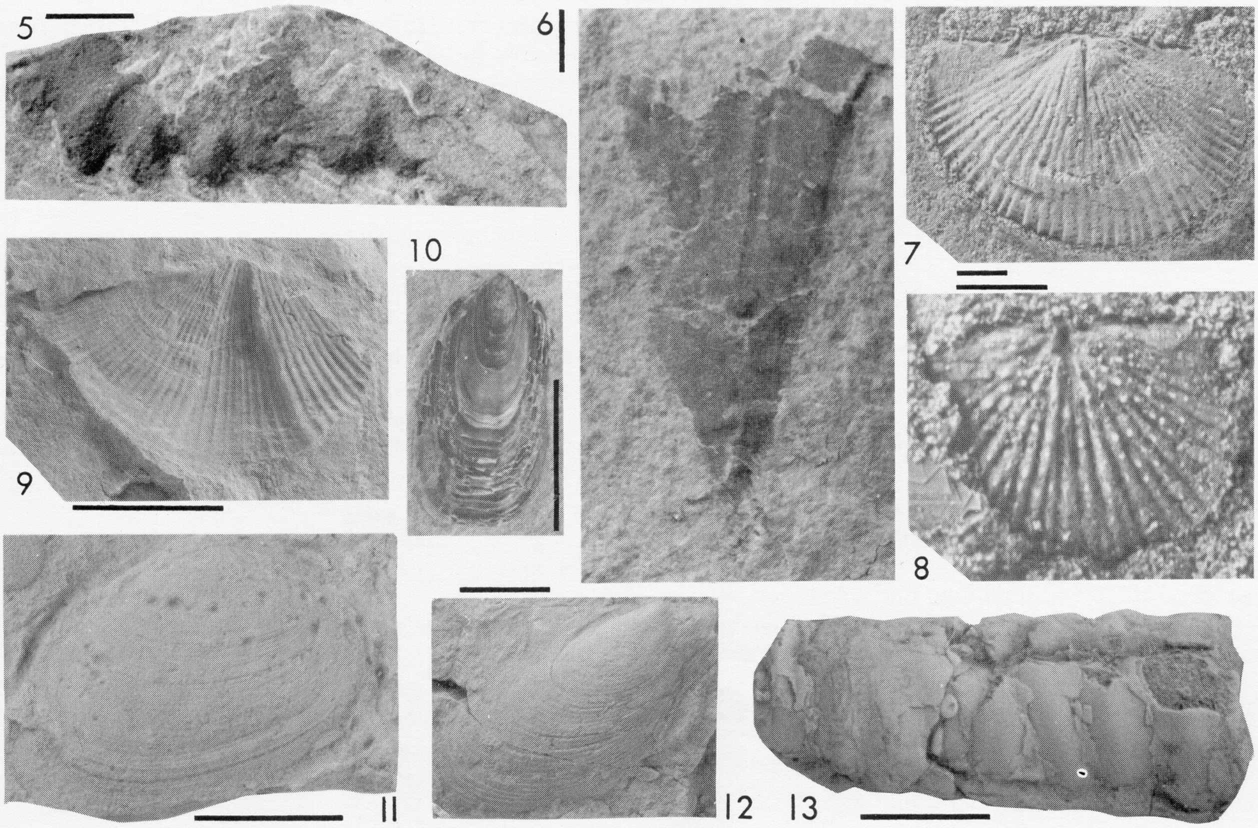
Associated Megafauna

A diverse macrofauna is found in the Drake Well exposure, particularly in siltstone beds between 1 and 3 m from the base. The interbedded shales of the outcrop are essentially devoid of body fossils. Examination of samples for microfossils, including conodonts, was unproductive. Articulate brachiopods dominate the section in both diversity and numerical abundance, with inarticulate brachiopods, pelmatozoan columnals, pelecypods, bryozoans, fish fragments, sponges, cephalopods and *Echinocaris* present approximately in order of decreasing abundance. In some beds, preservational quality varies markedly between groups, suggesting mixing. In the same bed, for example, complete sponges are preserved with bryozoans which are reduced to abraded fragments. Calcareous skeletal elements have been chemically altered or dissolved and in some siltstone units an iron oxide, probably limonite, is found lining the resulting molds.

The sponges *Titusvillia drakei* Caster, 1939, (Fig. 5) and a dictyospongiid (Fig. 6) are preserved in a siltstone 2 m from the base of the section. Although compressed, both genera may be found intact, indicating rapid burial. *Titusvillia drakei* is found as a natural mold and as a natural cast.

The Bryozoa, represented by delicate-branch and lacy-frond forms, are found as rare, abraded fragments in the same siltstone as the sponges. The colonial skeletons are no longer calcareous but are preserved as molds.

With the exception of the chonetid brachiopods



Figures 5 through 13- 5) *Titusvillia drakei* Caster. Bar scale equals 1 cm. 6) Dictyospongiid. Bar scale equals 1 cm. 7) Mold of the interior of the brachial valve of *Subglobosochonetes*? sp. Bar scale equals 1 mm. 8) Mold of the interior of a valve of *Subglobosochonetes*? sp. Bar scale equals 1 mm. 9) Mold of the interior of the brachial valve of *Cyrtospirifer* sp. Bar scale equals 1 cm. 10) *Lingula* sp. with well-preserved shell material. Bar scale equals 1 cm. 11) *Palaeoneilo* sp. Bar scale equals 1 cm. 12) *Leptodesma* sp. Bar scale equals 1 cm. 13) *Spyroceras*? sp. Bar scale equals 1 cm.

(Figs. 7 & 8), which are found throughout the lower and middle Corry members, brachiopods tend to be most common in the lower Corry at this locality. Whereas articulate brachiopods are preserved exclusively as molds of isolated valves (Fig. 9), the chitinophosphatic valves of inarticulate brachiopods, preserved in the same sediments, show no signs of dissolution. Valves of most articulates and inarticulates were not only disarticulated, but scattered as well. The abundant and relatively small valves of *Lingula* sp. (Fig. 10) are typically broken, whereas the articulates may be abraded, but tend to be unbroken. For example, chonetid spines are still occasionally preserved (Fig. 7).

Pelecypods (Figs. 11 & 12) tend to be found only in the horizons of maximum diversity of the fauna, at about 2 m above the base of the section. Like the brachiopods, they are almost invariably represented by molds of isolated valves in siltstone. Growth lines and ornamentation exhibited on the surfaces of molds tend to be indistinct, suggesting abrasion prior to burial.

The sole orthocerid cephalopod, *Spyroceras*? sp., (Fig. 13) found in place is preserved in a siltstone approximately 2.3 m from the base of the section. Pyritization of this nautiloid is nearly complete.

Pelmatozoans occur in siltstone units between 1 and 3 m from the base of the section, but only as scattered columnals and occasional stem sections. Lumina were filled with sediment following decomposition of the soft tissue within the stem, and the original calcite elements have been replaced, probably by a clay mineral or silica. As with the brachiopods and pelecypods, scattering shows that disarticulation was not caused by compaction.

Fish remains, consisting of bone and/or cartilage and isolated scales, are sparsely scattered throughout siltstone beds between 2 and 3 m from the base of the section. Judging by the bluish-white color of this material, it is still phosphatic.

Trace Fossils

Three ichnotaxa were identified at the Drake Well exposure; *Palaeophycus* (Fig. 14), *Cruziana* (Fig. 14), and *Teichichnus* (Fig. 14). The latter two traces are associated with the *Cruziana* ichnofacies (Rhoads, 1975), which is characteristic of shallow shelf and marginal marine environments (Ekdale et al., 1984, p. 194). The *Cruziana* ichnofacies is located below fair weather wave base, but above storm wave base, and is most often associated with environments of normal salinity and oxygenation, seasonal temperature variations, and medium to low energy levels (Rhoads, 1975). The substratum is generally stable, except during storms. Oscillation ripples can be found, and horizontal grazing

Figure 14-Trace fossils collected from the Corry Sandstone. *Palaeophycus* is exposed along the lower portion of the photo; *Cruziana* is present in the left central portion of the photo; and *Teichichnus* occupies the upper right hand corner. Scale, in lower left, is in millimeters.

traces are dominant, instead of vertical burrows which predominate in higher energy environments or those with fluctuating salinity conditions (Frey and Pemberton, 1984).

Ekdale et al. (1984, p. 194) reported that the *Cruziana* ichnofacies contains sediments ranging from well-sorted silts and sands, with possible discrete mud and shell layers, to poorly sorted, highly bioturbated sediments. Physical sedimentary structures include parallel-laminated to rippled and trough-crossbedded sands, and hummocky cross-stratification resulting from major storm activity. Food supply tends to be abundant within the *Cruziana* ichnofacies, supplying suspension and deposit feeders, mobile carnivores, and scavengers. Intense feeding activity may at times obscure bedding and other sedimentary features.

At the Drake Well outcrop, abundant trace fossils are restricted to the middle Corry unit (Fig. 3). Most of the *Palaeophycus*, *Teichichnus*, and *Cruziana* traces are found in silt or sandstone layers, with only a few recovered from the shales. Further, traces in the lower and middle parts of the unit are associated with numerous body fossils. The occurrences of some traces in succeeding layers either represent escape behavior during a storm interval, or successful recolonization by the organism after a storm event.

When developed in siltstones, primary sedimentary structures such as ripples and hummocky crossbeds indicate rapid deposition and, in turn turbidity, which is deleterious to suspension and deposit feeders. Horizons characterized by numerous trace fossils, on the other hand, signal a decrease in the depositional rate, or other improvements in environmental conditions which would permit an increase in the activities of burrowers (Ekdale et al., 1984, p. 91).

PALEOECOLOGY

Paleogeographic reconstruction of North America during the Devonian suggests a warm water, subtropical, shallow shelf environment at this locality (Miller and Kent, 1987). Brachiopods and other faunal elements indicate normal marine salinity. Sedimentary evidence supports a soft bottomed, sometimes turbid, environment. Brachiopod morphology also suggests quiet water, low energy conditions.

The most abundant taxa are the brachiopods. Several genera are present, exhibiting a variety of adaptations and survival strategies. The diverse spiriferid brachiopods possessed spirolophous lophophores, indicating adaptation to quiet water, low energy environments, where an increase in lophophore surface area assists respiration and food gathering (Fursich and Hurst, 1974). The spiriferid brachiopods also developed a large fold and sulcus structure to further maximize feeding in low energy environments (Fursich and Hurst, 1974).

Most of the brachiopods were adapted for life on a soft substrate. *Syringothyris* developed a large triangular interarea to distribute its weight over a greater surface area. The chonetids possessed small convex valves and minimal body mass, and were able to float upon the substrate, using hinge spines as stabilizers.

As the sediments fined upward, sponges seem to have been eliminated from the community, probably because of their intolerance for silty sediments (Sass, 1960). Limited stratigraphic distribution of the sponges may reflect patchy original colonization limited by firmness of the substrata and by turbidity. Caster (1941, p. 37-38), based on his examination of titusvilliid sponges and the rocks in sequences containing these sponges, concluded that a complex sedimentary cycle was responsible for their preservation. This cycle included sudden regional sinking of the sea bottom, followed by shallowing of the sea, and then submergence. However, there is little evidence for such a complex scenario.

Some of the taxa found at Drake Well may have been allochthonous. Pelmatozoans may or may not have been part of the community. The environment indicated by the faunal associations is within the limits of stemmed echinoderms; however, only scattered columnals and stem pieces were encountered in the section. Cephalopods and fish, represented by scales and bone and/or cartilage, represent nektonic organisms. Similarly, orbiculoid brachiopods may have been epiplanktonic. Recovery of these taxa do not provide details of the paleocommunity environment.

The Corry fauna is concentrated in the lower unit. This suggests that optimum conditions prevailed during deposition of this part of the formation. As the sediments of the Corry became progressively finer, certain taxa were selectively excluded. The dominant brachiopods in the section are the chonetids. Perhaps, due to their small mass and their spines, they were able to attach to floating algae and therefore were not choked by the very fine sediment. Alternatively, the flat aspect and small size of the chonetids may have made it possible for them to float on a soft substratum. The chonetids may have been pioneers. Thus, each time the community was destroyed, they became original settlers of the next community.

Corals are absent from this outcrop of the Corry, although the temperature and water depth may have been favorable for their growth. All but rugose corals were intolerant of suspended sediment, which may have limited their colonization. Alternatively, their absence may reflect lethal changes in salinity as the result of periodic influx of fresh water during storms.

An offshore environment of deposition is compatible with the degree of energy and turbulence suggested by the faunal analysis; however, the interbedding of siltstones with shales suggests relatively rapid shifts in sediment type and the rate of deposition. The Corry could represent a somewhat protected embayment with access to a full marine environment, perhaps between two deltas as Sass (1960) has suggested. Periodic storms probably brought in loads of silt, which rapidly buried members of the community and forced repopulation.

Laminated shales and mudstones represent relatively slow deposition in a low energy environment. Siltstone lenses commonly scattered throughout the shales and mudstones are up to several meters in length. These siltstone lenses indicate that there may have been intermittent episodes of increased energy conditions which would have deposited coarser particles from "clouds" of sediments which may have been stirred up from storm or nearshore flood events. The silty accumulations are preferentially preserved in small localized "lows". This suggests deposition below, but near, normal wavebase and close to shoreline, possibly near a delta channel.

Rippled and cross-laminated siltstones and shales suggest some water movement, possibly storm-generated waves that produce deeper water oscillations. An even higher energy environment is indicated by thick, hummocky cross-stratified, siltstone beds. Scour and sole marks are current-related features which indicate shelf-floor disturbances possibly created by storm-triggered density currents.

Blocky to slabby siltstones probably represent a steady, rapid deposition of sediments from suspension or from highly concentrated sediment dispersions (Reineck and Singh, 1980, p. 395). Blocky strata may also reflect later destruction of layering, perhaps by bioturbation or dewatering.

In general, the sedimentary structures indicate that the substratum was a place of constant deposition or reworking of sediments. The finely laminated units represent times of slowest deposition. Siltstone concentrations due to winnowing or tempestite floods reflect storm events. The Corry Sandstone here is interpreted to represent deposition close to wavebase and near the shoreline. Changes in bedding would result from fluctuations in density currents or an increase in wave energy due to flood or storm events. Caster (1934), Pepper et al. (1954), and Sass (1960) indicated that the Corry Formation was deposited in an embayment of the Devono-Mississippian epicontinental sea, with deltas on the north, west and southwest. Based upon the structures present in the outcrop, there is no reason to reject this interpretation.

Problems exist in the use of these analyses to evaluate macrofaunal community structure in the Devonian Corry Sandstone. Since the study focuses on one exposure, assessing geographic distributions and differences within the community is limited. In addition, the thickness of rock considered may represent a span of time too abbreviated and physical conditions too transitional to allow the establishment of more stable communities. However, other evidence suggests that the Corry paleoenvironment was dominated by chonetids and other brachiopods living on a soft substrate in a generally low energy, sometimes turbulent, shallow sea situated in an embayment between two deltas. As the deltas shifted position, or as new distributary channels developed, finer sediments which were beyond the tolerance of the community were deposited and the community died out. Periodically storms reworked the sediment, transporting and burying allochthonous elements along with the established community.

ACKNOWLEDGMENTS

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PETROLEUM SOURCE ROCKS AND STRATIGRAPHY OF THE BAKKEN FORMATION IN NORTH DAKOTA

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ABSTRACT

The Bakken Formation (Devonian and Mississippian) of North Dakota consists of upper and lower black, organic-rich shales separated by a calcareous siltstone middle member. The formation is a relatively thin unit [maximum thickness of 145 ft (44.2 m)] with the lower shale attaining a maximum thickness of 50 ft (15.2 m) and the upper shale a thickness of 23 ft (7 m). The shales are hard, siliceous, pyritic, fissile, and noncalcareous. They contain abundant conodonts and tasmanites-type spores and have planar laminations accented by pyrite. The upper and lower shales were apparently deposited in an offshore, marine, anoxic environment where anoxic conditions may have been caused by a stratified water column resulting from restricted circulation. Organic matter deposited in the black shales was derived mostly from planktonic algae.

Organic geochemical analyses used to evaluate the Bakken shales as petroleum source rocks include organic carbon measurements, chromatographic analysis of organic extracts, pyrolysis, vitrinite reflectance, and visual kerogen typing. The Bakken shales are very organic-rich (average of 11.33 wt% organic carbon) and contain predominantly amorphous kerogen which is inferred to be sapropelic. The onset of hydrocarbon generation occurred at an average depth of 9,000 ft (2,740 m) based on interpreting plots of geochemical parameters with depth (e.g., ratios of hydrocarbon to nonhydrocarbon, saturated hydrocarbon to organic carbon, pyrolytic hydrocarbon to organic carbon, and the pyrolysis production index). Hydrocarbon content and thermal kerogen breakdown increase greatly in the shales where they are buried more than 9,000 ft (2,740 m). The effective source area of the Bakken, as determined by maps of the above chemical parameters, lies mostly in McKenzie, Williams, Dunn, and Billings counties. Oil generation in the shales probably began about 75 million years ago (Late Cretaceous time) at a temperature of about 100° C, and initial expulsion of oil from the Bakken probably occurred 70 million years ago (Late Cretaceous time).

Vertical fracture systems, located primarily along the Nesson Anticline, Antelope oil field, and the Billings Anticline seem to be the most reasonable pathways for migration of oil to occur from the Bakken. The amount of oil generated by the Bakken in North Dakota, as calculated from pyrolysis data, is 92.3 billion barrels of oil. If only 10% of this oil was actually expelled from the shales it could easily account for the 3 billion barrels of known type two oil reserves in the Williston Basin.

INTRODUCTION

This study is a stratigraphic and geochemical investigation of the black shales of the Bakken Formation in the North Dakota portion of the Williston Basin, where it is known only from the subsurface (Figure 1). The Bakken shales, which have been cited as possible hydrocarbon source rocks (Murray, 1968; Dow, 1974), provide a good opportunity to study geochemical changes in source-rock maturation with depth in a single stratigraphic unit, as numerous samples of the formation in North Dakota are available from the North Dakota Geological Survey.

The Williston Basin is an intracratonic basin with the deepest basement located near Williston, North

Proceedings of the F.D. Holland, Jr., geological symposium, 1992, J.M. Erickson and J.W. Hoganson, eds., North Dakota Geological Survey Miscellaneous Series No. 76.

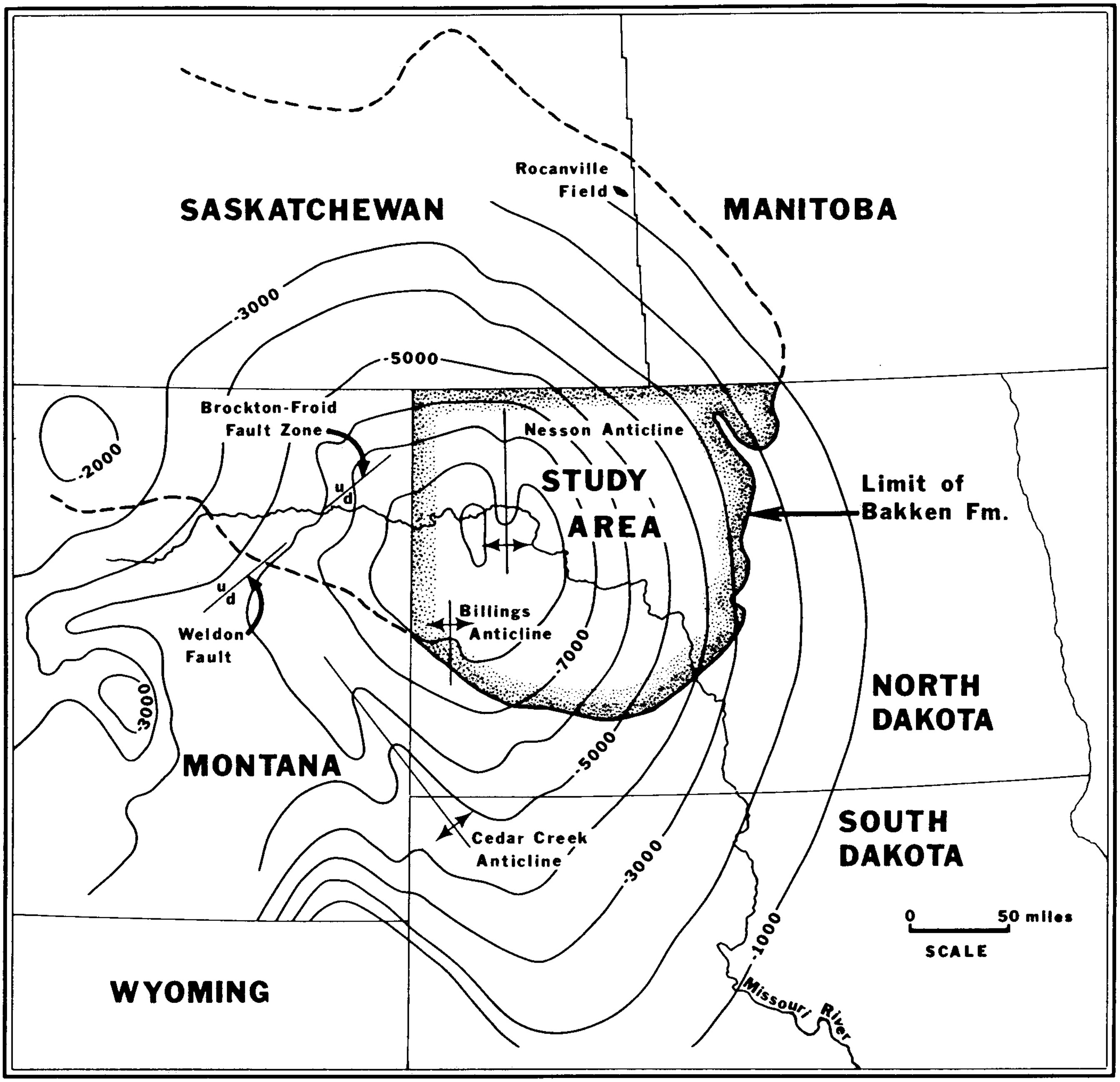

Figure 1-Location of study area and major structural features of the Williston Basin. The heavy line represents the approximate limit of the Bakken Formation. Structural contours are drawn on the base of the Mississippian strata.

Dakota (Carlson and Anderson, 1965). Nearly all systems are represented in the rock record, with a sedimentary column more than 15,000 ft (4,570 m) thick. Major structural features within the basin include the Nesson, Billings, and Cedar Creek Anticlines (Figure 1).

Figure 2 shows the position of the Bakken Formation in the North Dakota stratigraphic column and the relation of this formation to underlying and overlying units. The Bakken is easily divided into three members and these are used informally here: the upper shale member, the middle (siltstone) member, and the lower shale member. Conodonts have been used to date the lower Bakken shale as Famennian (Upper *Polygnathus styriacus* Zone) and the upper Bakken shale as Kinderhookian (Lower *Siphonodella crenulata* Zone) by

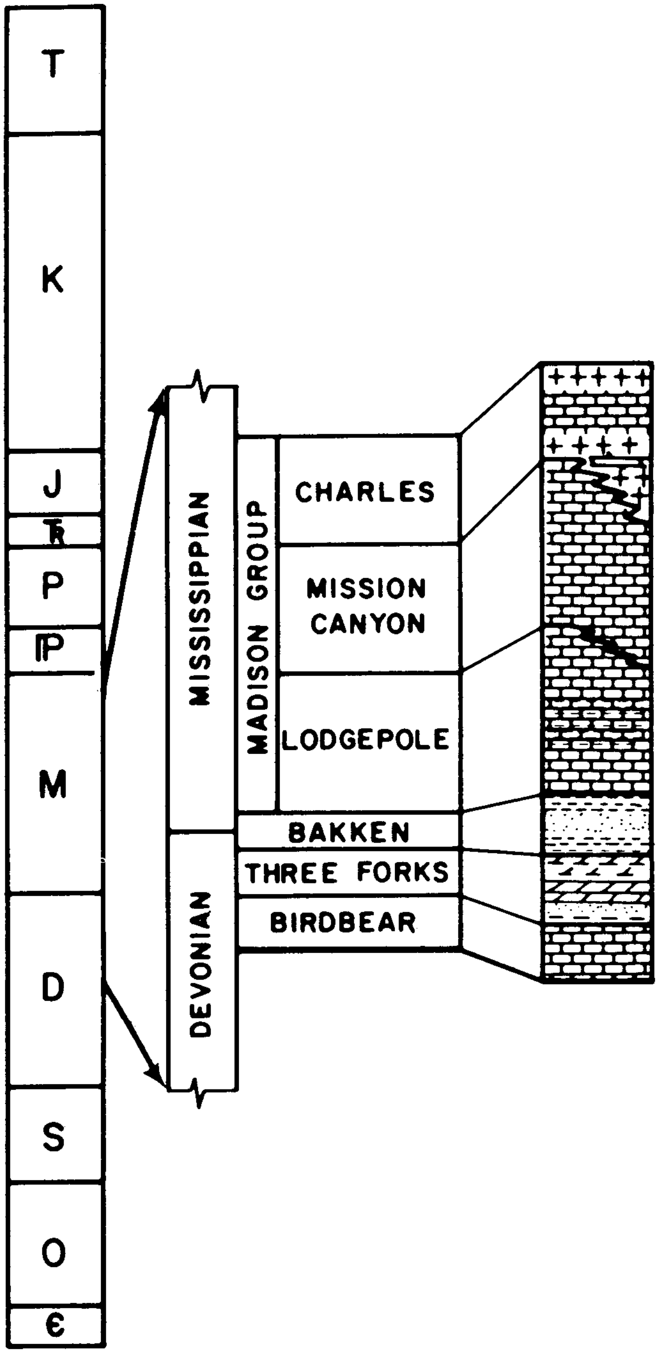

Figure 2-A portion of the North Dakota stratigraphic column, showing the Bakken Formation and its relation to adjacent units.

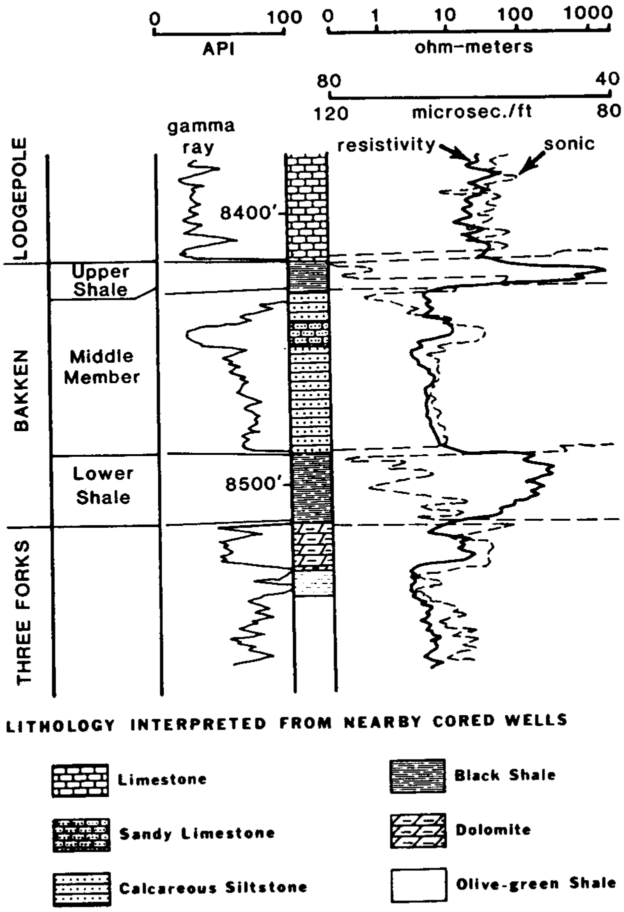

Figure 3-Well logs and interpreted lithology of the Tipperary Oil and Gas Corporation Olsen No. 1 well, SE SW sec 26, T160 N, R97 W, Divide County.

Hayes and Holland (1983).

STRATIGRAPHY

Well Log Characteristics

The Bakken displays characteristic log responses that are unique in the Paleozoic rock section of the Williston Basin (Figure 3) and it is widely used as a "marker" unit in the basin. The shales of the formation always display very high gamma ray readings (greater than 200 API units) which are almost always off the logscale and not quantifiable. They also display high interval transit times (80-120 microsec/ft) on the sonic log. High resistivity readings (greater than 100 ohm-meters) are seen from the shales in the deep portions of the basin greater than 7,000-8,000 ft [(2,130-2,440)] and low resistivity (less than 10 ohm-meters) is observed from the shales in the shallower portion of the basin less than [7,000 ft (2,130 m) deep]. The middle member displays more "normal" readings on the above mentioned logs; these readings are those characteristic of well cemented carbonates and fine-grained clastics.

Areal Extent

In North Dakota the limits of the three members of the Bakken Formation display an onlapping relationship with each successively younger member being more extensive than the previous one (Figure 4). The limit of the upper shale is believed to be a depositional limit, as the contact of this shale with the overlying Lodgepole Formation has been said to be conformable (Heck, 1979). The limit of the middle member is also thought to be a depositional one, as the upper shale appears to lie conformably on the middle member. It is uncertain whether the limit of the lower shale was modifed by erosion prior to or during deposition of the middle member. The middle member displays evidence of high energy and shallow water depositional conditions in some parts (e.g., cross bedding and oolites) and thus it is possible that erosional modification of the lower shale depositional limit occurred. The onlapping relationship of the three members is most likely the result of an overall transgression of the Late Devonian to Early Mississippian sea.

Overlying Units

In North Dakota, the Bakken is everywhere overlain by the Lodgepole Formation which consists, in the section immediately above the Bakken, of dense, dark gray to brownish-gray limestone and dark gray calcareous shale. Minor amounts of chert and anhydrite are also present in the limestone of the Lodgepole, which has a maximum thickness of 900 ft (274 m) in eastern McKenzie County (Heck, 1979).

A thin black shale and black, organic-rich, limestone occur above the Bakken in some parts of McKenzie, Billings, Dunn, and Mountrail counties (Kume, 1963). Fuller (1956) reported a similar black shale bed in Saskatchewan. This dark shaly unit is usually separated from the upper Bakken shale by a

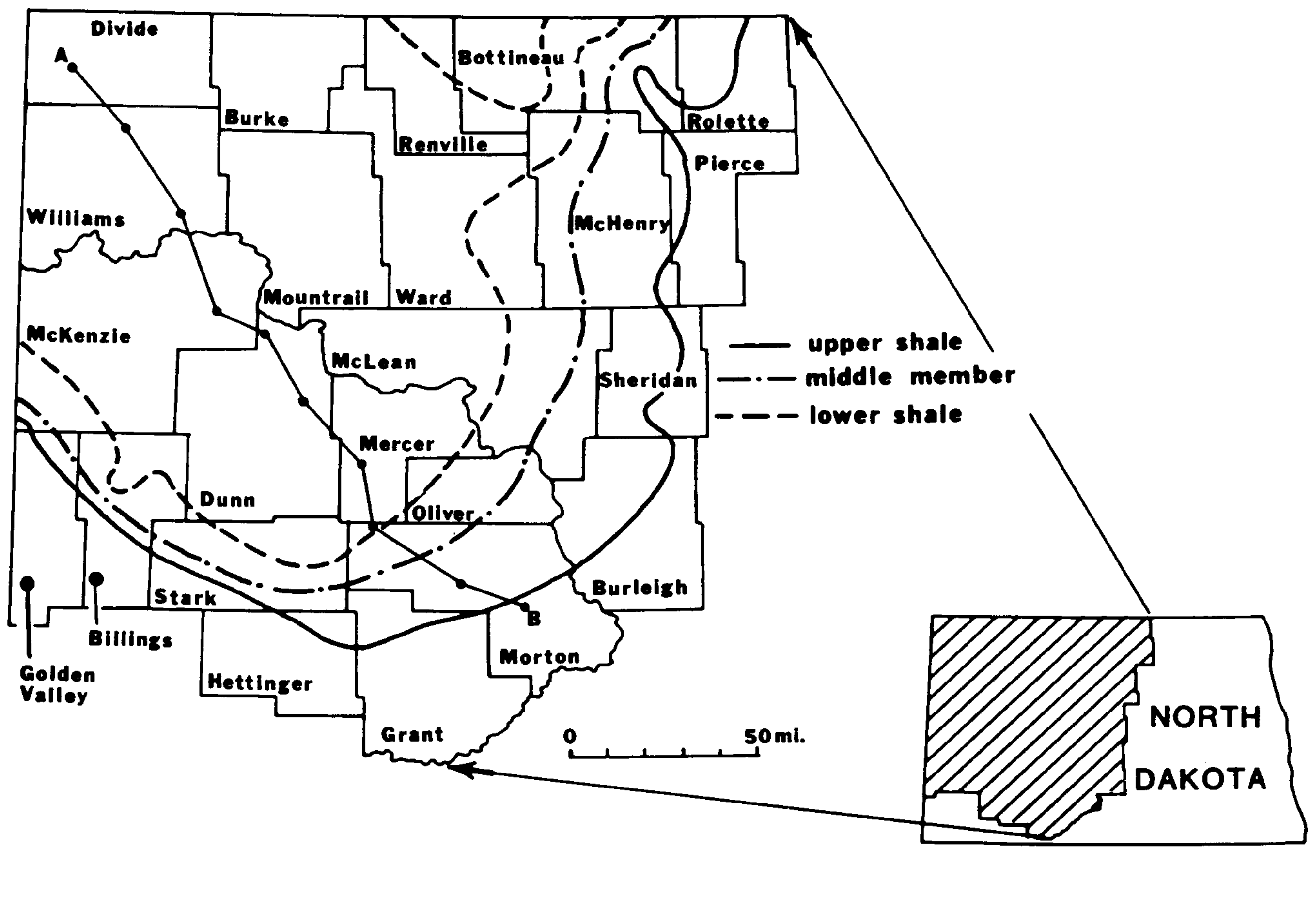

Figure 4-Approximate subsurface limits of the three members of the Bakken Formation, location of cross section A-B, and county designations of the study area.

medium gray to brownish-gray, dense limestone that is commonly fragmental and contains abundant pelmatozoan material. The Routledge shale occurs locally above the Bakken in Rolette County and is similar in lithology to the Bakken shale (Stanton, 1956), but the Routledge has a slightly lower reading on the gamma ray log. Stanton (1956) believed the Routledge to be the result of continuation of Bakken-type shale sedimentation in areas of significant salt solution collapse of the Devonian Prairie Formation.

Underlying Units

In the area of study, the Bakken is everywhere underlain by the Three Forks Formation of Late Devonian age, which has a maximum thickness of approximately 250 ft (76 m) in eastern McKenzie County. The Three Forks is composed of thinly interbedded greenish-gray and reddish-brown shales, light brown to yellow-gray dolostone, gray to brown siltstone, quartzose sandstone, and minor occurrences of anhydrite (Kume, 1963). The contact between the Bakken and Three Forks appears conformable in the deeper portions of the basin and unconformable on the basin flanks. A well log cross section of the Bakken-Three Forks interval (Figure 5) displays the relationships between the Bakken members and four informal members (A, B, C, and D) of the Three Forks. The four informal members of the Three Forks used in this study are similar to the subdivisions made by Fuller (1956) in Saskatchewan. Throughout most of the area studied the Bakken appears to rest conformably upon the Three Forks, as seen in well log cross sections. Near the limit of the lower Bakken shale, truncation of upper members of the Three Forks occurs beneath the Bakken and an angular uncomformity is inferred for this area. The Bakken-Three Forks contact, as observed by the author in cores of the deep basin area, displays an abrupt lithologic change, but no features of erosion were observed except in NDGS (North Dakota Geological Survey) well no. 7579 (Shell Oil 42-24A USA) in southwestern McKenzie County where a slight undulatory contact between the Three Forks and the Bakken (middle member) can be seen. In Saskatchewan an unconformity between these two formations was suggested by Fuller (1956) where a pebble bed occurs at the base of the Bakken in several wells. Observing the thinning of the A member of the Three Forks to the northwest in Figure 5, leads one to believe that the Bakken-Three Forks contact may also be unconformable in this area (Williams and Divide counties).

A quartz sandstone in the upper Three Forks, informally referred to by workers in the Williston Basin as the "Sanish Sand", locally underlies the Bakken. Kume (1963) described the sandstone as a well-cemented, well-sorted, very fine-grained quartz arenite. Kume stated that the sandstone has features indicative of beach or nearshore marine depositional environments, and claimed that the sandstone has an erratic occurrence over the area of McKenzie, Williams, Mountrail, and Bottineau counties.

Thickness

The Bakken Formation ranges in thickness from a maximum of 145 ft (44 m) in western Mountrail County to a feather edge along its depositional limit (Figure 6). The depocenter for the formation is located immediately east of the Nesson Anticline and is elongated in a nearly north-south direction (Figure 6). In the eastern portion of the study area, the formation thickness is highly variable. Large increases in thickness are probably the result of solution and subsequent collapse of extensive salts in the Middle Devonian Prairie Formation. Erosion on the surface of the Three Forks prior to Bakken deposition may also have contributed to thickness changes of the Bakken in this area, as the Bakken would be thicker in low areas of this erosional surface and thinner over high areas.

Thinning of the Bakken in certain areas can be interpreted to represent structural highs active at the time of Bakken deposition. Three prominent areas that are interpreted as positive can be seen in the eastern portion of the study area (Figure 6): one in extreme northeastern Renville County, one in southeastern Ward and southwestern McHenry counties, and one in southeastern Bottineau County where the Bakken is absent in a narrow area trending northwest-southeast. The Nesson Anticline does not appear to have been active during this time, as no significant thinning of the Bakken is observed in that area.

The isopach map of the lower Bakken shale (Figure 7) shows the Bakken depocenter to be well developed during the time of deposition of the lower shale where a maximum thickness of 50 ft (15 m) occurs. A peculiar curved extension with abrupt thickening of the lower shale occurs in the northeastern portion of the study area and surrounds a large positive area in Renville and Bottineau counties. This thickening is probably the result of salt collapse in the Devonian Prairie Formation prior to, or during, Bakken deposition.

The middle member isopach map (Figure 8) also displays a well-defined depocenter in western Mountrail County where the middle member reaches a maximum thickness of 85 ft (26 m). Salt solution in the Prairie Formation and erosion on the Three Forks surface probably contributed to the abrupt thickness increases in Bottineau and northwestern McHenry counties. The high in western Bottineau County was still active in middle Bakken time and a high in central McHenry County became evident at this time. A small area of thin middle member in eastern McKenzie County may

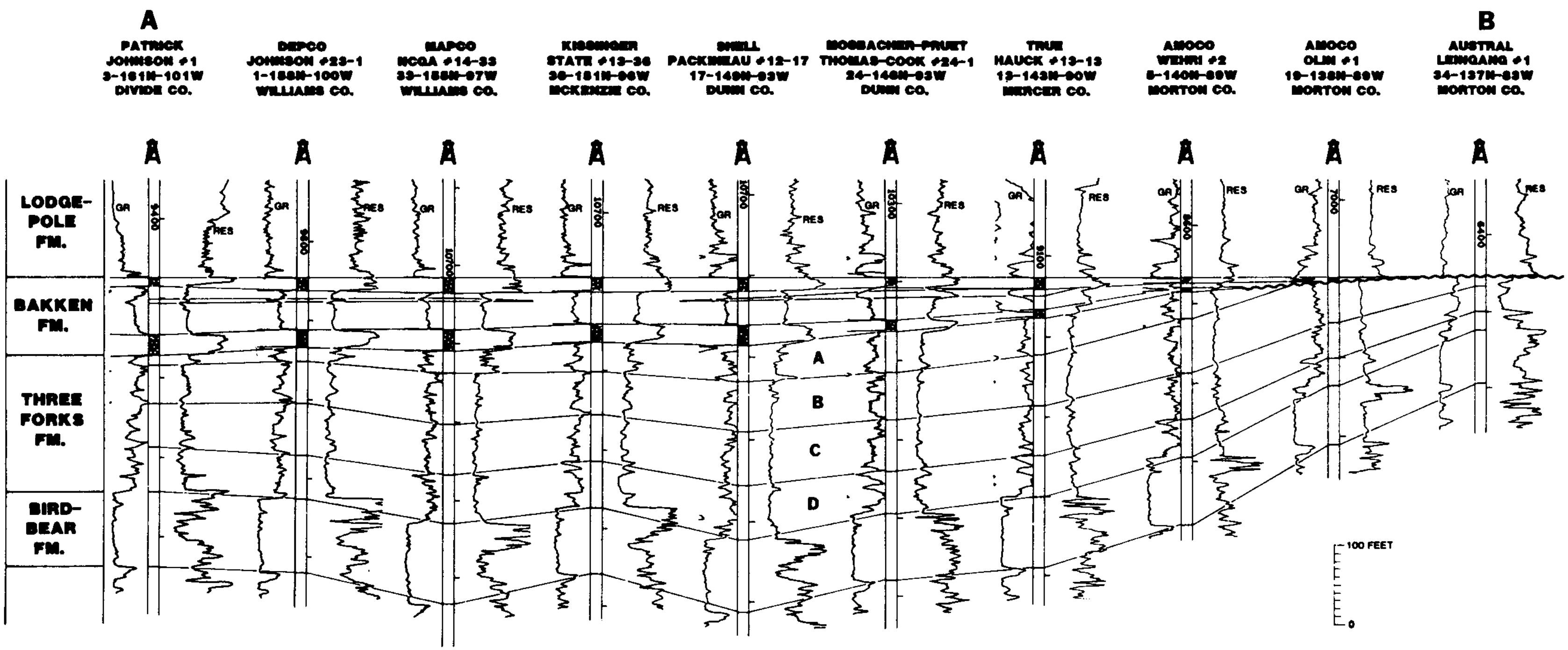

Figure 5-Stratigraphic cross section of the Bakken Formation and adjacent units. The top of the Bakken Formation is used as a datum. Location of the section is shown in Figure 4.

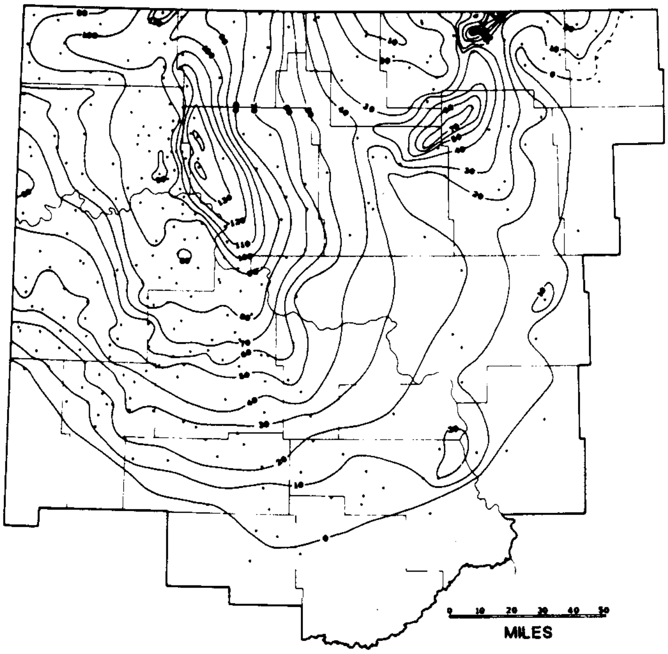

Figure 6-Isopach map of the Bakken Formation.

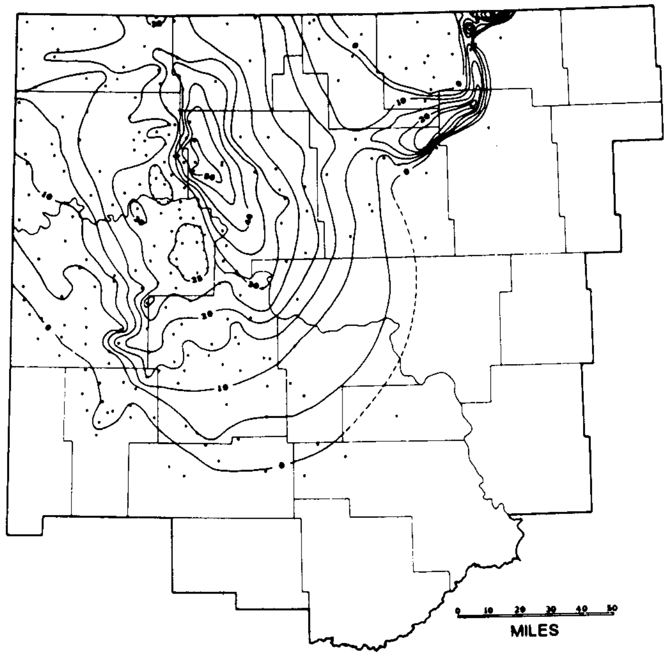

Figure 7-Isopach map of the lower Bakken shale.

be the result of some uplift on the southern end of the Nesson Anticline.

The upper shale isopach map (Figure 9) shows the thickness distribution of the upper shale to be much more even than that of the two previous members. The apparent depocenter in eastern McKenzie County and southwestern Mountrail County is very broad and not well defined. The surface upon which the upper shale was deposited appears to have been very flat over a large area and subsidence in the area of the formation depocenter was reduced during this time. Areas of abrupt thickness increases in the eastern portion of the study area are probably the result of salt collapse in the Prairie Formation and erosion on the Three Forks.

Lithology

The upper and lower Bakken shales are hard, siliceous, pyritic, fissile, generally noncalcareous, organic-rich (average of 11.33 wt% organic carbon) and dark black when wet. The shales tend to break with a smooth, conchoidal to flat horizontal fracture. The conchoidal fracture is probably due to a high quartz content (detrital grains and secondary cement) in the shales. Pyrite is commonly concentrated in lenses and laminations, or is finely disseminated throughout the shales. The pyrite-accented laminae are very even and planar, displaying only occasional disruptions. The upper and lower shales are identical in lithology and show remarkable lithologic uniformity throughout their extent. Two thin [3 ft (.9 m) thick], black limestones occur within the lower shale in cores from NDGS well nos. 1748 (Amerada Petroleum 1 Reed-Norby Unit) and 1405 (Gofor Oil 2 C.E. Peck) in McKenzie County. These limestones are generally coarsely crystalline and much less rich in organic material (0.87 wt% organic carbon) than the shales.

In thin section the shales are seen to be composed mostly of dark indeterminate material of which a large percentage is probably organic material. This organic material is distributed rather uniformly in the shales and not concentrated in lenses or laminations. Quartz appears to be the dominant mineral present as seen in thin section and on X-ray diffraction charts. Detrital grains are scattered throughout and some silica-filled fractures occur. Some calcite and dolomite can be seen in thin section, with dolomite often observed as euhedral rhombs. It is uncertain how much of the Bakken shale is composed of muscovite, illite, or other clay minerals, but this amount seems to be less than would be expected in a "normal" shale, as the muscovite/illite peak on X-ray diffraction charts made for this study, is small.

The middle member of the Bakken varies in lithology and includes calcareous siltstone, sandstone, dolostone, silty limestone, and oolitic limestone. The sandstone is usually brownish-gray, fine to medium-grained, subrounded to subangular, and calcareous. The limestones are brownish-gray to medium-gray, silty, argillaceous, and in one unit near the top of the middle member (Figure 3) are oolitic and contain quartz sand. Siltstone is the predominant lithology of the middle

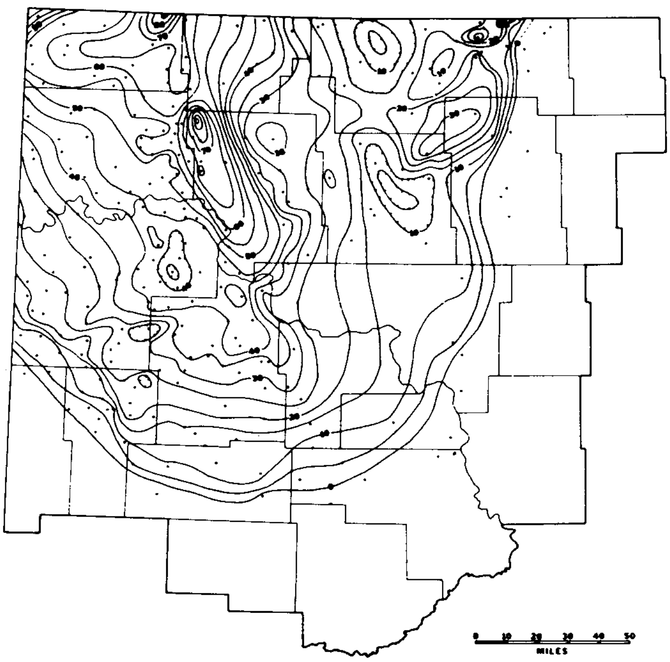

Figure 8-Isopach map of the Bakken middle member.

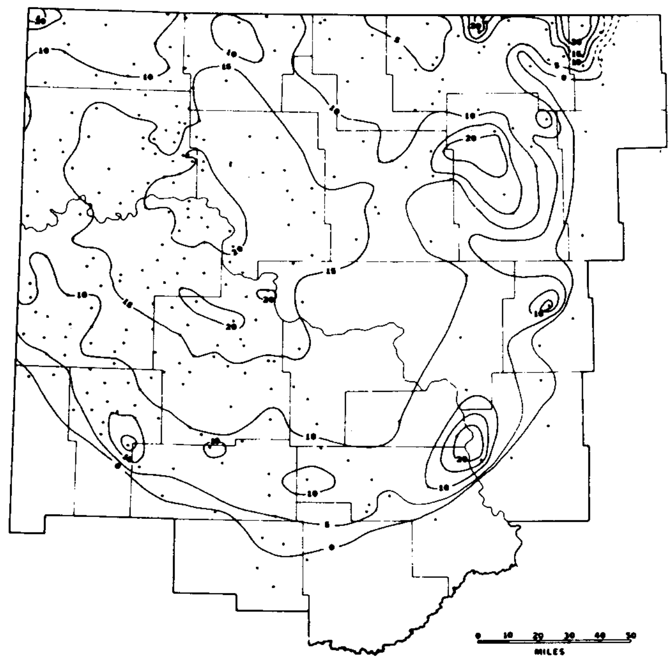

Figure 9-Isopach map of the upper Bakken shale.

member. The siltstones are very calcareous to noncalcareous, commonly dolomitic, argillaceous, olive-gray to medium-gray, and their grain size commonly approaches very fine sand. All lithologies within the middle member are very well cemented with calcite and silica, and have low permeability and porosity. The middle Bakken displays many different types of bedding including small scale trough cross bedding, planar cross bedding, wave ripple cross lamination, irregular laminations and planar laminations. Bidirectional (herringbone) cross bedding is present in several cores of the middle member. Soft-sediment deformation in the form of small folds and faults is also apparent.

Paleontology

Conodonts are the most common macrofossil found in the black shales of the Bakken and are often concentrated in thin beds. Tasmanite (tasmanite palynomorphs), amber colored spores, are also very abundant locally. These spores are believed to be the remains of unicellular, planktonic, marine algae (Wall, 1962). Fish remains in the form of scales, teeth, and some bone material are relatively common in the Bakken shales (Hayes, 1984).

Small cephalopods, ostracodes, conchostracans (clam-like shrimp related to ostracodes), small brachiopods (*Lingula sp.*), and *Foerstia* (small algal mats or mounds) are additional macrofossils of the Bakken shales (Thrasher, 1985). A large piece of terrestrial (woody) plant material is present in the upper shale in NDGS well no. 8177 (Marathon Oil 18-44 Dobrinski) in southwestern Ward County. This type of plant material is extremely rare in the black shales.

Brachiopods are the most abundant fossils found in the middle member, along with moderately abundant pelmatozoan fragments. A few tabulate corals (*Syringopora*) and abundant trace fossils (*Chondrites sp.* and *Scalarituba*) have also been observed in cores of the middle member (Thrasher, 1985).

Depositional History

Devonian Three Forks sedimentation ended in the Williston Basin in Late Devonian with the deposition of shallow marine to terrestrial sediments (McCabe, 1959) during a marine regression to the northwest. During Late Devonian to Early Mississippian time, major uplift and erosion occurred along the margins of the Williston Basin (Sandberg, 1964). Transgression of the sea began again in Late Devonian time with the deposition of the lower Bakken shale.

The nature of the Bakken shales indicates a pronounced basinwide change in depositional environment from oxic conditions during Three Forks time to highly anoxic during part of Bakken time. As the sea transgressed in early Bakken time, some type of change occurred in basin geometry, climate, or water circulation, that caused anoxic, possibly stagnated conditions.

These anoxic conditions ended in middle Bakken time during an influx of coarser clastics into the basin. The source of the clastics is unknown, but a source to the north and northwest seems likely, based upon Bakken isopachs and the northward-increasing clastic ratio of the middle member (Nordquist, 1953). The middle member has a fauna and bedding features indicative of a normal shallow marine to nearshore marine depositional environment.

Transgression of the sea continued in middle and upper Bakken time as evidenced by the onlapping relationship of the Bakken members upon the Three Forks unconformity (Figure 4). This onlapping relationship also suggests that the Bakken sea may have become progressively deeper as the sea transgressed. Several minor regressions probably occurred in the study area during middle Bakken time, as Christopher (1962) suggests for the Bakken in Saskatchewan. Bedding features, oolitic carbonate grains, and trace fossils indicate very shallow water conditions during part of middle Bakken time. Anoxic conditions returned to the basin with deposition of the upper shale as transgression continued. Normal, oxygenated water conditions then prevailed in Mississippian Lodgepole time as carbonate sedimentation resumed in the basin.

Depositional Environment

The exact depositional environment for black shales such as those of the upper and lower Bakken is problematical. Such shales can form under conditions varying from deep marine waters to terrestrial swamp. The possible depositional environments proposed by previous workers include a vast marine swamp with restriction of circulation due to prolific organic development (McCabe 1959); a stagnant, marginal-marine, lagoonal environment (Raasch, 1956); and a deep-water, marine environment with deposition below wave base (MacDonald, 1956).

The planar and thin laminations observed in the Bakken shales suggest deposition in very quiet waters, probably below wave base of open water. The presence of planktonic algal spores (tasmanites), fish remains, cephalopods, ostracodes, conodonts, and inarticulate brachipods indicates marine to marginal-marine water conditions. The high amounts of organic material and pyrite indicate chemically reducing and anoxic depositional conditions. The depositional environment of the Bakken shales would also have to have been very uniform over a large area to account for the widespread lithologic similarity of the shales. The great predominance of amorphous-sapropelic organic matter (probable algal or phytoplankton origin) over terrestrial (woody or humic) material (see section on kerogen typing) suggests an offshore depositional environment.

The nektonic (fish, cephalopods, ostracodes), planktonic (algal spores), and epiplanktonic (inarticulate brachiopods) fossil fauna of the Bakken shales indicates the probable existence of a stratified water column in the "Bakken Black-Shale Sea" as Ettensohn and Barron (1981) suggest for much of the Devonian-Mississippian "Black-Shale Sea" of North America. Lineback and Davidson (1982) also suggest a stratified water column for the Williston Basin during Bakken time. The presence of a pycnocline which separates oxygenated surface waters from anaerobic bottom waters, normally results from restrictions in mixing of surficial and deeper waters. The location of the Bakken sea in a warm, temperate climate (less than 10° north of the Equator) (Ettensohn and Barron, 1981) could account for the lack of mixing between surface and bottom waters. Byers (1977) states that in a warm, temperate climate the surface waters rarely cool enough to sink to deeper levels and displace the colder bottom waters. During deposition of the Bakken shales, a heavy "rain" of organic material (predominantly marine plankton) fell to the deeper, stagnant waters and was deposited under anoxic conditions. The water depth necessary to maintain anoxic conditions in the "Bakken Black-Shale Sea" is difficult to resolve. A minimum depth of 150 ft (46.6 m) seems necessary in order to have the bottom waters below both the photic zone and wave action.

PETROLEUM GEOLOGY

A total of 4,683,566 barrels of oil have been produced from the Bakken within the study areas as of October 1981. Production has been established in at least 18 North Dakota oil fields (Figure 10) with the Antelope field in eastern McKenzie County the most prolific producer of Bakken oil. Most of the oil production from this formation is related to three anticlinal structures in North Dakota; the Antelope Anticline, the Billings Anticline, and the Nesson Anticline. The Antelope field accounts for 85% of the production from the Bakken, where 21 wells have produced oil from this formation. Elkhorn Ranch is the next largest with 12 Bakken wells and eight percent of the total production. All other fields have three or fewer Bakken wells, and rely on other prolific pay zones in the Paleozoic section for most of the field's production. Outside of the study area, Bakken production has been established in Montana and Saskatchewan. In Montana, Bakken oil is pumped from four small fields in central Richland County (North Enid, Putnam, Brorson, Spring Lake), and one field in northeastern Sheridan County (Salt Lake). In Saskatchewan, the middle Bakken member produces at the Rocanville field (Figure 1) where it is predominantly a sandstone with well developed porosity (an average of 18.8%) (Von Osinski, 1970).

At Antelope field, the Bakken has been various-

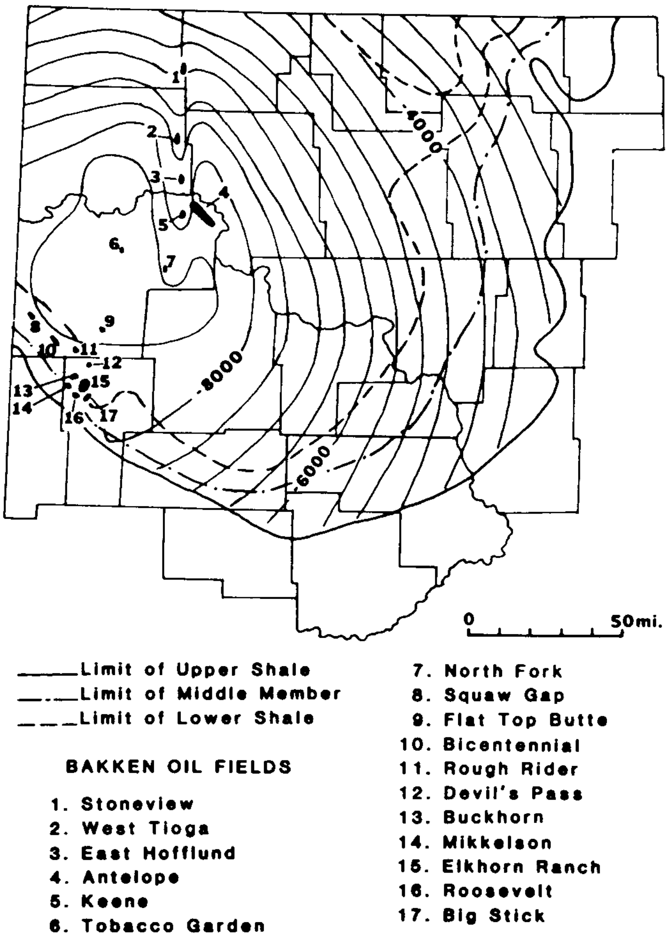

Figure 10-Location of Bakken oil fields with superimposed formation member limits and structure contours on top of the Bakken.

ly perforated in the lower, middle, and upper members. The underlying "Sanish Sand" interval is usually perforated along with the Bakken in this field. In other Bakken oil fields, the location of perforations also varies and in some wells all three members are perforated. Murray (1968) noted that production in the Antelope field does not vary with reservoir lithology, in that similar rates of production were established in wells where only the Bakken was perforated. No attempt has been made to separate the production by zones and consequently the direct contribution of the Bakken shales to oil production is unknown. Likewise, in the Antelope field it is unknown how much of the "Bakken" production actually originated from the upper Three Forks in the "Sanish Sand" interval.

The reservoir properties of the Bakken are generally very poor in the area studied. Core analyses from the NDGS well files reveal the middle member to have porosities in the range of one to six percent, and permeability less than 0.1 md. In the Dallea Petroleum Corp. No. 2 Hamlet Unit in eastern Williams County (sec. 30, T159N, R95W) a sandy limestone unit in the middle member (Figure 3) has an average porosity of eight percent and an average permeability of 0.2 md. This unit of the middle member seems to have the best porosity development in the formation. The adjacent rock units of the Three Forks and Lodgepole also display very low porosity and permeability and can be considered marginal reservoir rocks. Fracturing, which renders the rock permeable, is believed by several workers (Murray, 1968; Finch, 1969; Meissner, 1978) to be the principle factor responsible for oil production from the Bakken.

To account for the high initial rates of production from the very "tight" Bakken and Sanish lithologies in Antelope field (an average of nearly 200 BOPD), Murray (1968) concluded that fracturing was directly related to oil production in the Sanish pool of the Antelope field. He believed the type of fracturing present at Antelope is a tension-fracture system and is best developed in areas of greatest structural curvature on the Antelope anticlinal structure. The best oil wells are seen to be associated with the areas of greatest curvature (northeast flank of the Antelope Anticline) and according to Murray, the areas of better-developed fracturing. Oil production is low to nonexistent on the crest of the anticline where the best production or accumulation of oil would be expected.

Shows of oil and gas in the Bakken are very common in the deep portion of the Williston Basin, yet drill stem tests of most of the shows recover only gas- and oil-cut mud and have low, unstabilized shut-in pressures (Meissner, 1978). Little water is recovered in Bakken drill stem tests, or produced from Bakken oil fields until advanced stages of depletion. This fact led Meissner to suggest that hydrocarbons are the only movable fluid found in the Bakken in the deep portions of the basin.

The Bakken was observed by Murray (1968), Finch (1969), and Meissner (1978) to be anomalously overpressured at Antelope and throughout much of the deep basin by Meissner (1978). At Antelope, the Bakken displays a fluid pressure gradient of 0.73 psi/ft which is considerably higher than the 0.46 psi/ft displayed by overlying and underlying normally pressured formations (Meissner, 1978). Meissner attributed this overpressuring to hydrocarbon generation in the Bakken shales which would result in excess volumes of oil in the shale pore spaces. This anomalous overpressure was believed by Meissner to be maintained by the isolation of the Bakken by very impermeable rocks of the Three Forks and Lodgepole, thus hindering the expulsion of the excess fluid.

ORGANIC GEOCHEMISTRY

To evaluate the Bakken shale as a petroleum source rock, it is necessary to know how the organic geochemistry of the shale varies within the study area. Organic geochemical analyses of the Bakken shales were performed in two different geochemical laboratories: the U.S. Geological Survey Laboratory in Denver, Colorado, and the Conoco Exploration Research Laboratory in Ponca City, Oklahoma.

The following organic geochemical analyses were performed:

1. Total organic carbon measurements
2. Extraction of soluble organic material and analysis of this material by thin layer chromatography and gas chromatography.
3. Pyrolysis
4. Vitrinite reflectance
5. Visual kerogen typing

Conoco performed organic carbon measurements, extraction of soluble organics, thin layer chromatography, vitrinite reflectance, and visual kerogen typing. The U.S. Geological Survey performed pyrolysis, additional vitrinite reflectance and organic carbon measurements, and provided gas chromatograms of the saturate hydrocarbon fraction of Bakken extracts taken at the USGS laboratory.

Maps and graphs made from these data were used to interpret the stages of oil generation in the Bakken shales. Hydrocarbon data from the upper and lower shales were averaged together for map points where both of the shales were sampled separately. Curves drawn on graphs plotting geochemical parameters against depth have been fitted visually. Depths used are present-day burial depths acquired directly from well logs; no attempt was made to adjust these depths to a possible maximum burial depth of the past, as there is no evidence to suggest that previous burial depths significantly exceeded present depths.

Sampling

Samples of the Bakken shales were obtained from cores and cuttings stored in the Wilson M. Laird Core and Sample Library of the North Dakota Geological Survey in Grand Forks. Locations of samples for which geochemical analyses were made, and the type of sample used, are depicted in Figure 11.

Composites were made of core samples by taking a small chip from the center of the core at intervals of approximately six inches to one foot. These chips were combined to form a composite sample for the interval of shale cored.

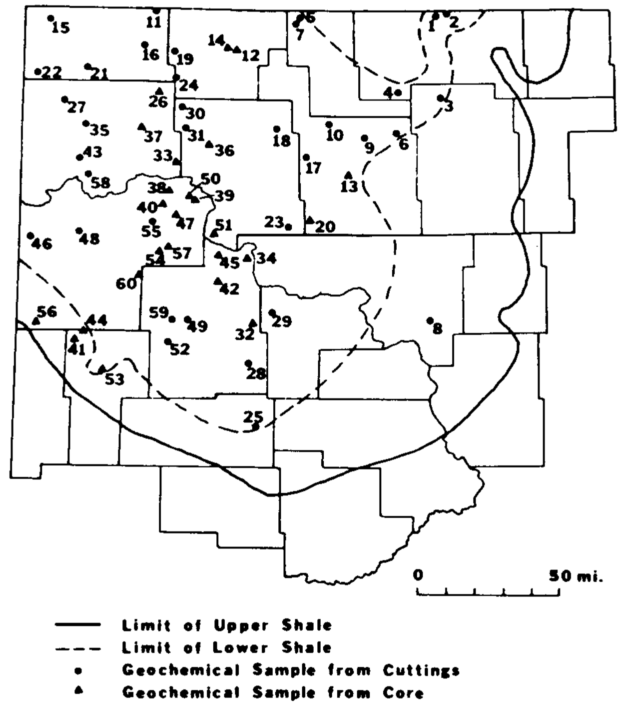

Figure 11-Map showing location and type of shale samples taken for geochemical analysis. Numbers correspond to map numbers in Tables 1 and 2.

In order to obtain an adequate geographic and depth distribution of geochemical samples, well cuttings were utilized in areas where cores were not present (Figure 11). Sampling of well cuttings was done by placing the cuttings for a five to ten foot depth interval under a binocular microscope and wetting them with water. Picking Bakken shale from the well cuttings was more easily done when they were water-wet, as the Bakken chips could be differentiated from other dark colored shales based on their dark black color and hardness. If a sufficient amount of Bakken shale was present in the cuttings samples, then geochemical samples for both the upper and lower shale were obtained. In the case of insufficient amounts, cuttings of both shales (if present) were mixed to form a composite sample for that particular well.

Explanation of Organic Geochemical Methods Used

Total Organic Carbon Measurements

Organic carbon is a measure of the total organic matter (kerogen and bitumen) preserved in the rock, expressed as a weight percent of the rock. This measurement was obtained by measuring CO_2 evolved during high-temperature combustion of a sample of rock after inorganic carbon was removed by acid (HCL) treatment.

Extraction of Soluble Organics

At the Conoco laboratory, soluble organic matter contained in the rocks was extracted in a Soxhlet apparatus using a mixture of toluene and isopropyl alcohol as an organic solvent. After a 12 hour period of extraction the solvent containing the dissolved bitumen was air dried at room temperature leaving the $C_{15}+$ organic compounds as a residue. This residue was separated by thin layer chromatography into three fractions: saturated hydrocarbons, aromatic hydrocarbons, and resins and asphaltenes (grouped together).

Pyrolysis

A commercial pyrolysis device (ROCK-EVAL 1) was used for the thermal analyses of this study. Initial temperature of the oven during analysis was 250°C (485°F) and the temperature was increased 25°C (77°F) per minute up to 550°C (1022°F). During combustion relative amounts of volatile organics (bitumen) are recorded in graphic form. Generally two peaks separated by a saddle are obtained on a pyrolysis thermogram. The area of the first peak is referred to as S_1 and it is related to the Soxhlet-extractable hydrocarbon content of the source rock. The area of the second peak is referred to as S_2 and it is related to the amount of pyrolyzable hydrocarbons attached to the kerogen or the hydrocarbon-generating potential of the kerogen (Claypool and Reed, 1976).

Visual Kerogen Typing

Kerogen concentrates were obtained by digesting the sample with HCL and HF acid for 12 hours in each acid. Acid-insoluble minerals were not separated from the residue. Microscope mounts were used to obtain a visual estimate of the relative amounts of five kerogen morphological types (algal, amorphous, herbaceous, woody, and coaly) present in each kerogen concentrate.

Vitrinite Reflectance

Heavy liquid (zinc bromide, density=2.5 g/cc) separation was used to remove the very fine-grained amorphous kerogen particles from the kerogen isolate before it was used for vitrinite reflectance. Small portions of the separated kerogen isolate were mounted in plastic plugs and polished. Reflectance measurements were made on as many vitrinite particles as possible in one sample, generally between 20 and 40.

Results of Organic Geochemistry

Organic Carbon Measurements

Organic carbon content of the Bakken shales ranges from five to 20 percent by weight, with an average of 11.33 percent. These values are very high compared to the one percent minimum organic carbon value for a possible source rock in the Rocky Mountain region (Merewether and Claypool, 1980).

Figures 12 and 13 display the map distribution of organic carbon in the upper and lower shales respectively. Both shales have high organic matter contents throughout their extent, with a slightly lower organic content occurring in some areas near the depositional limits.

Examples of vertical distribution of organic matter in the Bakken shales are illustrated in Figure 14. From the two wells that were sampled in detail, it can be seen that significant vertical variations in organic content occur. This could affect the representative values of organic carbon obtained from composite samples. Consequently the maps of organic carbon in the Bakken shales should be taken only as approximations.

Kerogen Typing

Kerogen of the Bakken shales is predominantly (70 to 95 percent) amorphous. Powell et al. (1982) demonstrated that amorphous organic matter can originate from algal, terrestrial, or microbially degraded organic material. It seems likely the amorphous Bakken kerogen has an algal origin, as the hydrocarbon-generating capacity of this material determined from pyrolysis is quite high (greater than 500 mgHC/gOC at shallow depths) and indicates a high atomic hydrogen to carbon ratio for the kerogen. Amorphous kerogen with high H/C ratios can be termed sapropelic. Sapropel refers to organic matter that originated from fatty, lipid organic materials such as spores and planktonic algae deposited in subaquatic muds (marine or lacustrine), usually under oxygen-restricted conditions (Hunt, 1979).

Minor amounts of other kerogen types are present. Herbaceous kerogen (derived mostly from terrestrial material) ranged from zero to 20 percent. Woody kerogen, which is fibril material with recognizable cellular structures and exclusively terrestrial, was almost nonexistent. It occurred in only five samples in amounts of five percent or less. Coaly kerogen (recycled opaque material) occurred in amounts of 30 percent or less.

Tasmanite spores were identified in many of the kerogen samples examined. This spore type is thought to be equivalent to the present day unicellular marine alga *Pahysphaera pelagica* (Wall, 1962). The presence of this spore type in the Bakken shales is consistent with the postulated marine sapropelic origin of Bakken organic matter. Tasmanites are also recognizable in thin sections of the shales. They are often compressed into

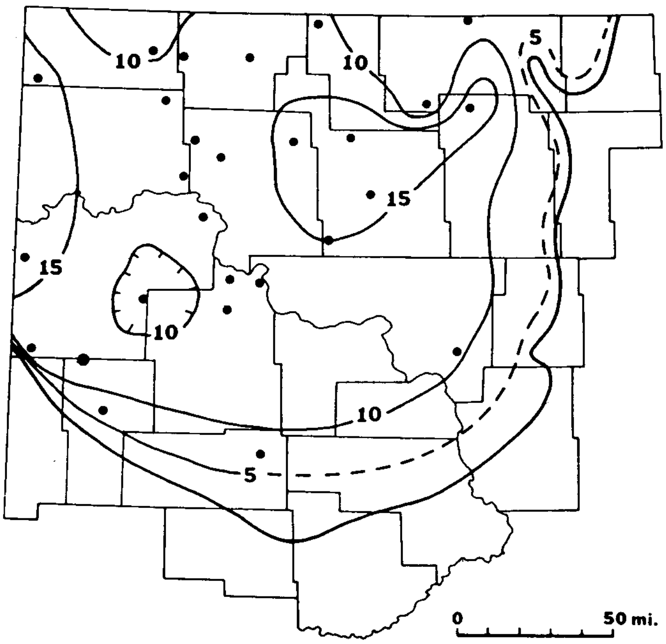

Figure 12-Contour map of weight percent organic carbon of upper Bakken shale. Contour interval is five percent.

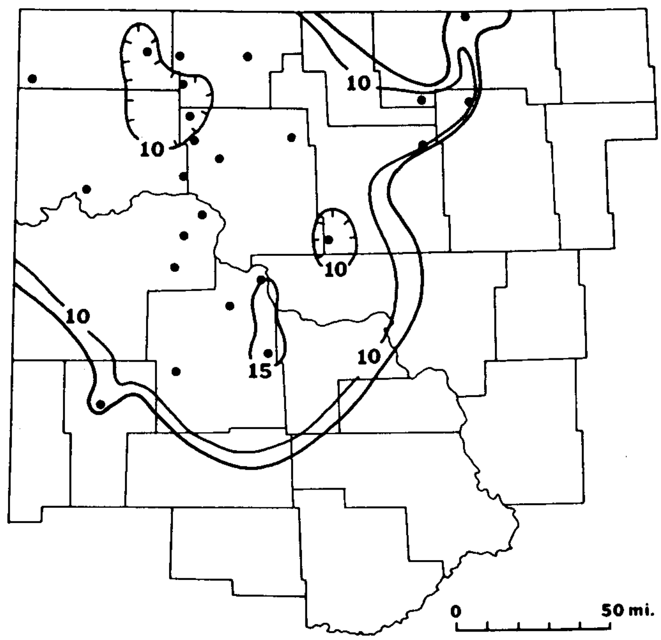

Figure 13-Contour map of weight percent organic carbon of lower Bakken shale. Contour interval is five percent.

discs and partially replaced by pyrite. Tasmanites are also visible to the naked eye in cores of the shales and are quite abundant locally.

Extractable Organic Matter

Solvent-extractable organic matter (bitumen) in the Bakken shales ranges between 2,100 and 15,400 ppm of the rock and does not exhibit any clear trend with increasing depth (Table 1). Samples from shallow depths [3,000-4,000 ft (910-1,220 m)] commonly have total bitumen contents as high as those obtained from deep [greater than 9,000 ft (2,740 m)] samples. However, there are differences in the composition of bitumen from shallow samples and bitumen from deep samples. Shallow bitumen is composed mostly of resins and asphaltenes, whereas the deep basin bitumen is composed of 40 to 70% hydrocarbons.

Hydrocarbons extracted from the Bakken shales greatly increase in concentration in the deeper parts of the basin. The ratio of hydrocarbons to nonhydrocarbons in the $C_{15}+$ extracts increases slightly with increasing depth at first and then shows significant increase below 9,000 ft (2,740 m) (Figure 15). The first break in the curve on this graph, where hydrocarbon content begins to increase significantly [about 9,000 ft (2,740 m)], is interpreted to represent the average depth for the threshold of hydrocarbon generation in the shales. The large increase in hydrocarbons that occurs in some samples from greater than 10,000 ft (3,050 m)

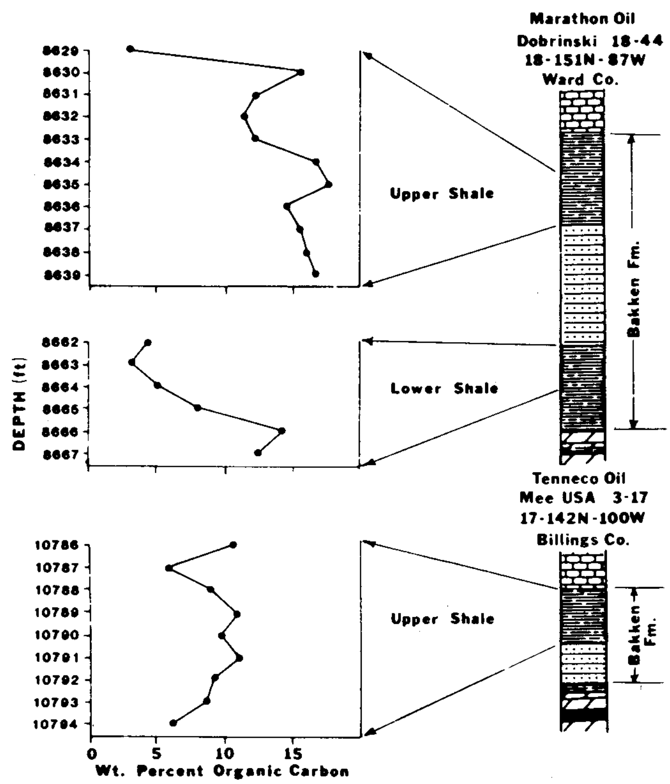

Figure 14-Vertical distribution of organic matter in three Bakken shale sections showing variation in organic carbon content.

Map No.	Sample No.	Depth	TOC	Bitumen (ppm)	Saturates (%)	Aromatics (%)	Resins & Asphaltenes (%)	HC/OC (mg/gm)	HC/nonHC	Sat/OC (mg/gm)	Aro/OC (mg/gm)
2	457	3890-904	5.25	3309	5.94	5.13	88.93	7.0	0.12	3.7	3.2
3	2675	4690-760	15.40	11786	4.66	11.51	83.83	12.4	0.19	3.6	8.8
4	4790A	5335-45	5.36	5779	11.20	7.45	81.35	20.1	0.23	11.9	8.1
4	4790B	5370-80	11.65	5882	4.50	8.80	86.71	6.7	0.15	2.3	4.4
5	6466	5816-20	10.71	3810	10.19	12.78	77.03	8.2	0.30	3.6	4.6
8	8711	6210-20	5.50	2996	10.85	22.61	66.54	18.2	0.50	5.9	12.3
9	4990	6576-86	11.30	7733	6.77	9.36	83.86	11.0	0.19	4.6	6.4
12	4508A	7501-03	14.40	11650	9.80	30.54	59.66	32.6	0.68	7.9	24.7
12	4508B	7543-46	13.60	8940	9.22	30.32	60.47	26.0	0.65	6.1	19.9
13	105	7562-68	15.60	12280	6.63	17.03	76.34	18.6	0.31	2.0	5.2
14	4958	7577-80	17.79	11075	9.16	26.41	64.43	22.1	0.55	5.7	16.4
15	4507	7970-8080	11.86	12184	12.20	17.48	70.32	30.5	0.42	12.5	18.1
19	6607A	8560-80	12.00	13377	29.01	29.01	57.83	46.6	0.73	14.6	32.1
20	8177A	8629-39	15.00	12050	9.95	25.62	64.44	28.6	0.55	8.0	30.6
19	6607B	8640-70	6.89	8962	18.19	45.85	35.96	44.1	1.78	12.5	31.6
20	8177B	8663-67	7.07	3850	6.26	21.74	72.01	15.3	0.17	3.4	11.8
21	4837	850-8940	13.00	8460	13.21	25.02	61.78	24.9	0.62	8.6	16.3
23	6780	9030-100	14.90	12633	9.70	20.28	70.02	25.4	0.43	8.2	17.2
26	3007	9409-13	11.80	5690	14.08	34.08	51.84	23.2	0.93	6.8	16.4
27	7164	9550-626	12.60	15400	8.15	13.70	78.15	26.7	0.28	10.0	16.9
29	3492A	9608-24	10.50	8433	15.82	25.84	58.34	33.5	0.71	12.7	20.8
29	3492B	9658-68	16.30	12717	13.81	30.24	55.96	34.4	0.79	10.7	23.6
32	2618	9838-37	15.10	12870	11.26	24.99	63.75	30.9	0.57	9.6	21.3
33	4340A	9885-906	11.95	5770	22.79	28.57	48.64	24.8	1.06	11.0	13.8
33	4340B	9967-10008	10.97	5080	25.79	32.08	42.14	32.1	1.37	14.3	17.8
34	793A	9993-10024	12.45	11965	10.49	21.01	68.50	30.2	0.46	10.1	20.2
34	793B	10051-82	17.07	13310	10.31	18.08	71.60	22.2	0.40	8.0	14.1
35	6896	10107-86	12.90	13250	10.58	21.72	67.70	33.2	0.48	10.9	22.3
36	5088A	10155-69	13.50	9470	9.64	25.47	64.90	24.6	0.54	6.7	17.9
37	3363	10213-23	10.90	2280	30.84	34.79	34.38	13.7	1.91	6.5	7.3
36	5088B	10240-86	11.00	12910	14.57	25.33	60.10	46.8	0.66	17.1	29.7
38	3167	10242-64	11.10	2120	40.44	30.51	29.04	13.6	1.00	7.7	5.8
39	1202A	10257-77	10.58	6040	16.58	15.74	67.67	18.5	0.48	9.5	9.0
40	2967	10285-303	9.97	6280	33.42	29.47	37.12	39.6	1.69	21.2	18.6
39	1202B	10321-43	13.44	8739	12.36	13.90	73.75	17.1	0.36	8.0	9.0
41	8474	10362-72	10.30	6330	20.03	31.03	48.94	31.4	1.04	12.3	19.1
42	413A	10391-410	10.38	9128	14.05	11.28	74.68	22.3	0.34	12.4	10.0
42	413B	10452-68	7.48	7030	19.01	13.39	67.61	30.4	0.48	17.9	12.6
43	7004	10450	12.80	9029	12.39	27.82	59.79	28.4	0.67	87.4	19.6
44	9351	10463-73	10.10	4098	28.76	33.45	37.80	25.2	1.65	11.7	13.6
45	607	10508-21	12.39	9420	12.10	24.26	63.63	27.6	0.57	9.2	18.4
47	2820	10633-50	11.00	6770	25.22	26.76	48.03	32.0	1.08	15.7	16.5
48	4723	10680-730	7.94	4993	21.89	21.01	57.11	27.0	0.75	13.8	13.2
49	6887	10710-30	8.89	3448	12.99	14.91	72.11	10.8	0.39	5.0	5.8
50	1748	10720-53	10.85	4100	28.40	29.93	41.67	22.0	1.40	10.7	11.3
51	4113	10725-38	11.00	8020	13.50	32.18	54.33	33.3	0.84	9.8	23.5
53	7887A	10786-94	7.76	3350	44.33	33.66	28.6	66.3	1.97	19.1	9.5
54	1405	10796-813	13.23	4250	23.24	29.02	47.74	16.8	1.09	7.5	9.3
55	7008	10796-887	9.34	4814	41.50	21.20	37.30	32.3	1.68	21.4	10.9
53	7887B	10800-01	10.14	3840	47.19	20.73	32.09	25.7	2.12	17.9	7.9
56	7579	10856-60	13.70	14060	8.30	21.75	69.95	30.8	0.43	8.5	22.3
57	1858	10963-69	13.09	6739	19.43	23.46	57.11	22.1	0.75	10.0	12.1
58	999	10994-11010	12.44	4904	18.83	35.84	45.33	21.6	1.21	7.4	14.1
59	4611	11010-76	8.60	6501	29.07	19.62	51.32	36.8	0.95	37.2	14.8
60	527A	11205-20	7.33	5417	43.02	11.48	45.51	40.3	1.20	31.8	8.5
60	527B	11262-86	7.62	6880	43.76	12.71	43.53	51.0	1.30	39.5	11.5

Table 1-Results of thin layer chromatography and associated organic carbon determinations listed in order of increasing depth. Map numbers correspond to numbers in Figure 11 and sample numbers refer to NDGS well numbers, with A corresponding to the upper shale and B to the lower shale. Percentages refer to percent of total extract.

is interpreted to represent the stage or peak of intense generation. Many samples from depths of 10,000 ft (3,050 m) or greater have HC/nonHC values nearly equal to shallow samples on this graph, which results in a large variation in values at these depths. This large variation is due partly to lack of hydrocarbon generation and possibly to effects of primary migration depleting the hydrocarbon content of some deep samples. The map distribution of the HC/nonHC ratio (Figure 16) shows a general increase towards the basin deep.

A useful organic geochemical parameter that is often used to evaluate maturity in source rocks is the ratio of extractable hydrocarbon to organic carbon. When plotted against depth, this parameter does not have a well defined trend for the Bakken shales (Fig-

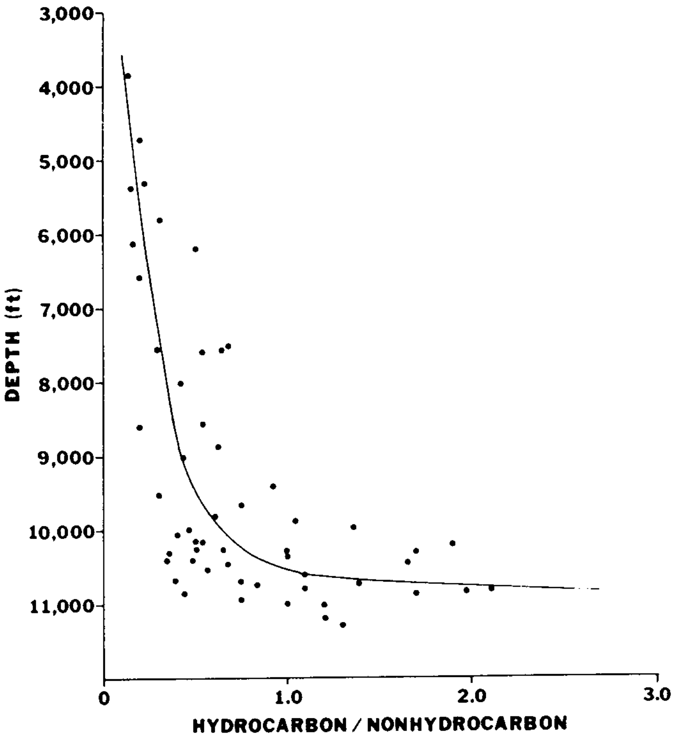

Figure 15-Ratio of C_{15}+ hydrocarbons to nonhydrocarbons versus depth for the Bakken shale.

ures 17). A general increase with increasing depth can be vaguely seen, but there is considerable scatter below 7,000 ft (2,130 m). One possible explanation for the scatter of data points is primary migration of hydrocarbons affecting the indigenous hydrocarbon content by depleting it. Other possibilities are partial loss of indigenous hydrocarbons in the sample, contamination of the sample by oily substances in the drilling mud, lack of hydrocarbon generation in some deep samples, or analytical error in the thin layer chromatography. When the hydrocarbon fraction is separated into its two components, aromatics and saturates, and their changes with depth are obsèrved separately (Figures 18, 19), it can be seen that most of the scatter in the HC/OC ratio is due to the aromatics. It is possible that other aromatic compounds containing NSO heteroatoms may be present in the aromatic hydrocarbon fraction obtained by thin layer chromatography, thus this fraction may not represent aromatic hydrocarbons alone (Harry Dembicki, Jr., personal commun., 1982). This might cause an inaccuracy in the amount of aromatic hydrocarbons measured and thereby introduce scatter in the hydrocarbon data. The scatter observed in the aromatic graph might also be explained by preferential primary migration of the aromatic hydrocarbons. The saturated hydrocarbons alone, when plotted against depth (Figure 19) show a better defined trend, similar to the HC/nonHC ratio.

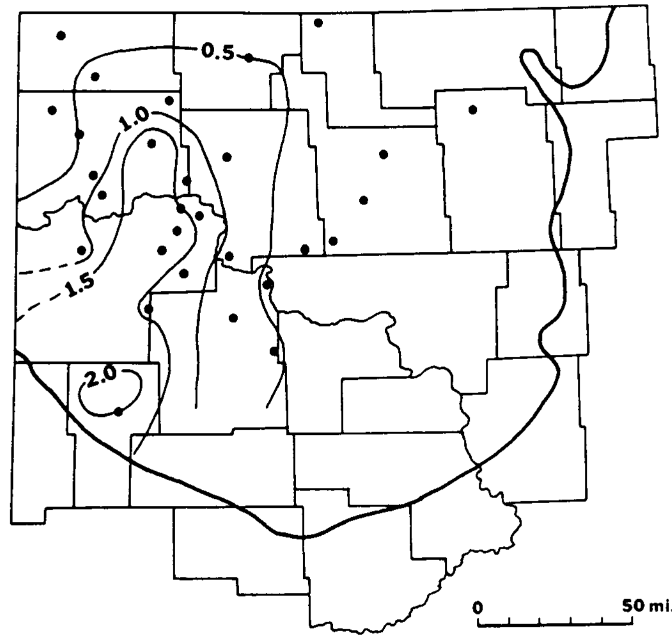

Figure 16-Contour map of the ratio of C_{15}+ hydrocarbons to nonhydrocarbons for the Bakken shale. Contour interval is 0.5.

The map distribution of the HC/OC ratio (Figure 20) is rather complex and probably affected by migration or analytical error (amount of aromatic HC present). Distinct areas of low HC/OC values along the south and west sides of the Nesson Anticline, along the Billings Anticline, and in the area of the Antelope oil field could be interpereted as areas where migration of hydrocarbons from the Bakken has taken place. Vertical fracturing and faulting of the Bakken and adjacent rock units is known to occur in these areas (Murray, 1968; Dow, 1974; Meissner, 1978; Gerhard et al., 1982) and could provide a migration pathway for oil generated in the Bakken shales.

Gas chromatograms of the saturate hydrocarbon (alkane) fraction of Bakken extracts taken by the USGS (separate from Conoco samples) are used in Figure 21 to exhibit changes in the distribution of these hydrocarbons with depth. The pattern at 7,562 ft (2,305 m) has a bimodal distribution due to a high concentraion of heavy alkanes (C_{26}-C_{32}), and is typical of hydrocarbon distributions of source rocks that have not yet entered the oil generation (catagenesis) phase. During catagenesis a shift occurs toward the lower molecular weight molecules due the synthesis of smaller molecules and the cracking apart of larger molecules (Hunt, 1979). At 9,409 ft (2,868 m) the alkane distribution peaks between C_{13} and C_{18}, and displays a steady decrease in

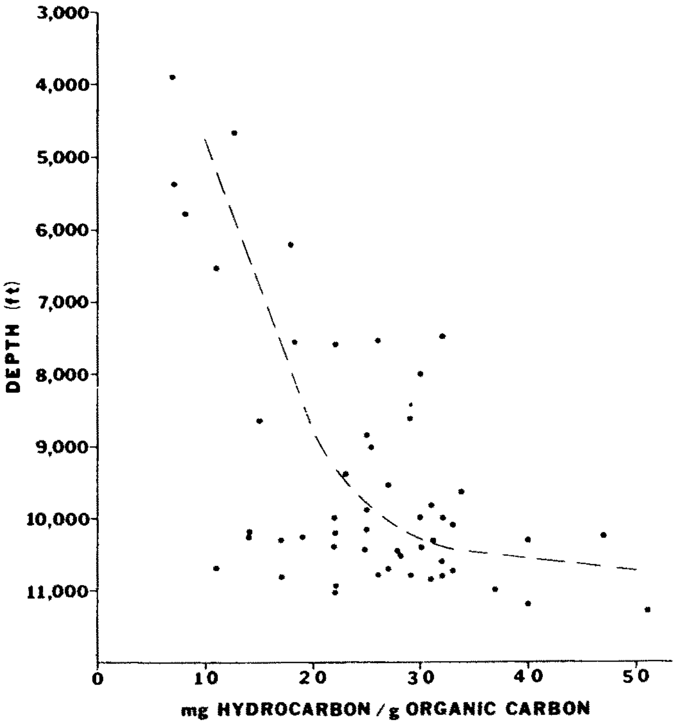

Figure 17-Ratio of C_{15}+ hydrocarbons to organic (mg/g) versus depth for the Bakken shale.

concentration of heavy molecules. This pattern type is typical of source rocks that have reached maturity. The patterns at very deep depths display a large amount of C_{14}-C_{18} hydrocarbons and have passed well into the oil generation phase.

Pyrolysis

The second pyrolysis peak or S_2 refers to the amount of hydrocarbons generated from the kerogen of the source rock during pyrolysis. When the S_2 value is normalized to organic carbon and then plotted against depth (Figure 22) a trend is obtained which represents the progessive breakdown of kerogen with depth. At approximately 9,000 ft (2,740 m) the visually fitted curve has a break in slope and the hydrocarbon-generating capacity of the kerogen decreases as oil is generated. From Figure 22, the average threshold of oil generation is interpreted to occur at about 9,000 ft (2,740 m) of depth. The samples below 9,000 ft (2,740 m) (Table 2) that have values roughly equal to shallow samples represent a lack of hydrocarbon generation in certain deep areas of the basin (extreme eastern Dunn County) as shown in Figure 23.

The production index is a commonly used parameter that is an indication of the extent of the conversion of kerogen to petroleum hydrocarbons

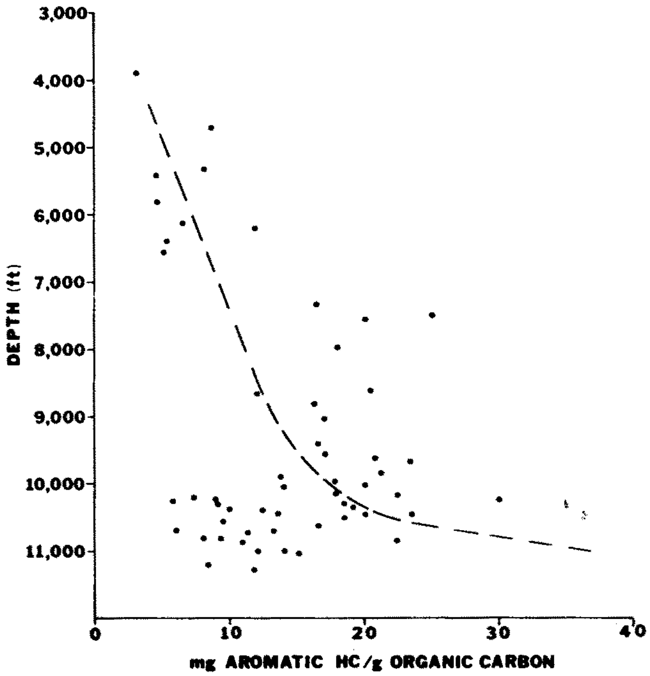

Figure 18-Ratio of C_{15}+ aromatic hydrocarbons to organic carbon (mg/g) versus depth for the Bakken shale.

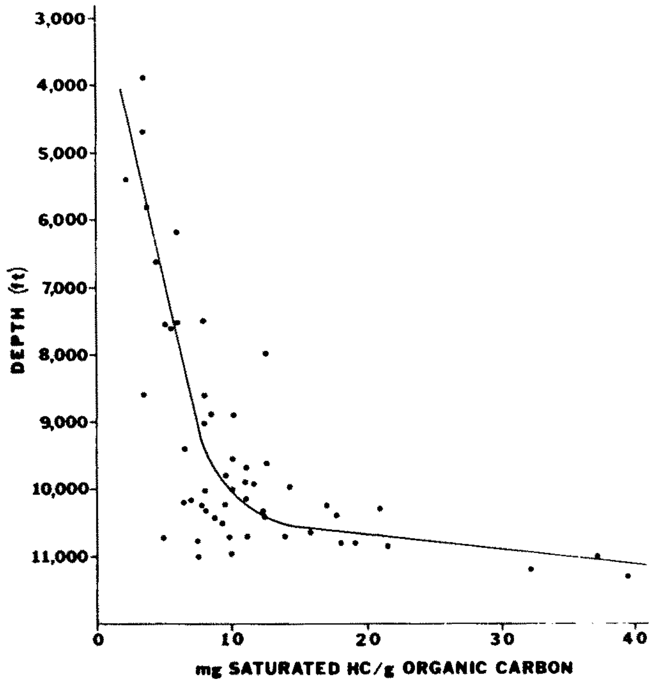

Figure 19-Ratio of C_{15}+ saturated hydrocarbons to organic carbon (mg/g) versus depth for the Bakken shale.

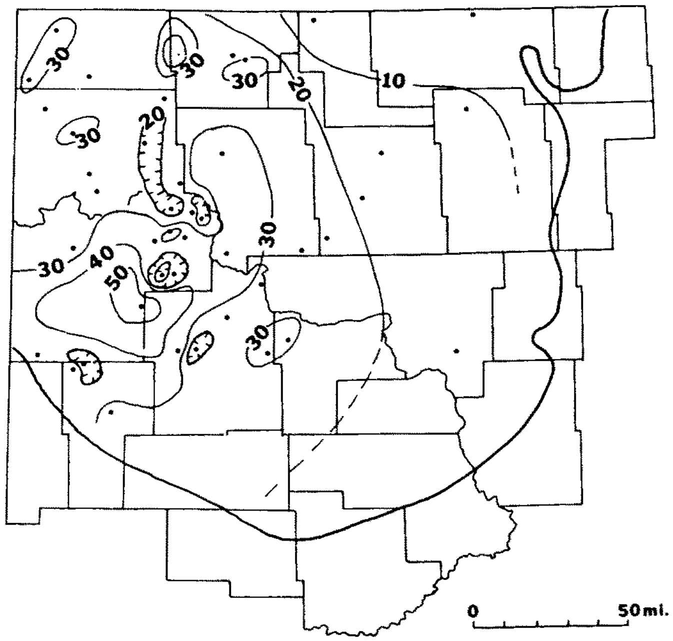

Figure 20-Contour map of the ratio of C_{15}+ hydrocarbons to organic carbon (mg/g) for the Bakken shale. Contour interval is 10 mgHC/gOC.

(Merewether and Claypool, 1980). This parameter is a numerical expression representing the ratio of extractable hydrocarbon to the sum of extractable hydrocarbon plus pyrolyzable hydrocarbon ($S_1/(S_1 + S_2)$). A plot of this parameter versus depth for the Bakken shales (Figure 24) displays a well-defined trend with an abrupt increase occurring at about 10,000 ft (3,050 m). The average depth for the threshold of hydrocarbon generation as seen on this graph could be placed at about 9,000-9,500 ft (2,740-2,900 m) and the average depth for intense hydrocarbon generation at approximately 10,000 ft (3.05 km) and deeper. The low index values below 9,000 ft (2,740 m) (Table 2) represent areas in the deep portion of the basin where very limited hydrocarbon generation has occurred. The map distribution of this parameter (Figure 25) shows a clear increase in hydrocarbon generation to the deep part of the basin, as would be expected. The production index does not show much effect that could be attributed to migration. This parameter may be less sensitive to migration effects, as it accounts for kerogen breakdown.

Vitrinite Reflectance

Vitrinite turned out to be rare in the shales of the Bakken. Only a few samples contained enough vitrinite to obtain a significant number of readings. The reflectance values that were obtained (Table 3) are plotted against depth in Figure 26. The visually fit line suggests the probable rate of change of vitrinite reflectance with depth. If this line can be assumed to be accurate, it would support conclusions on the average depth at which oil generation began as drawn from pyrolysis and extractable hydrocarbon data. A vitrinite reflectance value of 0.6 is often taken to represent the onset of oil generation (Hunt, 1979) and this value occurs at a depth of about 9,500 ft (2,900 m) in Figure 26. The map distribution of reflectance values (Figure 27) displays a pattern similar to extractable hydrocarbon and pyrolysis maps.

DISCUSSION

Bakken-Source Rock Maturity

The maturity of the Bakken shales can be interpreted from graphs and maps made from extractable hydrocarbon and pyrolysis data. The average depth for the threshold of oil generation has been picked from plots of the geochemical data, at that depth where the visually fit line significantly changes slope. Intense hydrocarbon generation is taken to begin at that depth where an abrupt change in the slope of the line occurs and the line approaches horizontal (Figure 28). From Figures 15, 19, 22, 24, and 28, the average threshold of oil generation in the Bakken is interpreted to occur at 9,000 ft (2,740 m) and the average threshold of intense oil generation is interpreted to occur at 10,000 ft (3,050 m) and deeper. From the vitrinite reflectance graph (Figure 26) the Bakken is seen to be thermally mature below 9,500 ft (2,900 m) and has not reached the completion of oil generation, which is generally taken to be 1.3 percent (Hunt, 1979).

Figure 29 is a map of the maturity zones in the Bakken and is derived from maps of extractable hydrocarbon and pyrolysis data (Figures 16, 23, 25). The Bakken shales in the eastern part of the area studied are immature as judged from their low hydrocarbon contents (less than 0.5 HC/nonHC) and high values of pyrolytic hydrocarbons (greater than 500 mgHC/gOC). The second zone depicts the area where the shales are just entering the stage of oil generation. Here the hydrocarbon contents are slightly higher (0.5-1.0 HC/nonHC) and kerogen breakdown is beginning, as seen in lower pyrolytic hydrocarbon values (300-500 mgHC/gOC). The last zone, in the deepest part of the basin, illustrates the area of intense hydrocarbon generation, where hydrocarbon contents are high (greater than 1.0 HC/nonHC) and pyrolytic hydrocarbon values are much lower (less than 300 mgHC/gOC). This last zone is considered the effective source area for the Bakken where enough hydrocarbons have been generated to charge oil reserves in overlying or underlying rock units.

By comparing the mapped source rock maturity areas and a structure contour map of the top of the

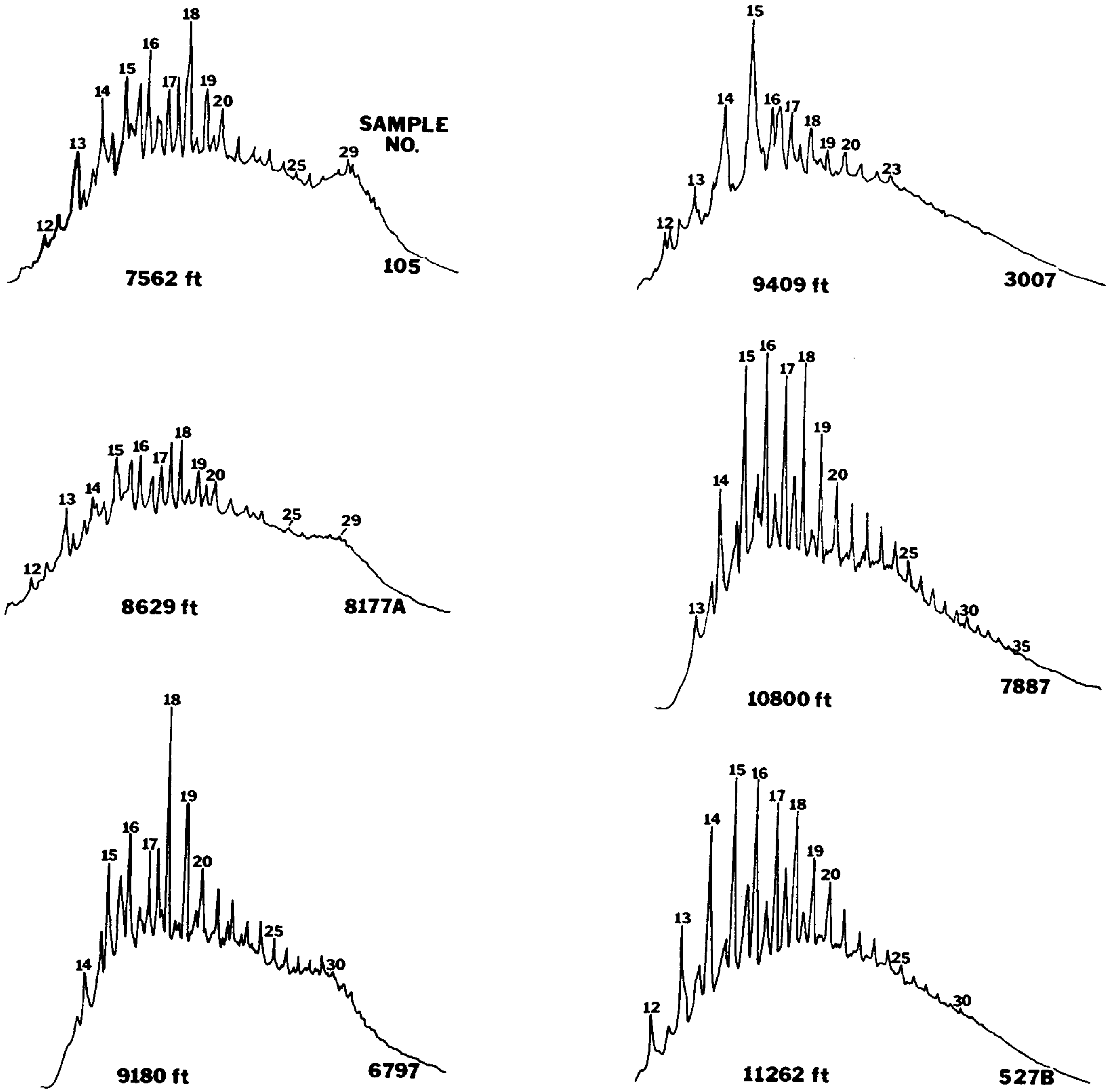

Figure 21-Gas chromatograms of saturated hydrocarbons extracted from the Bakken shale showing change in molecular distribution with depth. Sample numbers correspond to those in Table 1.

Bakken (Figure 29), it becomes evident that the relationship between maturity and depth is not uniform across the basin. In eastern Dunn County and western Mercer County the Bakken is 9,500 ft (2,900 m) to 10,000 ft (3,050 m) deep and is only marginally mature. The maturity zones deviate from structure mostly to the north and northwest. The nonuniformity of this relationship is probably best explained by different rates of heat flow in some areas of the basin, such as in the area of the Nesson Anticline.

Possible Effects of Migration on Hydrocarbon Data

Primary migration of hydrocarbons could affect the graphs and maps of hydrocarbon data by causing depletion of the indigenous hydrocarbon content of the

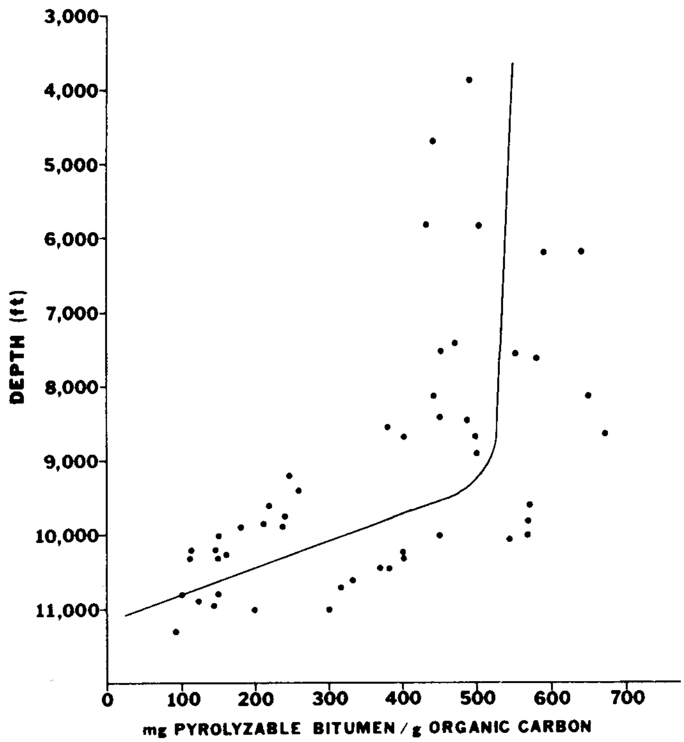

Figure 22-Ratio of pyrolyzable hydrocarbons to organic carbon (mg/g) versus depth for the Bakken shale.

Bakken shales. HC/nonHC values less than one and greater than 10,000 ft (3,050 m) deep (Figure 15) are partially the result of limited hydrocarbon generation in some deep portions of the basin. Values less than one on the HC/nonHC map (Figure 16) that occur within the intense generation (mature) area of Figure 29, are probably the result of loss of indigenous hydrocarbons by migration.

The map distribution of the HC/OC ratio has interesting coincidences between low hydrocarbon content in deep (mature) basin areas and areas where migration of oil out of the Bakken might be expected, as on the flanks of the Nesson Anticline, the Antelope Anticline, and the Billings Anticline (Figure 20). Fracturing with some possible associated faulting is known or likely in these areas, especially at Antelope field (Meissner, 1978) and along the west flank of the Nesson Anticline (Gerhard et al., 1982). Oil generated in the Bakken escaping along these faults and fractures might explain the low hydrocarbon to organic carbon ratios observed in these areas. Higher hydrocarbon to organic carbon ratios than expected, such as those in Divide and Burke counties, might be explained by northward primary migration of Bakken oil through microfractures developed in the shales or through the organic matter (kerogen) matrix.

As great deal of the scatter (and complex map pattern) in the HC/OC ratio is due to variation in the aromatic hydrocarbon content, analytical error in determining the actual amount of aromatic hydrocarbons present is a probable explanation for the erratic distribution of HC/OC values. Preferential migration of the aromatic hydrocarbons is another possibility, but preferential migration of aromatic hydrocarbons would not be expected for continuous-phase or bulk oil migration (the most likely form of primary migration for the Bakken as demonstrated by Jones, 1980).

Burial History and Time of Initial Oil Generation

Burial history is an important factor in the timing of maturation of a source rock. For first-order reaction rate oil generation theory, the temperature and length of time at a particular termperature to which a source rock has been subjected are the two most important factors in determining its maturity. The first-order chemical reactions that take place to breakdown kerogen into oil are time and temperature dependent. Either a 10°C increase in temperature or a doubling of the exposure time of a source rock to a given temperature will double the reaction rate of oil generation (Dow, 1977).

The graphical representation of the Bakken burial history is illustrated in Figure 30. Each line on the graph represents the burial history for a particular well in the basin, and the depth indicates the amount of burial at a particular time. The bottom line (A) represents burial history of the Bakken in the deeper portion of the basin. The three other lines represent the burial history in shallower portions of the basin. The upward deflections represent major unconformities. Formation ages and the timing and duration of erosional events were obtained from Bluemle et al. (1981). The amount of uplift or sediment loss represented by the magnitude of the upward deflections is qualitative, as little information on the amount of section lost at these unconformities is readily available. The last upward deflection represents possible loss of section since the Paleocene (approximately since the time of deposition of the Sentinel Butte Formation) and, again, is a rough estimate.

The present day geothermal gradient for the Williston Basin in Figure 30, has been taken from Nixon (1973). To make time-temperature calculations from burial history, one starts by estimating from Figure 30, the amount of time the Bakken has spent in each of the 10°C temperature intervals. This amount of time is then multiplied by a temperature factor which increases exponentially for each higher temperature interval. This time-temperature index (TTI) for each interval is then added together to arrive at the total TTI of a given rock unit at a given time. These are very simple TTI calculations using the method of Waples (1980) and assuming that the geothermal gradient has remained very similar to the present day gradient. These calculations are sum-

Map No.	Sample No.	Depth	TOC	S_1	S_2	S_3	T°C	Prod. Index	S_1/OC	S_2/OC
1	286A	3855-75	9.39	2.04	46.00	3.78	414	.042	22	490
1	286B	3900-10	7.32	0.47	16.72	1.69	407	.027	6	228
3	2675A	4689-705	12.01	2.00	53.18	4.03	417	0.36	17	443
3	2675B	4730-60	15.10	2.14	48.15	4.61	411	.043	14	319
6	4992	5840-50	11.11	3.20	47.78	2.28	412	.063	29	430
7	6401	5850-60	17.55	4.66	72.89	2.82	417	.060	27	417
8	8711	6210-20	10.82	3.34	63.78	1.17	407	.050	31	589
10	392	6960-90	17.13	1.63	22.82	1.00	419	.067	10	133
11	5989	7360-470	12.99	6.35	60.49	1.20	430	0.95	49	466
12	4508B	7543-46	13.50	5.28	61.54	0.68	423	.079	39	456
13	105	7562-68	15.60	4.22	85.57	2.24	450	.047	27	549
14	4958	7557-80	15.17	7.24	88.40	0.82	428	.076	48	482
16	6798A	8100-30	6.99	3.35	30.94	2.03	435	.098	48	442
17	7612	8110-50	14.17	7.32	92.46	2.34	420	.073	52	652
16	6798B	8180-200	9,88	3.54	34.03	1.98	434	.094	36	344
18	528A	8504-15	15.48	4.73	69.40	3.73	421	.064	31	448
18	528B	8445-55	10.79	3.47	52.26	2.30	421	.062	32	484
19	6607A	8560-80	12.87	3.52	48.94	1.76	437	.067	27	380
20	8177A	8629-39	15.00	6.55	100.79	2.34	418	.061	44	672
19	6607B	8640-70	11.78	5.06	46.63	1.26	439	.098	43	395
20	8177B	8663-67	7.10	1.59	27.69	0.74	420	.054	22	397
22	6673A	8870-90	15.17	5.45	77.60	1.84	433	.065	36	512
22	6673B	8930-50	10.15	4.00	49.75	1.90	431	.074	19	490
24	2033A	9090-110	8.39	7.10	37.40	2.07	436	.159	85	466
25	6797	9189-90	10.15	2.74	54.10	1.54	417	.048	27	533
24	2033B	9190-230	9.91	6.06	23.48	1.36	439	.205	61	237
26	3007	9509-13	13.41	4.90	34.95	0.89	443	.123	37	261
28	3044	9620-70	11.02	1.92	34.42	3.89	419	.053	17	312
29	3492	9610-70	14.68	7.88	83.30	2.13	424	.086	54	567
30	5072A	9625-40	10.61	1.80	23.11	2.25	437	.072	17	218
30	5072B	9720-65	9.71	4.49	23.15	1.72	437	.162	46	238
31	5831A	9800-30	11.69	4.18	24.49	2.03	438	.145	36	209
32	2618	9828-37	15.10	7.12	86.32	1.21	421	.076	47	572
33	4340A	9885-906	10.70	4.78	19.17	1.11	446	.199	45	179
31	5831B	9918-40	10.01	4.55	15.89	2.01	441	.222	45	238
33	4340B	9967-10008	11.01	4.50	14.65	1.36	439	.234	41	151
34	793A	9993-10024	14.52	8.72	82.81	1.55	431	.095	60	570
34	793B	10051-82	14.74	8.62	80.27	1.53	429	.096	58	545
36	5088A	10155-69	13.50	5.27	54.74	0.76	440	.088	48	405
37	3363	10213-23	10.90	4.47	15.93	0.68	445	.219	41	146
36	5088B	10240-86	11.00	5.74	44.24	0.67	437	.115	52	402
38	3167	10242-64	11.10	5.84	12.34	0.85	448	.321	53	111
39	1202A	10257-77	9.71	4.36	15.53	1.70	440	.219	45	160
40	2967	10285-303	9.97	5.87	10.70	1.58	452	.354	59	107
39	1202B	10321-43	11.82	5.27	16.82	1.32	446	.239	45	142
42	413B	10452-68	12.91	6.54	49.09	1.00	438	.118	51	380
46	6839	10530-40	18.69	3.79	15.35	2.77	440	.200	20	82
51	4113	10725-38	11.00	4.56	35.51	0.83	431	.114	41	323
52	6489	10725-35	11.48	5.95	17.37	0.69	445	.255	52	154
53	7887A	10786-94	8.01	4.23	8.61	0.90	453	.329	53	108
53	7887B	10800-01	9.26	5.09	9.10	1.12	450	.359	55	98
56	7579	10856-60	13.70	3.58	59.07	1.50	440	.057	26	26
57	1858	10963-69	10.99	5.60	15.94	1.01	440	.260	51	145
58	999	10994-11010	11.38	5.22	22.67	0.95	436	.187	46	199
59	4611	11010-76	6.86	6.88	20.85	1.18	437	.248	100	304
60	527B	11262-86	7.62	4.93	7.04	0.76	446	.412	65	92

Table 2-Results of thermal analyses (pyrolysis) and associated organic carbon determinations listed in order of increasing depth. T refers to the temperature (°C) recorded at the maximum of the S_2 peak. Map numbers correspond to numbers in Figure 11 and sample numbers refer to NDGS well numbers, with A corresponding to the upper shale and B to the lower shale.

marized in Table 4 for wells represented by lines A and B in Figure 20.

According to Waples (1980) a TTI value of 15 signals the onset of oil generation. For the Bakken this value occurs at approximately 9,000 ft (2,740 m) of burial which is synonymous to the depth estimated from geochemical results. A value of 160 marks the end of oil generation; and for line A, a TTI value of 265 in the temperature interval of 120-130°C (the deepest part of

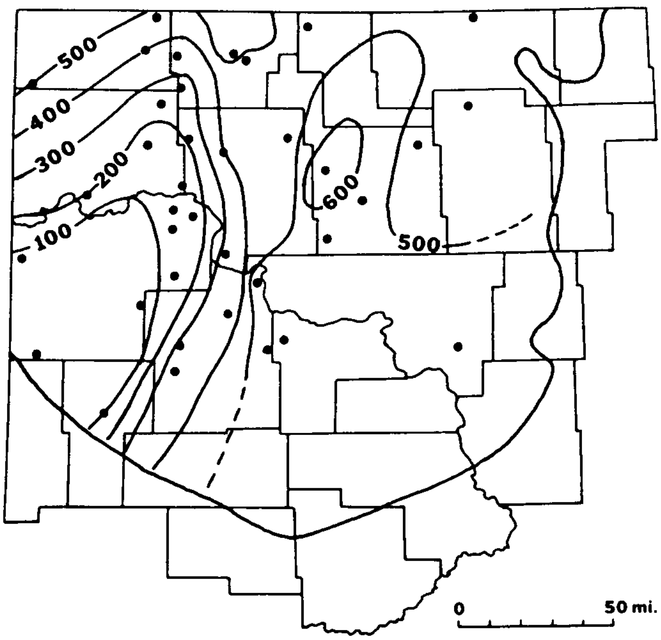

Figure 23-Contour map of the ratio of pyrolyzable hydrocarbons to organic carbon for the Bakken shale. Contour interval is 100 mgHC/gOC.

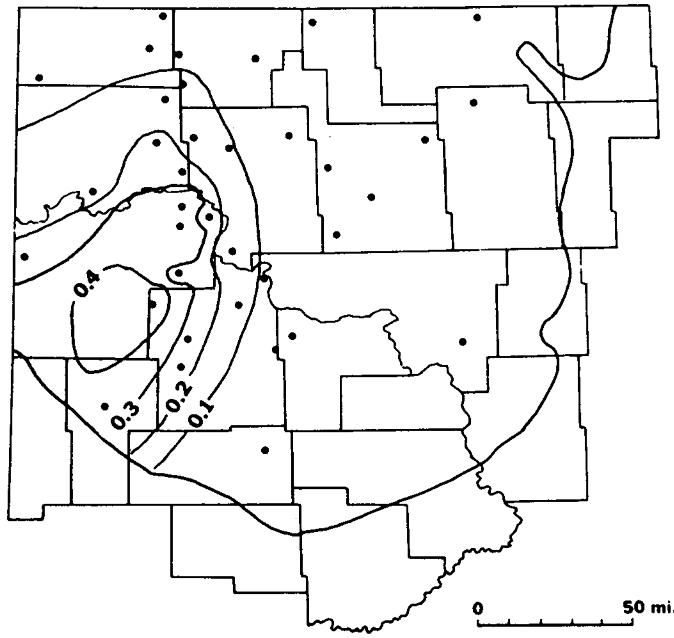

Figure 25-Contour map of the pyrolysis production index ($S_1/S_1 + S_2$) for the Bakken shale. Contour interval is 0.1.

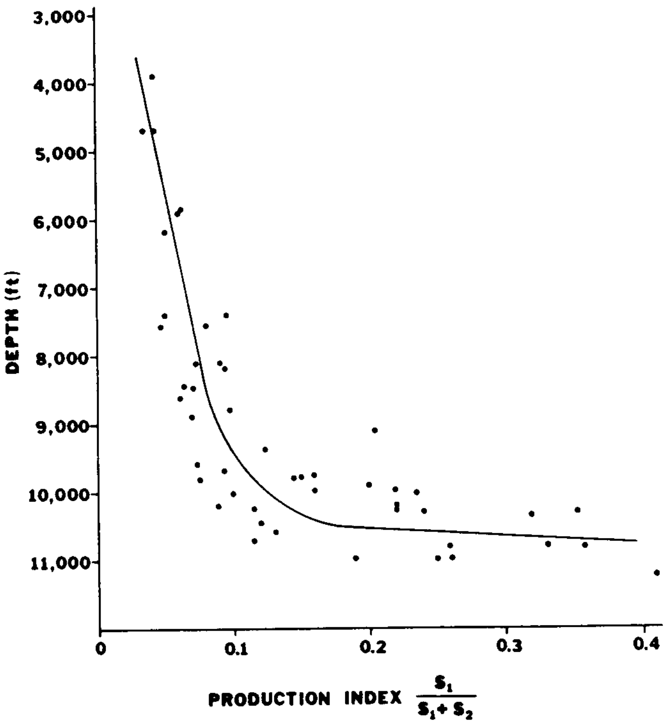

Figure 24-Ratio of the S_1 pyrolysis peak to the sum of the S_1 and S_2 pyrolysis peaks (production index) versus depth for the Bakken shale.

Table 3-Results of vitrinite reflectance analyses.

Sample No.	Depth	Mean	Standard Deviation	Number of Readings	Performed By
1	4,690	0.27	0.03	45	USGS
2	5,855	0.24	0.04	39	USGS
3	6,200	0.26	0.05	25	USGS
4	7,360	0.28	0.04	28	USGS
5	7,970	0.44	0.17	40	Conoco
6	8,450	0.34	0.14	10	USGS
7	9,210	0.56	0.16	25	USGS
8	10,267	0.76	0.12	8	USGS
9	10,720	0.80	0.18	40	Conoco
10	10,790	1.13	0.08	40	USGS
11	10,800	0.87	0.20	40	Conoco
12	10,970	0.77	0.17	40	Conoco
13	11,000	0.73	0.17	23	Conoco
14	11,270	0.94	0.09	34	USGS

the basin) would indicate that oil generation has been completed in the Bakken at that point in the basin. However, this is not substantiated by pyrolysis or extractable hydrocarbon data.

The conclusions or interpretations derived from this method of source-rock analysis should be considered as approximations which carry much less weight than those derived from geochemical data. One inherent drawback in the simple TTI method is that it assumes a constant geothermal gradient during the geologic

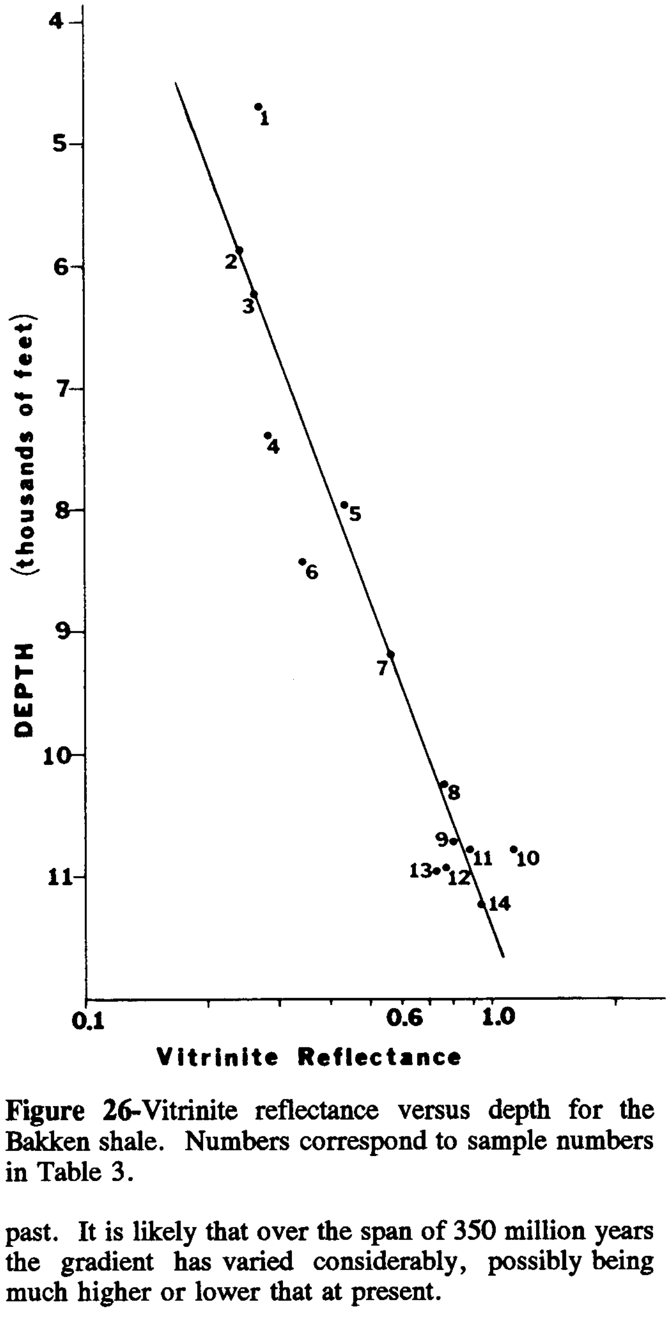

Figure 26-Vitrinite reflectance versus depth for the Bakken shale. Numbers correspond to sample numbers in Table 3.

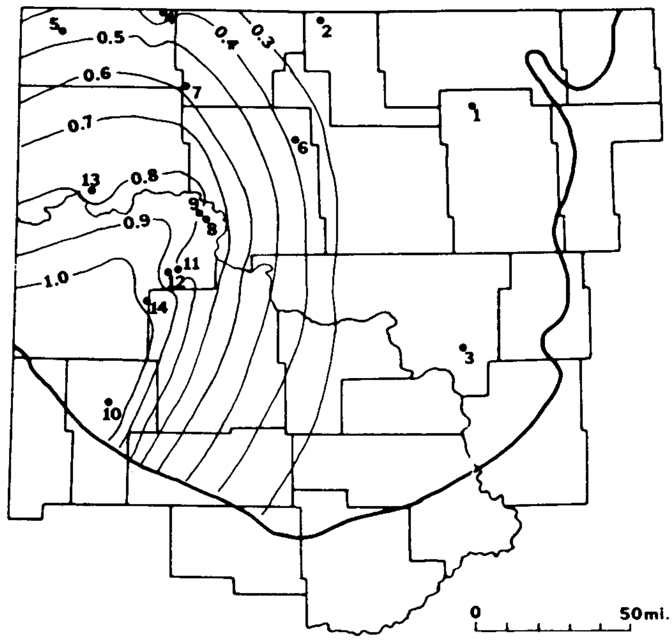

Figure 27-Contour map of vitrinite reflectance of the Bakken shale.

past. It is likely that over the span of 350 million years the gradient has varied considerably, possibly being much higher or lower that at present.

Two conclusions that can be drawn from Figure 30 are the probable temperature of oil generation and the time of initial oil generation in the Bakken. The temperature at which oil generation was initiated in the Bakken would be approximately 100°C [burial depth of 9,000 ft (2,740 m) in Figure 30] assuming that the geothermal gradient has not changed significantly. The time of initial oil generation for the deepest Bakken shale (line A) would be approximately 75 million years ago (Late Cretaceous time).

Expulsion and Migration of Bakken Oil

The type of primary migration taking place in the Bakken is not well known, but continuous-phase (or bulk) oil migration refers to the movement of oil within and out of a source rock in a single, continuous, oil (liquid) phase. This movement is believed to be caused by high differential pressures within the rock. Jones (1980) presented some mass balance calculations to demonstrate that continuous-phase migration was the most likely for the Bakken and that migration by aqueous solution was unlikely.

The timing of initial oil expulsion from a source rock is difficult to resolve in source-rock studies, and it usually involves a certain amount of guesswork. From the burial history diagram of Figure 30, one can see that initial oil generation is labelled as having begun approximately in Late Cretaceous time (75 m.y. ago). There must have been a certain amount of time lapse between the start of oil generation and oil expulsion in the Bakken. For continuous-phase migration, the pore spaces of the Bakken shales would probably have to attain a high oil saturation in order to develop the abnormal pressures necessary for expulsion. Assuming that expulsion could occur as soon as some critical oil saturation of the pore spaces had developed, it would seem logical that expulsion occurred when a burial depth of approximately 9,500 to 10,000 ft (2,900-3,050 m) was attained. At this depth, intense oil generation had been reached and more than enough oil would have been generated to saturate the shale pores and develop abnormal pore pressures. As seen on the burial history dia-

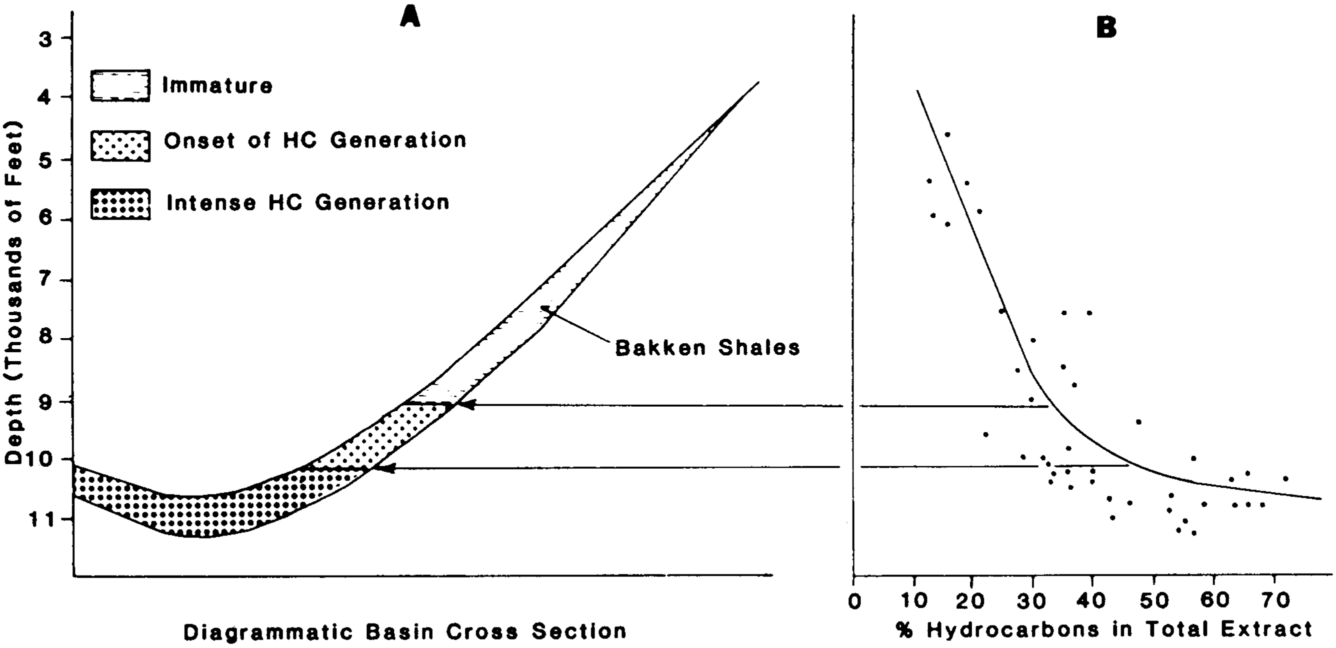

Figure 28-Interpretations of source rock maturity (A) as made from a graph of solvent-extractable $C_{15}+$ hydrocarbon content (B) of the Bakken shales versus depth. The onset of hydrocarbon generation is taken at that depth where the line in B first significantly changes slope and intense hydrocarbon generation is taken at that depth where an abrupt change in slope of the line occurs and the line approaches horizontal.

gram (Figure 30), the Bakken reached this depth of burial in the deep portion of the basin (line A) 70 million years ago (Late Cretaceous time).

In a study of oil types and source rocks of the Williston Basin, Williams (1974) identified three major oil types and their possible source-rock units. The correlation of oil types and respective source rocks was based on similarity in composition (carbon isotype ratios, distribution of $C_{15}+$ parafins, C_4-C_7 hydrocarbon type distribution) of oil types and extracts (of soluble organic matter) from selected possible source-rock units. Type two oil, as defined by Williams, matched extracts taken from the Bakken shales, and thus the Bakken was considered to be the probable source rock for this oil in the Williston Basin. Thode (1981) also stated that the Bakken was the probable source for this oil, based on similarities in sulfur isotopes. Type two oil is predominantly found in reservoirs of the Madison Group.

Dow (1974) elaborated on the exploration significance of the oil typing and source-rock correlation work done by Williams (1974). The stratigraphic distribution of the oil types defined by Williams and their probable source rocks are illustrated in Figure 31. Type two oil occurs not only in rocks of the overlying Madison Group, but also in a few reservoirs of the underlying Birdbear Formation. The volume of type two oil in the Birdbear is very minor and most of this type of oil is found in the Madison Group. Dow's proposed migration scheme for type two oil was based on vertical migration of Bakken oil through fractures located primarily on the Nesson Anticline. He suggested that this upward vertical migration into the Madison Group was retarded completely upon reaching the salts of the Charles Formation. According to Dow lateral migration of Bakken oil then took place along the base of the Charles salts and through porosity zones in the Mission Canyon Formation (Figure 32). Bakken oil in post-Madison rocks is present only beyond the depositional edge of the Charles salts (Dow, 1974). Extensive lateral migration of Bakken oil must have taken place mostly to the north and northeast from the effective source area of the Bakken as suggested by the map distribution of type two oil in Madison rocks (Figure 33). Meissner (1978) believed that downward migration of Bakken oil into the Birdbear was controlled by fractures also, and that overpressuring in the Bakken provided a driving force to push oil downward into the more normally pressured Birdbear reservoirs. Meissner also stated that this downward migration through the Three Forks Formation must have been inefficient, compared to upward migration to the Madison Group, and is essentially limited to the western flank of the basin where the Lodgepole Formation becomes siliceous and fracturing occurs preferentially downward through the

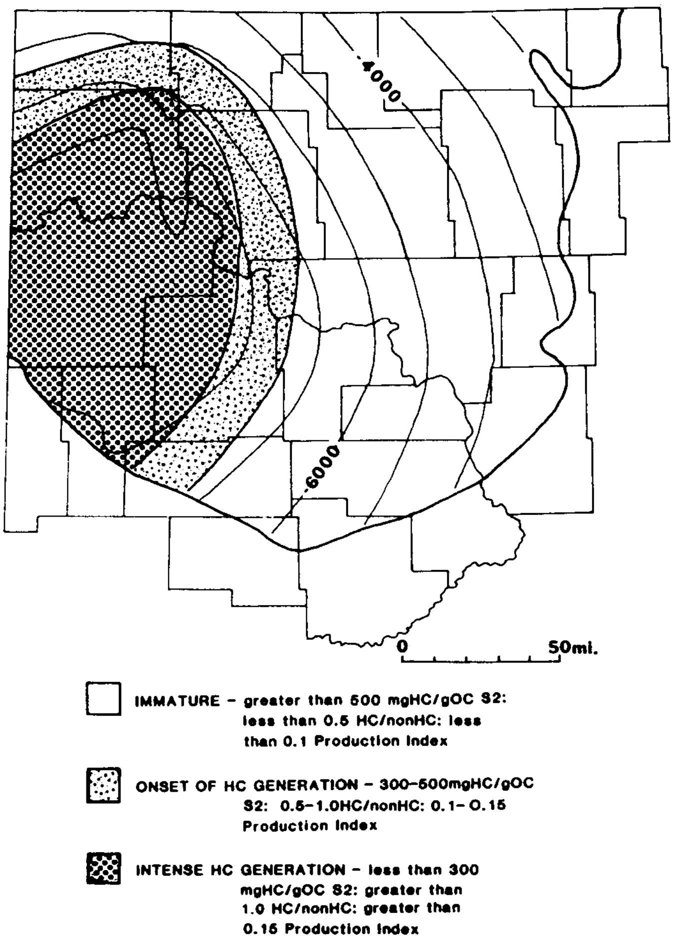

Figure 29-Map of source-rock maturity zones in the Bakken shales with superimposed structure contours on top of the Bakken Formation.

Three Forks.

Due to the impermeable nature of the overlying Lodgepole and the underlying Three Forks Formation, it would seem that fracture systems are the most reasonable means for oil to migrate from the Bakken and for secondary vertical migration to occur. These fracture systems are known to occur along the Nesson Anticline (Dow, 1974), at Antelope oil field (Murray, 1968), and are likely to occur in the vicinity of the Billings Anticline. Major faults along the west side of the Nesson Anticline (Gerhard et al., 1982) and along the Antelope Anticline (Finch, 1969) also probably served as conduits for Bakken oil migrating upwards in the Madison.

Despite the extremely low permeability of the Bakken middle member (less than 0.1 md), it seems likely that abnormal formation pressures have enabled some lateral migration to occur in this member. Strong oil shows in the middle member are occasionally present in immature or marginally mature areas. The presence of oil in this member at Rocanville field in Saskatchewan (Figure 1) suggests that extensive lateral migration may have taken place, if in fact this oil has been generated from the Bakken shales in the deep portion of the basin.

Volume of Hydrocarbons Generated

Calculations of the total amount of hydrocarbons generated by the black shales were based on the extent of thermal kerogen breakdown as observed from pyrolysis data. This involved using the pyrolyzable hydrocarbon data normalized to organic carbon in Figures 22 and 23. The onset of hydrocarbon generation or kerogen breakdown, and the rate of change of this parameter with depth can be observed in Figure 22. Immature kerogen is seen to have an average potential to generate oil of approximately 500 mgHC/gOC in Figure 22. Using this number as a base, stages or intervals of increasing hydrocarbon generation can be recognized from the depth relation in Figure 22 (e.g., the 500-400 mgHC/gOC interval has generated 100 mgHC/gOC, the 400-300 mgHC/gOC interval has generated 200 mgHC/-gOC, etc.). Using Figure 23, four generation stages were designated by areas A, B, C, and D each having a higher amount of oil generated per gram of organic carbon (Table 5). Next the maturity areas were subdivided into areas of similar thickness by superimposing the maturity areas onto the upper and lower shale isopach maps (Figure 7, 9). The volume of shale present in acre-feet of each of these thickness areas was calculated, using a planimeter, for each maturity area of the upper and lower shales (Table 5). Then using the organic carbon maps of Figures 12 and 13 these areas were assigned TOC (total organic carbon) values. In the case of the lower shale a TOC value of 10% was used throughout. The yield in barrels of oil per acre-foot of rock was then calculated for these substages using the following equation, and assuming the density of the Bakken shale to be equal to 2.1 g/cc and the density of oil to be equal to 0.9 g/cc.

$$\left(\frac{gHC}{gOC}\right)\left(\frac{TOC}{gRock}\right)\left(\rho_{rock}\right)\left(\rho_{oil}\right)\left(\frac{6.29\times10^{-6}\,Bbls\ HC}{cc\ HC}\right)\left(\frac{12.33\times10^{8}\,cc\ Rock}{acre\text{-}ft\ Rock}\right) = \frac{Bbls\ Oil}{Ac\text{-}Ft\ Rock}$$

These yields are listed in Table 5. The upper shale had varying yields for each maturity area, as it presented a more complex situation created by varying TOC values. Total oil generated in each stage (maturity area) was then calculated by multiplying the total acre-feet of rock by the hydrocarbon yield in barrels per acre-foot (Table 5). This method of estimating the amount of oil

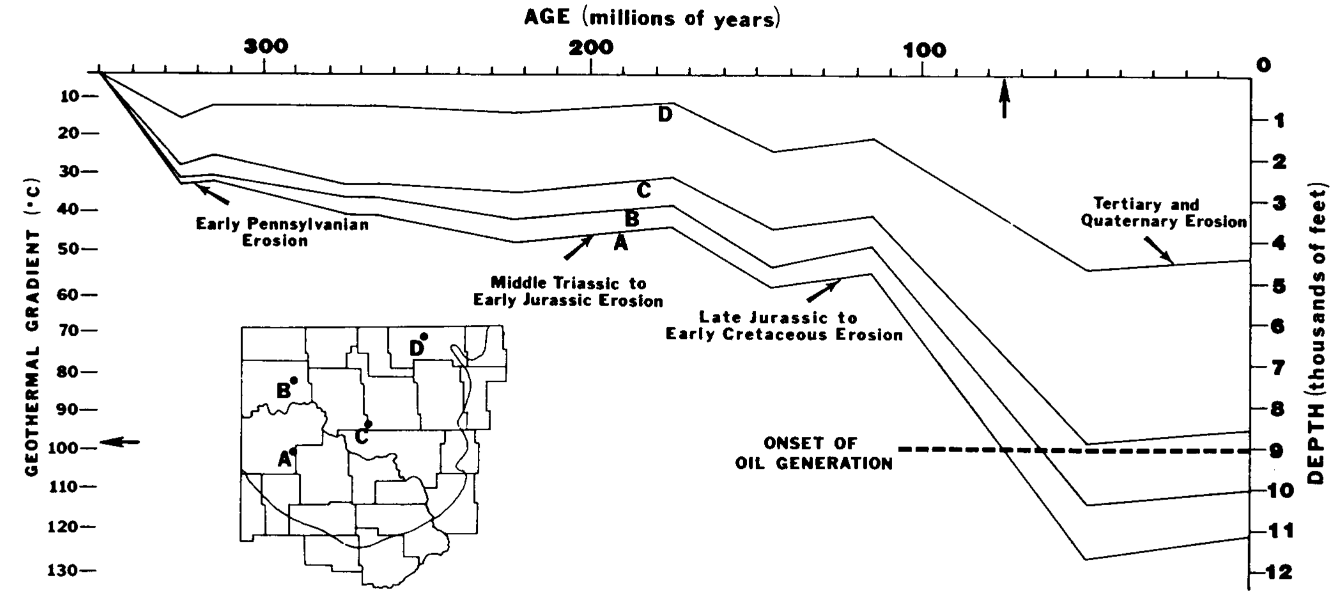

Figure 30-Graphical illustration of the burial history of the Bakken Formation in four wells (A=California Oil No. 1 Rough Creek, NDGS 527; B=Texaco No. 1 Clarence Pederson, NDGS 3363; C=Marathon Oil No. 18-44 Dobrinski, NDGS 8177; D=Placid Oil No. 36-5 Rosendahl, NDGS 6126). Upward deflections represent possible loss of section from major unconformities. Present-day geothermal gradient is plotted on the left hand side of the diagram.

Table 4-Calculation of time-temperature index (TTI) for burial history lines A and B in Figure 30.

Temp. Interval	Temp. Factor	Time (m.y.)	Interval TTI	Total TTI
Line A (California Oil No. 1 Rough Creek)				
30- 40 °C	2^{-7}	49	0.38	0.38
49- 50	2^{-6}	116	1.81	2.19
50- 60	2^{-5}	53	1.66	3.85
60- 70	2^{-4}	8	0.50	4.35
70- 80	2^{-3}	9	1.12	5.47
80- 90	2^{-2}	9	2.25	7.72
90-100	2^{-1}	9	4.50	12.22
100-110	1	9	9.00	21.22
110-120	2	10	20.00	41.22
120-130	4	56	224.00	265.22
Line B (Texaco No. 1 Clarence Pederson)				
30- 40 °C	2^{-7}	84	0.65	0.65
40- 50	2^{-6}	90	1.40	2.05
50- 60	2^{-5}	51	1.60	3.65
60- 70	2^{-4}	8	0.50	4.15
70- 80	2^{-3}	11	1.37	5.52
80- 90	2^{-2}	9	2.25	7.77
90-100	2^{-1}	11	5.50	13.27
100-110	1	9	9.00	22.27
110-120	2	54	108.00	130.27

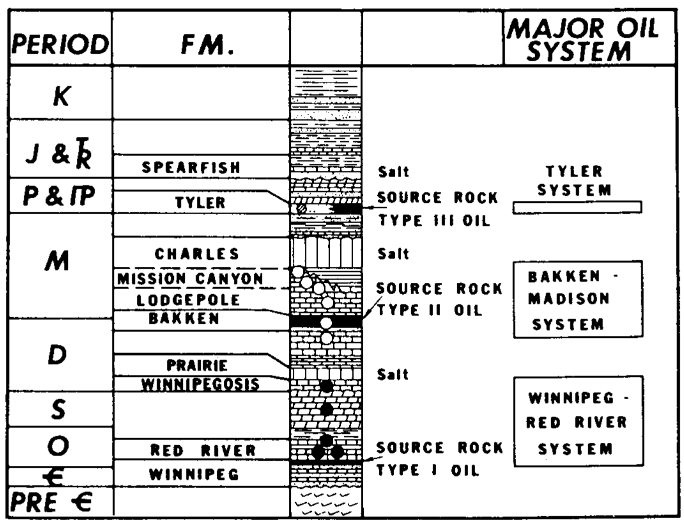

Figure 31-Schematic columnar section showing terminology, vertical distribution of source rocks and oil types of the Williston Basin (modified from Dow, 1974).

generated from a source rock assumes that laboratory pyrolysis oil generation and natural oil generation yield similar quantities of oil per acre-foot of rock. In actuality, natural oil generation is probably slightly less efficient than laboratory pyrolysis.

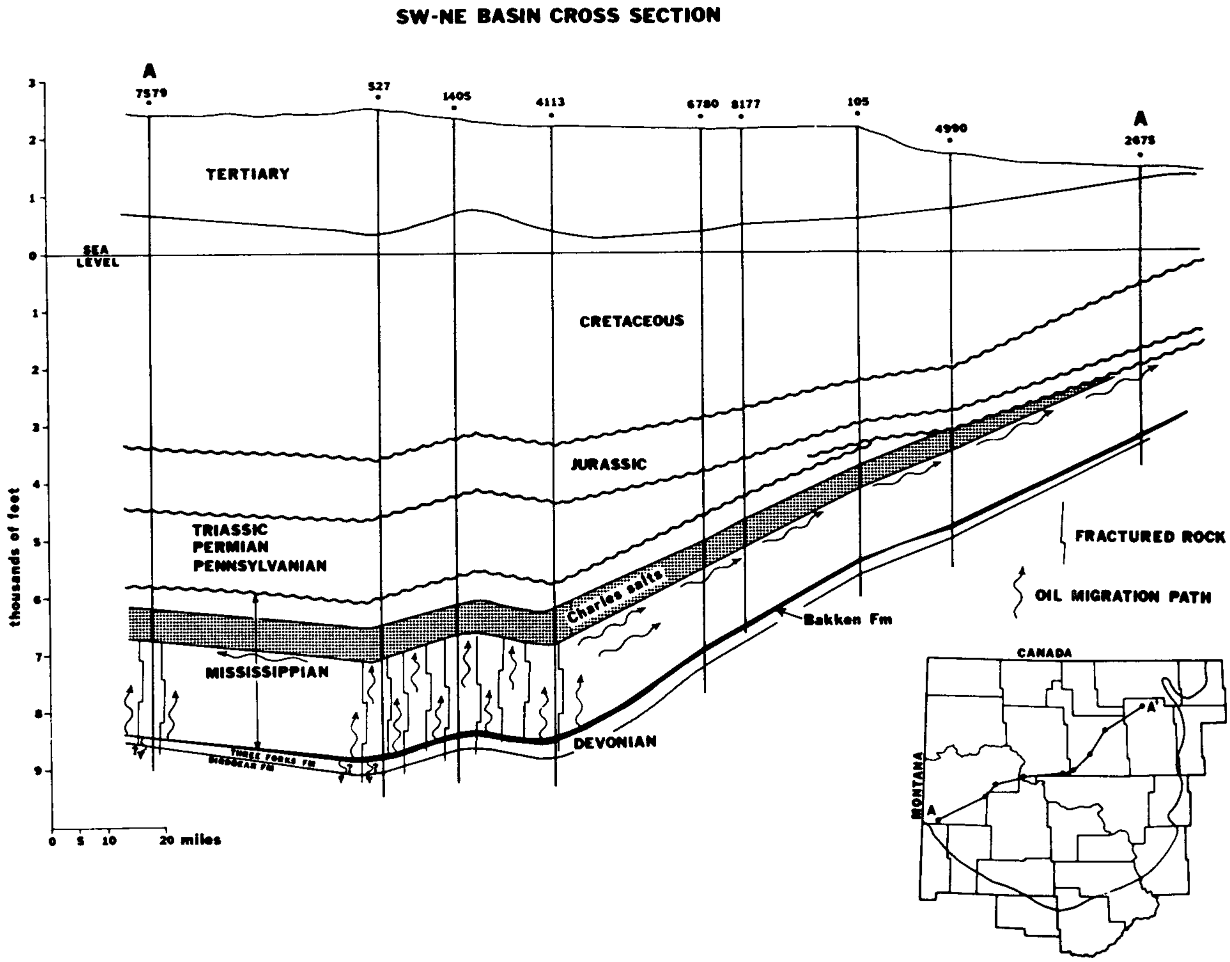

Figure 32-Regional cross section of the study area showing inferred fracture systems and migration paths of Bakken oil. Well numbers at the top of the section are those of the North Dakota Geological Survey. Major unconformities are represented by wavy lines.

The calculated total amount of oil generated by the Bakken is approximately 90 billion barrels of oil and accounts for the Bakken shale in North Dakota only. Mature Bakken in Montana probably could account for the generation of an additional 10 billion barrels of oil. According to Dow (1974) the known amount of in-place type two oil in the Williston Basin is approximately three billion barrels. If only 10% of the amount of oil generated from the Bakken in North Dakota (9.0 billion barrels) was actually expelled, it would easily account for the in-place type two oil, and leave at least 4 billion barrels as undiscovered reserves, oil lost at the surface, or noncommercial accumulations along migration pathways.

Oil Exploration in the Bakken Formation

A comparison between the areas of Bakken oil production and the areas of source-rock maturity shows nearly all of the production within the study area, to be within the intense hydrocarbon generation (mature) zone (Figure 34). The exception is the Stoneview field on the northern end of the Nesson Anticline, which lies within the early mature zone. Outside of the study area minor Bakken production has been established in the Salt Lake field of northeastern Montana (Meissner, 1978), and prolific Bakken production occurs from the Rocanville field in Saskatchewan (Von Osinski, 1970). The occurrence of most Bakken production within the intense generation zone probably results from the combination of oil produced directly from fractured and thermally mature Bakken shale, and the close proximity of the middle member to the mature shale.

As fracturing appears to be the principle factor controlling Bakken production, a logical exploration strategy for Bakken oil accumulations would concentrate on areas within the intense generation zone where fracturing could be expected (sufficient structural curvature). In this area, perforating the shales of the formation along with the middle member is recommended, as a significant portion of Bakken production may arise

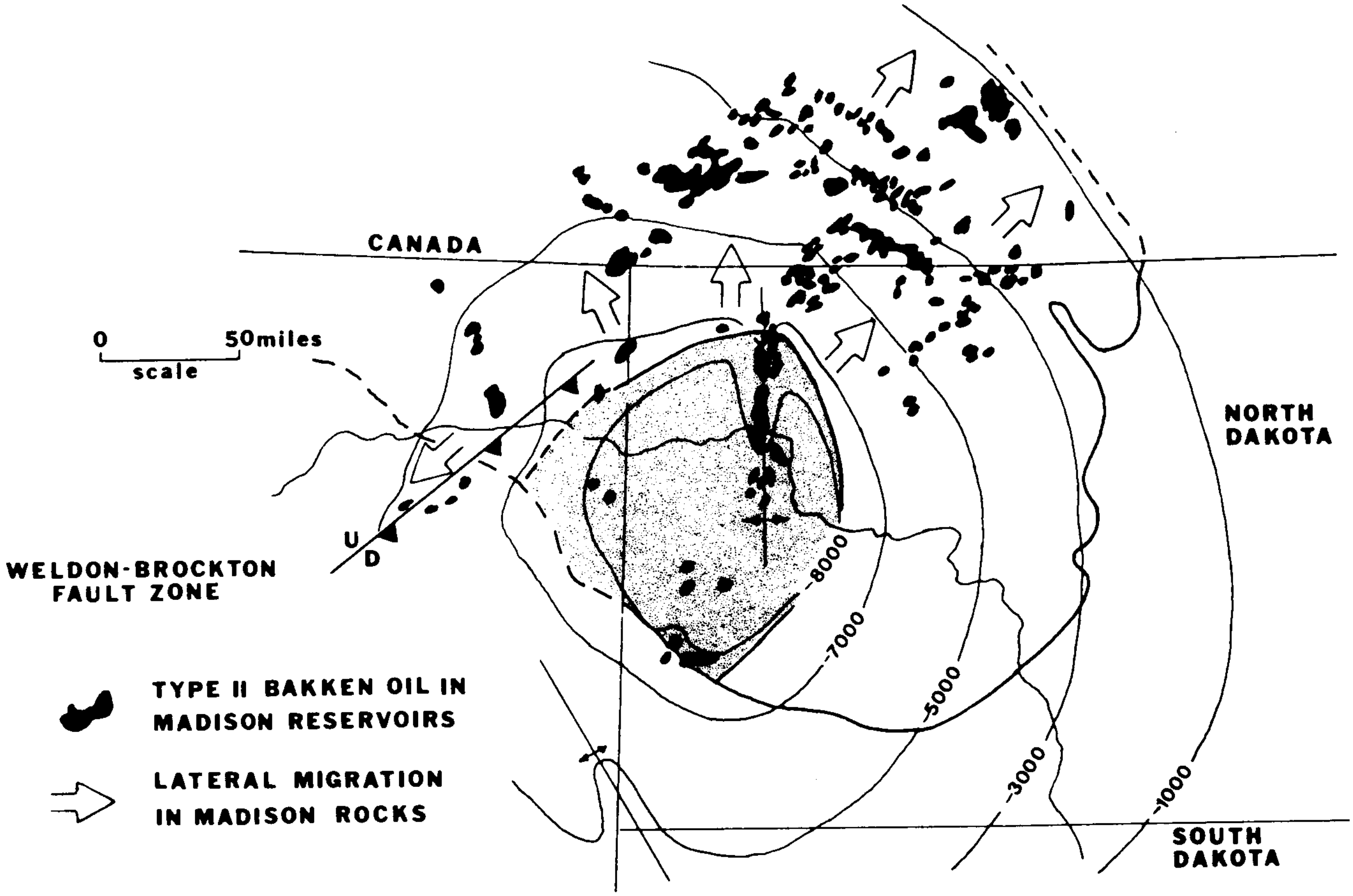

Figure 33-Bakken structure map showing distribution of type two oil in reservoirs of the Madison Group and lateral migration paths of type two oil from the effective Bakken source area (shaded) (modified from Dow, 1974).

Table 5-Results of calculations of amount of oil generated by the Bakken shales.

Maturity Area (From Figure 23)	Oil Generated	Average TOC	Yield (Bbls/Acre-Ft)	Volume of Shale (Acre-Ft)	Amt. of Oil Generated (Bbls)
		Upper Shale			
A (500-400 mgHC/gOC)	100 mgHC/gOC	5-11%	76-167	15,019,178	2,379,888,000
B (400-300 mgHC/gOC)	200 mgHC/gOC	5-13%	151-394	18,844,920	6,359,154,000
C (300-200 mgHC/gOC)	300 mgHC/gOC	5-13%	227-591	17,465,241	8,643,297,000
D (200-100 mgHC/gOC)	400 mgHC/gOC	8-13%	485-788	18,491,979	11,874,309,000
E (less than 100 mgHC/gOC)	425 mgHC/gOC	5-10%	322-644	20,919,876	13,311,821,000
				Total	42,568,469,000
		Lower Shale			
A (500-400 mgHC/gOC)	100 mgHC/gOC	10%	151	26,772,603	4,055,146,000
B (400-300 mgHC/gOC)	200 mgHC/gOC	10%	303	32,096,257	9,723,001,000
C (300-200 mgHC/gOC)	300 mgHC/gOC	10%	454	24,877,005	11,304,082,000
D (200-100 mgHC/gOC)	400 mgHC/gOC	10%	606	25,144,385	15,234,106,000
E (less than 100 mgHC/gOC)	425 mgHC/gOC	10%	644	14,631,016	9,418,449,000
				Total	49,734,784,000
				Grand Total	92,303,253,000

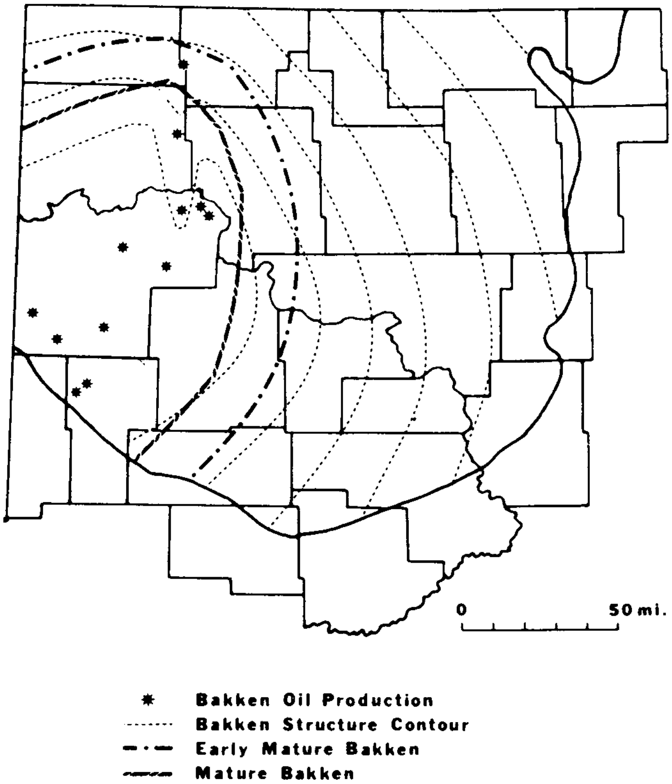

Figure 34-Map of Bakken oil production and geochemical maturity areas, with Bakken structure contours superimposed.

from fractured shale. It seems the Bakken has high oil saturations throughout the mature area and will produce oil wherever sufficient porosity is present or more importantly, where fracturing has been developed.

CONCLUSIONS

The Bakken shales were probably deposited in an offshore, marine environment where anoxic conditions were caused by a stratified water column resulting from restricted circulation. The derivation of organic matter from planktonic algae in this depositional environment resulted in very organic-rich black shales. This organic material is distributed rather evenly in the shales and not concentrated in lenses or laminations. The Bakken shales have high organic matter contents throughout their lateral extent, and high amounts of indigenous bitumen where they are immature. The amorphous-sapropelic kerogen present in these shales has a high hydrogen content and makes an excellent petroleum source material.

Hydrocarbon content and thermal kerogen breakdown increase greatly in the Bakken shales where they are buried, on the average, greater than 9,000 ft (2,740 m). The onset of hydrocarbon generation and intense hydrocarbon generation is postulated to occur at average depths of 9,000 ft (2,740 m) and 10,000 ft (3,050 m) respectively. The relationship between Bakken maturity and depth is not uniform across the basin, and deviates from a normal relation with present day structure to the north and northwest. The area of the Bakken that forms an effective source for oil lies mostly in Williams, McKenzie, Dunn, and Billings counties. Oil generation was probably initiated in the Bakken about 75 million years ago (Late Cretaceous time) at a temperature of 100°C, with initial oil expulsion from the Bakken probably occurring 70 million years ago (Late Cretaceous time). Expulsion of Bakken oil in the deep portion of the basin is suggested by low extractable hydrocarbon content where high indigenous contents would be expected.

Vertical fracture systems and faults located primarily along the Nesson, Antelope, and Billings anticlines seem the most reasonable way for oil to migrate from the Bakken into adjacent reservoir rock units. The amount of oil generated by the Bakken in North Dakota, as calculated from pyrolysis data, is 92.3 billion barrels of oil. If only 10% of this oil was actually expelled from the shales, it could easily account for the three billion barrels of in-place type two oil in the Williston Basin. Most of the present Bakken production lies within the area of intense hydrocarbon generation, and sites of fracturing of the Bakken within this area would seem to offer the greatest promise for future Bakken production.

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BRACHIOPODS AS A BIOSTRATIGRAPHIC TOOL FOR CORRELATING DEVONIAN-MISSISSIPPIAN ROCK SEQUENCES

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ABSTRACT

Zonation of brachiopod faunas that occur at or near the Devonian-Mississippian boundary in North America has become much more refined in recent years. Examination of subsurface sections of the Bakken Formation from western North Dakota, and re-evaluation of previously collected specimens from western Canada and the stratotype region of the Mississippian System in the upper Mississippi Valley have helped to discriminate two brachiopod faunas, one that appears similar to, and one that occurs in close association with, the generally distinctive *Syringothyris hannibalensis* brachiopod fauna of the upper Mississippi Valley. Conodont evidence has indicated that the *S. hannibalensis* fauna is of latest Devonian age, i.e. brachiopod fauna that occurs in close association with it is of earliest Mississippian age, and the fauna that appears similar to it is of early, but not earliest, Mississippian age.

A zonation scheme based on conodonts that has been evolving for about the past 30 years provides the chief framework for dating rocks at or near the Devonian-Mississippian boundary in North America. This scheme has become so refined over the past few years that it is now the main criterion for worldwide correlations. In turn it has greatly aided in refinement of a brachiopod zonation scheme. Used together the two schemes are proving to form a powerful means of correlating Devonian-Mississippian rocks. This is especially true for black shale sequences, which generally contain both brachiopods and conodonts and whose correlations are, in many places, still unclear after 100 years of research.

These refined correlations are leading to an ever-clearer understanding of the tectonic events that occurred at or near the systemic boundary. This research, in turn, is leading to yet another, tectonic/stratigraphic framework that is proving helpful in correlating the Devonian-Mississippian rocks. A coordinated study of the brachiopods, conodonts, and tectonic events therefore seems to have the greatest potential for resolving the numerous problems and uncertainties remaining with the correlation of the Devonian-Mississippian rocks.

INTRODUCTION

Rocks that occur at or near the boundary between the Devonian and Mississippian (or Carboniferous) Systems in North America are most commonly part of a black shale sequence. This sequence typically consists of two layers of dark gray to black shale separated vertically by a light colored layer consisting mostly of siltstone (Gutschick and Moreman, 1967). Other rock types that straddle the boundary in North America are carbonates in which case the boundary is frequently marked by an unconformity. In parts of eastern North America the boundary lies within clastic, deltaic deposits (Gutschick and Moreman, 1967).

Correlation of the black shale sequences is still not totally resolved despite over 100 years of research. In speaking of these rocks in the eastern United States, Roen et al. (1964, p. B43) wrote the 'black shale problem' ". . . concerns the nomenclature, correlation, and age of the organic-rich fine grained clastic sediments . . ." Gutschick and Moreman (1967, p. 1012) wrote, "The [Devonian-Mississippian] boundary problem [in the United States] centers on its position either in the lower

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lower black shales or within the clastic transitional beds between the black shales." Roen et al. (1964, p. B43) added, "the problems presented by the 'black shales' have been among the most difficult and the most popular in Appalachian stratigraphy."

Rocks of the black shale tripartite sequence in the east-central United States include the Ohio, Antrim, and Chattanooga Shales as the lower shale unit; the Berea Sandstone and Bedford Shale as the light colored medial unit; and primarily the Sunbury Shale as the upper shale. These mentioned units occur in the Appalachian, Illinois, and Michigan basins, the locations of which are indicated in Figure 1.

In the Western Interior the Bakken Formation contains all three units of the tripartite sequence (as shown on Figure 3), but the Exshaw Formation, Sappington Member of the Three Forks Formation (hereafter called the Sappington Member), Leatham Formation, and the Leatham Member of the Pilot Formation (hereafter called the Leatham Member) consist of black shale overlain by siltstone; thus these rock units correspond to the lower two units of the Bakken Formation. A dark shale unit that overlies the Sappington Member and the Leatham Formation, and thus is the stratigraphic equivalent of the upper Bakken shale, is called the Cottonwood Canyon Member of the Lodgepole or Madison Limestone. A dark shale unit that overlies the Exshaw Formation is the basal shale of the Banff Formation. The locations of these rocks are shown in Figure 2.

Historically, the most important macrofauna related to the determination of the systemic boundary in North America is the *Syringothyris hannibalensis* brachiopod fauna of the Louisiana Limestone (and the underlying upper Saverton Shale), found in the Mississippian stratotype region in northeastern Missouri. Because the brachiopods of the *S. hannibalensis* fauna are so distinctive from fossils in vertically adjacent beds and because the fauna has Mississippian affinities, they were

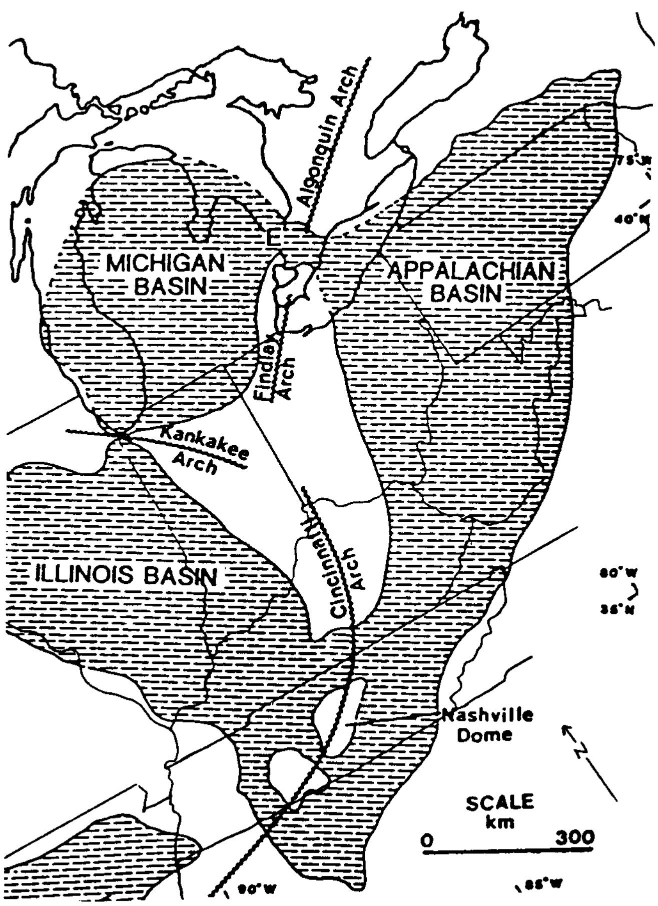

Figure 1-General distribution of upper Devonian black shales in the east-central United States, i.e. also showing major structural features, as depicted by Russel (1985). Adapted from Russel (1985).

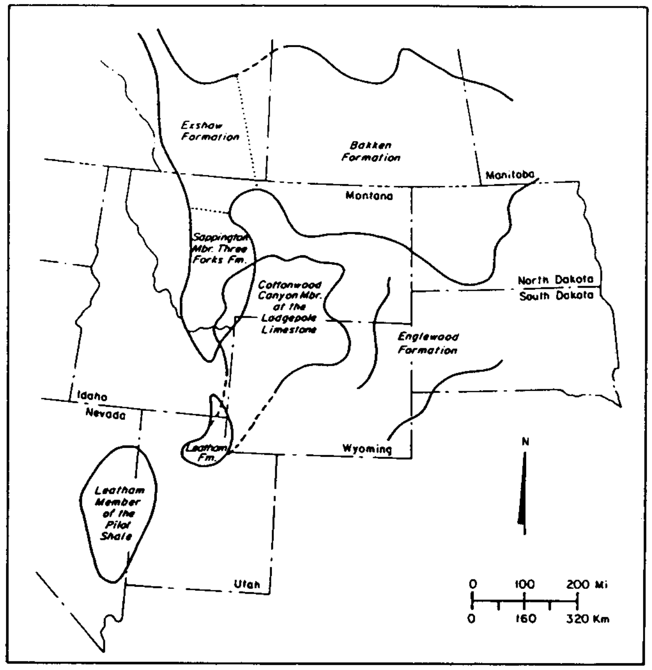

Figure 2-Approximate areal extent of the Bakken Formation and equivalent rock units in the western United States. Adopted from Hayes (1984); primary sources are Christopher (1961) and Meissner (1978) for the Bakken Formation, Macqueen and Sandberg (1970) and Gutschick and Rodriquez (1979) for the Exshaw Formation, Sappington Member of the Three Forks Formation, Leatham Formation, and Leatham Member of the Pilot Shale, Sandberg and Klapper (1967) for the Cottonwood Canyon Member of the Lodgepole or Madison Limestone, and Sandberg and Mapel (1967) for the Englewood Formation.

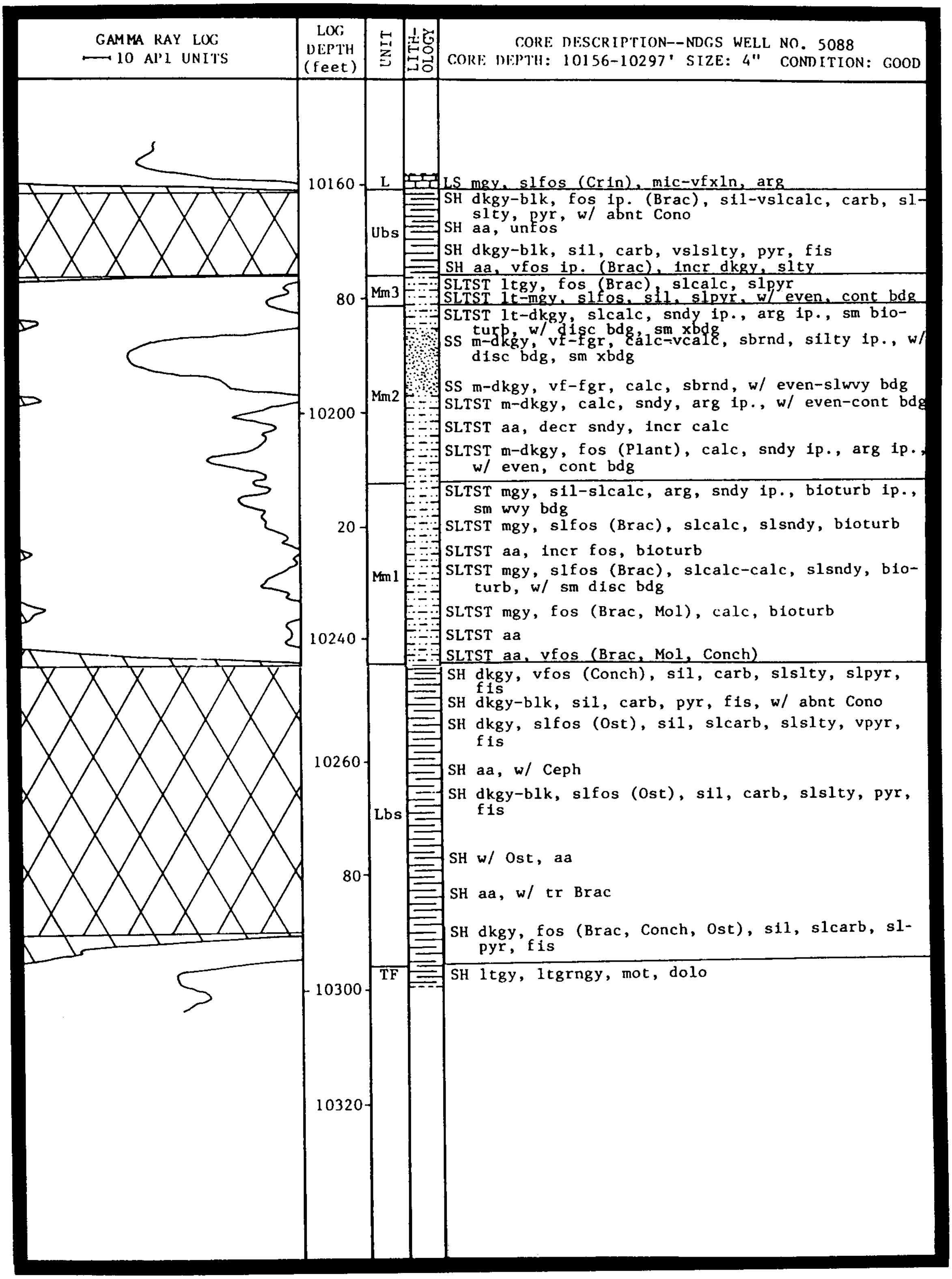

Figure 3-Core description of North Dakota Geological Survey core number 5088. Lithic abbreviations are after Mitchell and Maher (1957). The core depth shown is only of the Bakken Formation and does not include the portions of the subjacent formations also shown. Abbreviations for stratigraphic units are: TF = Three Forks Formation; Lbs and Ubs = lower and upper black shale members, respectively, of the Bakken; Mm1, Mm2, and Mm3 = units 1, 2, and 3, respectively, of the middle member of the Bakken; and L = Lodgepole Formation.

originally used to establish an earliest Mississippian age for the Louisiana Limestone. Later, conodont evidence provided by Scott and Collinson (1961) established a latest Devonian age for the Louisiana Limestone so this formation is now considered to occupy a stratigraphic position just below the Mississippian type section.

The *S. hannibalensis* fauna has been long established to occur in the lower portions of the previously mentioned siltstone units in the western United States (Gutschick and Rodriquez, 1967). For this reason, these units were originally considered to be of Mississippian age. Subsequently, the units have been regarded as being mostly Devonian with possibly some Mississippian beds at the top (Gutschick and Rodriquez, 1979).

A *Spirifer marionensis* brachiopod fauna from western Canada was named after a characteristic brachiopod of the Louisiana Limestone by Harker and Raasch (1958) and has been regarded as an equivalent of the Louisiana (Gutschick and Rodriquez, 1967). This fauna was regarded by Gutschick and Rodriquez (1967) as occurring in the lower portion of the Banff Formation, much of which (about 100 feet) was, on the basis of lithology, later reassigned to the underlying siltstone member of the Exshaw Formation by Macqueen and Sandberg (1970). Even before this reassignment, fossils of the Exshaw siltstone had variously been compared with those of the Louisiana (Harker and McLaren, 1958). A correlation of the Exshaw or Banff with the Louisiana later became controversial, however, because Macqueen and Sandberg (1970) showed that the Exshaw siltstone unit contains conodonts of early, but not earliest, Mississippian age, making the Exshaw siltstone significantly younger than the latest Devonian Louisiana Limestone.

Over the past 30 years or so, a conodont zonation scheme that has its basis in the scheme used to assign a latest Devonian age to the Louisiana has evolved into the chief worldwide framework for dating rocks that occur near the Devonian-Mississippian boundary. Carter (1988, p. 8) wrote of this scheme,

> In recent years, the widespread use of conodont faunal zones, based upon worldwide conodont distributions including those of western Europe, has revolutionized the means for discrimination of this critical [Devonian-Carboniferous] boundary. Sandberg et al. (1972) first proposed the modern international conodont zonal scheme for this boundary . . . This zonation is now adopted by the IUGS Subcommission on the Devonian-Carboniferous boundary stratotype as the primary means of recognizing the boundary in the northern hemisphere.

DISCUSSION

When Scott and Collinson (1961) determined a Devonian age for the Louisiana Limestone, they also found that the only formation in the stratotype region of the Mississippian System (the upper Mississippi valley) to have ever been confused with the Louisiana, the McCraney Limestone, was of Mississippian age. The McCraney was the only formation of the region to have the same characteristic lithographic texture as the Louisiana and carried a similar brachiopod fauna. Based on these two factors, many workers, such as Stainbrock (1950), had considered the Louisiana and McCraney to be equivalent units. Scott and Collinson (1961, p. 110-111) summarized the controversy of the Louisiana and McCraney as follows,

> Few Paleozoic formations in recent years have been subject to more disagreement concerning their age and correlation than have the Louisiana and McCraney Limestones . . . The remarkable lithic similarity of the two formations indicates that they represent similar environmental conditions. It is not surprising therefore that the benthonic faunas of the two formations are also so similar.

Another reason for the confusion between the *S. hannibalensis* fauna and the McCraney fauna reported by Scott and Collinson (1961) is that, the two formations, though occurring in the same general area, have never been identified in the same section.

Because many workers had considered the McCraney to be a part of the Louisiana, and the Louisiana fauna (*S. hannibalensis*) was considered to be quite distinct from other faunas in the region, Scott and Collinson (1961), in effect, showed that the latest Devonian Louisiana fauna was not as unique as previously thought.

In a similar way, conodont evidence from the Exshaw was instrumental in determining that the *Spirifer marionensis* brachiopod fauna of western Canada constitutes yet another fauna that had been previously compared with the fauna of the Louisiana but later shown to be of a significantly younger Mississippian age.

This was the state of affairs at the time when Bud Holland and I began a study of the macrofossils of the Bakken Formation of North Dakota. The different ages of the Louisiana and McCraney were well established but the *Spirifer marionensis* fauna was caught in an impasse of apparently having early Mississippian conodonts and brachiopods resembling the Devonian fauna of the Louisiana Limestone. The Bakken Formation was formally described in 1953 and its stratigraphy has been poorly understood due largely to the fact that the formation occurs entirely in the subsurface. Initial paleontological studies in the late 1950's and early 1960's had indicated that the siltstone, or middle member carried the *S. hannibalensis* fauna (Brindle, 1960; Christopher, 1961). This fauna was used to establish a Mississippian age for the Bakken siltstone. Most workers have generally regarded the middle member to be a single, homogenous bed. Only Christopher (1961) noted distinct beds within the siltstone member in Saskatchewan (which he subdivided into an A bed overlain by a B bed) and Penner (1958) noted a biostromal unit at the base of the middle member in Alberta which he treated as a fourth member of the Bakken.

Work on the Bakken essentially came to a stop in the early sixties and did not start again until the late seventies when Holland initiated a series of studies on the formation in North Dakota. By the time I started my study on the formation, in 1981, nearly 40 cores representing about 1500 feet of core of the Bakken had accumulated at the Wilson M. Laird Core and Sample Library in Grand Forks, North Dakota. Studies on the conodonts of the cores were conducted under Holland's guidance by Hayes (1984) and Huber (1986). Webster (1982) completed a core study on the general stratigraphy and petroleum geology of the formation.

I completed my study in 1985; a biostratigraphic summary of the results is shown as Figure 4. The present paper particularly concerns the presence of two brachiopod faunas found in the middle member. They appear to represent a first occurrence of a Devonian Louisiana fauna and a Mississippian fauna similar to it in the same section. A comparison of these two faunas is shown as Figure 5. The older fauna typically occupies the basal 40 percent of the siltstone member (up to about 30 feet thick) and the younger is in the upper 5 to 10 feet of the member. These faunas were used in part to designate three informal stratigraphic units within the siltstone member. Unit 1, the lowermost, contains the *S. hannibalensis* brachiopod fauna. Unit 2 comprises about 50 percent (up to about 40 feet) of the member and is generally unfossiliferous. It does, however, carry a concentration of terrigenous plant remains in its basal few feet. Unit 3, the top of the member, carries about one half the brachiopod species found in unit 1 but also contains a number of other species not found in unit 1 and a few not known from pre-Mississippian rocks (Figure 5). The general area where these units occur in North Dakota is indicated on Figure 6.

The Devonian-Mississippian boundary in the Bakken thus apparently lies somewhere between the base of unit 2 and the base of unit 3. I choose the base of unit 2 as the boundary largely because of a) The transgressive nature of the unit. The Devonian is thought to have ended with a major worldwide regression, resulting in mass extinctions (Sandberg et al., 1989). The transgressive nature of unit 2 is sharply contrasted by the regressive beds seen in the underlying unit 1; unit 1 has the smallest geographic extent of the Bakken in North Dakota (Figure 6). b) Terrigenous plant remains very similar to those found at the base of unit 2 occur at the base of the Mississippian stratotype section in western Illinois (Conkin and Conkin, 1973). c) I correlated the brachiopods of unit 3 with those of the Exshaw siltstone and McCraney Formation, both of early, but not earliest, Mississippian age. d) It seems more likely that a span of earliest Mississippian time is represented by unit 2 rather than there being an hiatus spanning earliest Mississippian time at the top of unit 2. No evidence of an hiatus was seen in the contact between units 2 and 3 in the cores; the contact appeared transitional and conformable.

My correlation of unit 3 with the Exshaw has recently been used by Raasch (1987) to help resolve the correlation conflicts of the Exshaw siltstone (the "Exshaw problem"). He summarized the problem (p. 628) in his discussion of the biostratigraphy of the Mount Arete section of the Exshaw siltstone in Alberta as follows,

> In contradiction to the seemingly incontrovertible evidence of the brachiopods, constituting an assemblage remarkably similar to those of the Louisiana and Sappington Formations and the Lower Unit of the Middle Member of the Bakken Formation, is the identification of *Siphonodella duplicata*, an early but not earliest Mississippian conodont . . . A possible explanation for this seeming anomaly is suggested by the findings of Thrasher (1987) in North Dakota . . . In the absence of the intervening 35-foot unit 2 [of the Bakken], the siltstones [of units 1 and 3] might easily have been interpreted as a single unit containing both latest Devonian and early Mississippian species. In the case of the Mount Arete occurrence, it is suggested that not only is this the case, but that the Devonian megafossils are part of a lag deposit incorporated in a younger, clastic matrix.

Thus he suggested that the Exshaw siltstone, like the Bakken siltstone, contains two similar-appearing brachiopod faunas, one that correlates with the Devonian Louisiana Limestone, the other a Mississippian fauna. He concluded (p. 39) that, for the Exshaw, " . . . it is conceivable that, from a regional aspect, units of differing ages may occur at different places on either side of the Devonian-Mississippian unconformity." This work of Raasch (1987) is evidently the first Canadian work to fully discuss the "Exshaw problem" and the first to offer a solution for it.

Brachiopods and the modern conodont scheme have also recently been used by Carter (1988) to clarify the

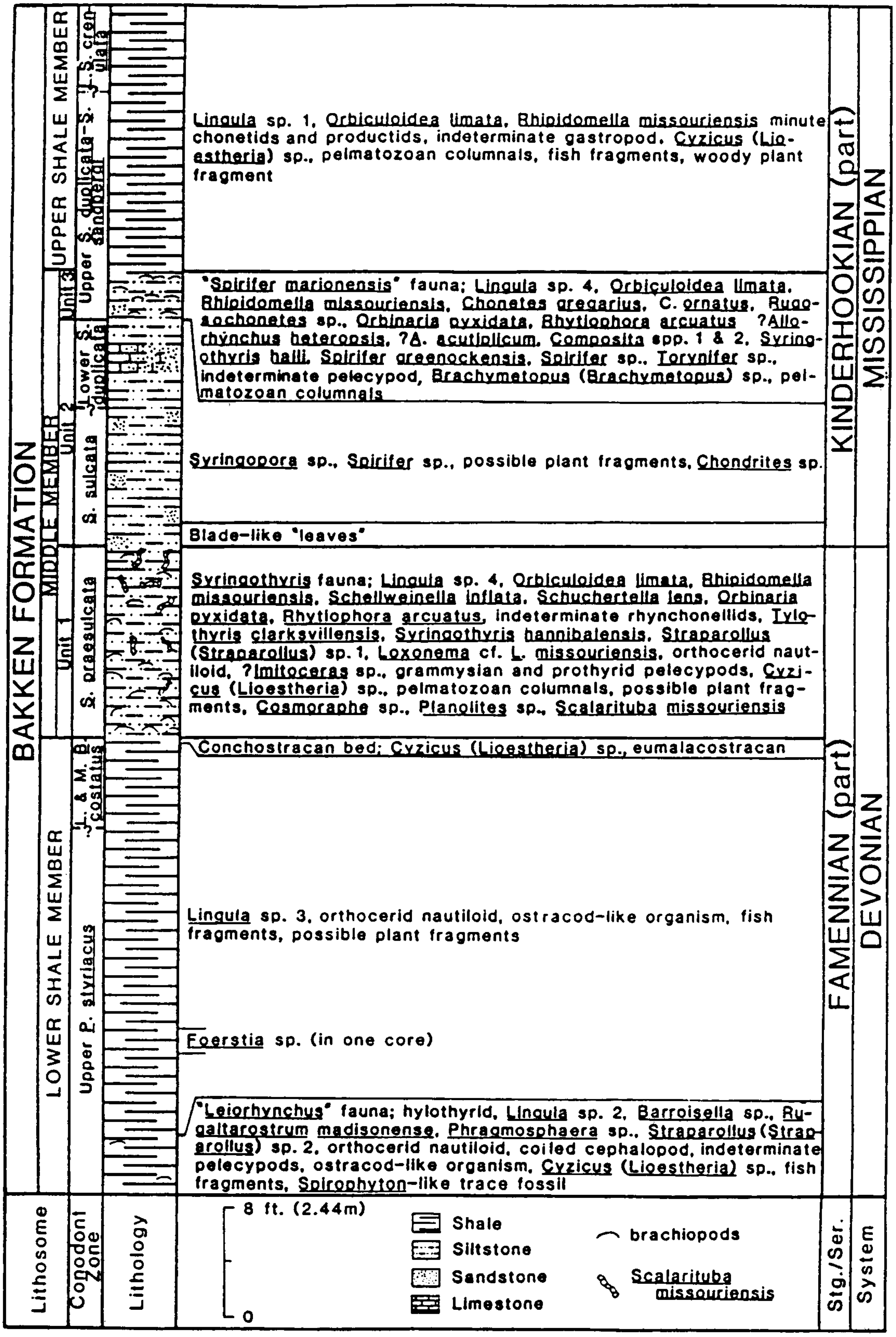

Figure 4-Composite core section showing the stratigraphic distribution of the macrofossils of the Bakken Formation in western North Dakota. Thicknesses of rock units are based on those of the type section. Conodont zones are those of Sandberg, 1979.

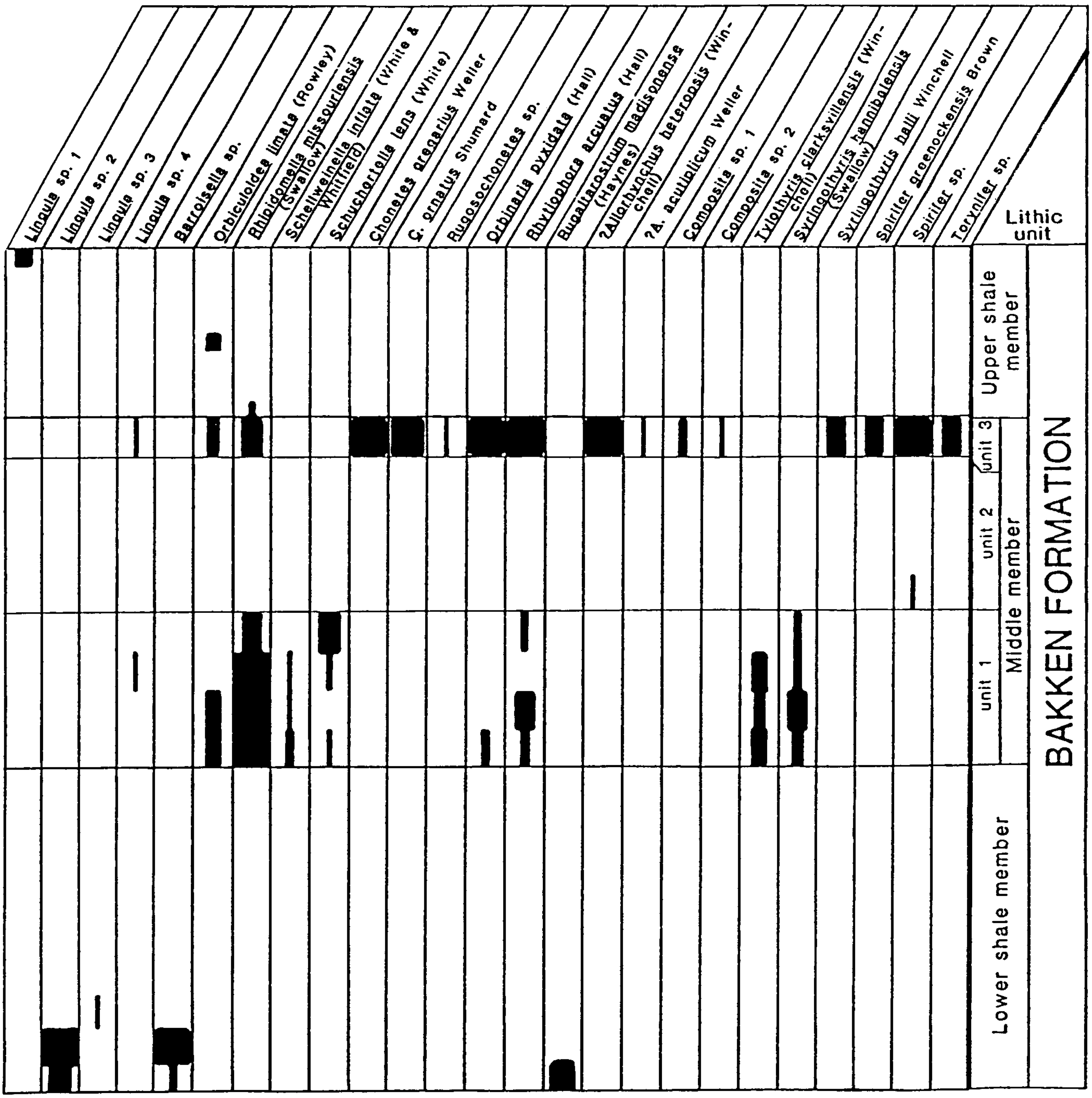

Figure 5-Fauna occurrence chart in the Bakken Formation. Widths of filled columns are proportional to number of specimens found at each stratigraphic level. Filled columns represent 10 or more specimens. The upper and lower shale members are broken into 10 stratigraphic levels, units 1 and 2 into four levels; unit 3 was not subdivided. Thicknesses of rock units are proportional to those of the type section.

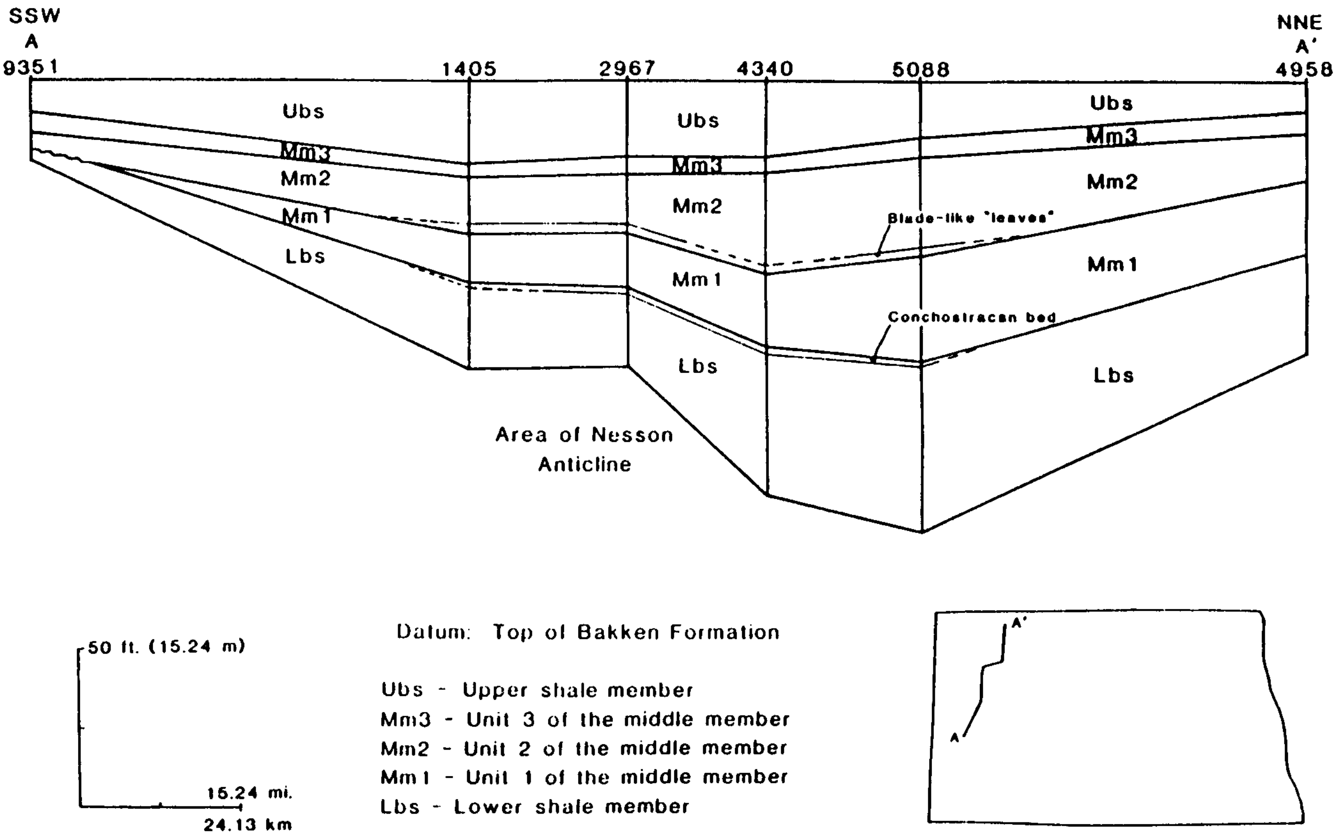

Figure 6-Stratigraphic cross section of the Bakken Formation, in western North Dakota. Well numbers are those of the North Dakota Geological Survey.

stratigraphic relationships of the Glen Park Formation which immediately overlies the Louisiana Limestone. By correlating an earliest Mississippian brachiopod assemblage within the framework of the modern conodont zonation scheme, he demonstrated that the type section of the Glen Park Formation in Missouri, long considered Devonian, was actually early Mississippian in age. Carter (1988) assigned the Glen Park Formation of northeastern Missouri, the "Glen Park", Horton Creek, and Hamburg Oolite of western Illinois, and the English River of southeastern Iowa to the *Siphonodella sulcata* conodont zone of earliest Mississippian age. He retained the name Glen Park for all these beds in Missouri and Illinois, and considered the English River to be a near-shore, sandy facies of the other beds.

Carter (1988, p. 13) also noted that the Louisiana Limestone contains the Devonian fauna most similar to that of the Glen Park, as 12 genera extend upward from the Louisiana into the Glen Park. He stressed the great difference between the faunas, however, partly by noting that 15 genera of brachiopods in the Glen Park-English River complex date back to the Devonian but that, "No fewer than 25 genera of articulate brachiopods occur first in the Glen Park Formation."

Future Studies

As brachiopod faunas become better defined and incorporated into the modern conodont zonation scheme, they become better tools for dating the rocks in the latest Devonian to early Mississippian interval. A careful comparison of the taxa found in the Louisiana, Glen Park, and McCraney and their equivalents may result in a better understanding of the evolution of brachiopods across the Devonian-Mississippian boundary. The ability to determine a few key index fossils from the best collected faunas may also become important for dating many sparsely fossiliferous rocks that occur near this boundary.

Conodont studies taking place by Sandberg et al. (1989) are suggesting that brachiopods in the upper siltstone beds of the Sappington, which have never been correlated with the Louisiana fauna, are indeed of Devonian age. Sandberg (1991, pers. com.) nevertheless accepts a probable Mississippian age for the brachiopods in the upper beds (unit 3) of the Bakken middle member.

Other applications of the modern conodont zonation scheme are currently on-going across the continent. A recent study by Sando and Sandberg (1987) has resulted in a whole new interpretation of the stratigraphy of southeast Wyoming. On the basis of conodonts, they assigned several outcrops of the Madison Limestone to the Englewood Formation and noted (p. 10) that the Englewood ". . . probably has a much wider distribution . . . in southern Wyoming than formerly recognized." On the basis of conodonts, they picked the Devonian-Mississippian boundary in the Englewood at an unconformity within the upper few feet of the top of the formation (p. 10, pl. 2). Sando and Sandberg speak confidently of their correlation and nowhere do they say that the correlations need further confirmation.

Raasch (1987, p. 625) noted that little has been published on Famennian (late Late Devonian) conodonts of western Canada but briefly mentioned some encouraging ongoing activity. Work et al. (1988, p. 772) have recently noted a core of Hannibal Shale, which immediately overlies the Glen Park, from Missouri that appears to have early but not earliest, Mississippian conodonts; they noted (p. 772), "A comprehensive study of the succession of conodont faunas recovered from this core is in progress . . ." House et al. (1986, p. 126) noted that, "the Lower Carboniferous record is surprisingly good in the Ohio areas . . . the sequence is thick, and the potential for documenting events across the Devonian/Carboniferous boundary is considerable, yet the area has been largely overlooked in this regard."

There is continuing confusion concerning the exact age of the McCraney Limestone. Carter (1988, pers comm.) noted that the McCraney of Illinois may not be of the exact age as the McCraney in Iowa: he considered both to be roughly of Hannibal age, however. Thompson (1986) wrote of a significantly younger Chouteau age for the McCraney in Illinois and described a "McCraney-like" limestone in Missouri that overlies the Chouteau Group. Although fossils are rare in most of the McCraney, the modern brachiopod and conodont zonation schemes seem promising to help further refine the age relationships of this formation.

The area that is currently perhaps the most ripe for fruitful investigation is studying the Devonian-Mississippian black shales in terms of the modern conodont zonation scheme. The conodont ages of the black shales in the Western Interior region are generally well documented but, although conodonts are generally common and well preserved (Gutschick and Moreman, 1967), there seems to be a general lack of conodont dating for these rocks in the east-central United States. Because conodonts are the principal dating method for the western black shales, direct comparisons of their ages with those in the east-central United States are thus difficult to determine.

One example of an issue regarding the age relationships of the western black shales with those in the east is the current uncertainty in the placement of the *Foerstia* zone within the modern conodont zonation scheme. *Foerstia* is a supposed pelagic algal form that ". . . marks a time zone within late Devonian shale sequences in the eastern United States" (Mathews, 1986, p. 1068). *Foerstia* has also been found in the Michigan basin (Mathews, 1983) and, in western North America, in the Exshaw shale member (Cross, 1982) and the Bakken lower shale member (Thrasher, 1987). *Foerstia* always occurs within the basal portions of the black shales which, in the Western Interior (i.e., the Exshaw and Bakken) occurs in rocks dated by conodonts as late Famennian (late Late Devonian) whereas the basal portions of the eastern black shales, many of which contain *Foerstia*, have been variously regarded as being as old as late Frasnian (early Late Devonian).

Work is currently underway on both the dating of the eastern black shales in general and *Foerstia* in particular in terms of the modern conodont scheme (Sandberg, 1991, pers. com.).

Further conodont studies of the western black shales might help to resolve some current regional uncertainties regarding their age and correlation. For example, a conchostracan bed at the top of the shale unit of the Sappington Member, Leatham Formation, and Leatham Member has been demonstrated by conodonts to be the same very late Devonian age throughout, but conodonts have shown this bed in the top portions of the Exshaw shale member in Canada to be of early Mississippian age. While the age of the Bakken lower shale has been well dated as late Famennian by the conodont studies of Hayes (1984) and Huber (1986), the conodont age of a conchostracan bed that occurs at the top of the member (Thrasher, 1987) has not been treated separately from the rest of the member. Such a determination could potentially yield more insight on the temporal relationships of this conchostracan bed in the Western Interior.

As the modern conodont zonation has become more refined, it has formed a powerful tool for dating tectonic events. Based in part on the conodont zones, Sandberg et al. (1983, p. 696) interpreted "a sequence of 20 eustatic changes and epeirogenic events" that straddle the Devonian-Mississippian boundary in the western United States. This work of Sandberg et al. (1983) has recently been updated (Sandberg et al., 1989) but was received too late to be incorporated into this paper. Event 12 of the 1983 study is the major eustatic regression that marks the end of the Devonian. This regression is seen in the siltstone members of the Sappington Member, Leatham Formation, Leatham Member, and unit 1 of the Bakken. Raasch (1988, pers comm.) speculated that the differences seen between the late Devonian and early Mississippian brachiopod faunas is related to this regression. If this regression can be traced into the eastern United States, it alone might be used to explain relationships there. The Berea Sandstone of the east-central United States, for example, is mostly unfossiliferous and is variously considered to be late Devonian and/or Mississippian in age. Because this unit is transgressive in some places and regressive in others, its age might be determined solely by its lithostratigraphic relations with adjacent beds.

SUMMARY

An ever-increasing refinement of a conodont zonation scheme has led to a method of worldwide correlation and has greatly facilitated the discrimination of several brachiopod faunas that occur at or near the Devonian-Mississippian boundary. The conodont and brachiopod faunas are showing tremendous potential to clarify rock relationships that had been largely heretofore unresolved. The refinement of the conodont and brachiopod zones has also helped gain an understanding of the tectonic events that occurred at or near the Devonian-Mississippian boundary; knowledge of these events also has potential for aiding correlation of these rocks.

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TYLEROCARIS HOLLANDI N. GEN., N. SP. (MALACOSTRACA: TEALLIOCARIDIDAE) FROM THE TYLER FORMATION (PENNSYLVANIAN) OF NORTH DAKOTA

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ABSTRACT

A new genus and species of pygocephalomorph malacostracan, *Tylerocaris hollandi*, is described from the Tyler Formation (Pennsylvanian) of North Dakota. The species extends the stratigraphic and geographic ranges of the family Tealliocarididae known previously only from the Mississippian of France and Scotland. It is the first reported tealliocarid of Pennsylvanian age and the first occurrence of the family in North America.

INTRODUCTION

The purpose of this paper is to describe a new genus and species of pygocephalomorph malacostracan and to suggest its phylogenetic relationship to other genera in the families Tealliocarididae and Pygocephalidae. *Tylerocaris hollandi* n. gen., n. sp. is based on material collected by Harold C. Ziebarth from the cored interval of the Tyler Formation in North Dakota Geological Survey well 2667 (Texaco Inc. Government - Mary Pace #1, SW 1/4 NW 1/4 sec. 14, T. 146 N., R. 101 W., McKenzie County, North Dakota). The type specimens are from the upper one-half of the Tyler Formation and are in a shale that is grayish black (N2, dry) in color (Goddard et al., 1948).

The Tyler Formation underlies most of the western one-half of North Dakota. It is underlain by either the Kibbey, Otter or Madison Formations (Mississippian) and is overlain by the predominantly clastic Amsden Formation of Pennsylvanian age. In North Dakota the Tyler Formation is 0-82 m (0-270 ft) thick. The unit is thickest in the northwestern part of the state and generally thins to the south and east. It is commonly about 46 m (150 ft) thick. Shale is the dominant lithology of the Tyler. Limestone, sandstone and locally, siltstone, silty to calcareous mudstone, anhydrite, and coal are present. For detailed coverage of the Tyler the following papers should be read: Harris (1958), Foster (1961), Willis (1959), Ziebarth (1962, 1964, and 1972), Brooks (1962), Roux and Schindler (1973), Campau and Loranger (1976), Land (1976, 1979), Grenda (1977, 1978a, and 1978b), Sturm (1982, 1983), and Maughan (1984).

Species found on the same bedding plane with *Tylerocaris hollandi* n. gen., n. sp. include *Lingula carbonaria* and *Aviculopecten eaglensis*. Taxa collected in the same sampled interval, depth 2486.6 m (8158.5 ft) to 2487 m (8160 ft), include *Rhombopora*? sp., *Lingula carbonaria*, brachiopod spines, *Plicochonetes dotus*, *Aviculopecten eaglensis*, *A. phosphaticus*, *Limipecten otterensis*, the conodont form species *Hindeodella ensis*, *H. montanaensis*, *H. pachymandala*, *H.* sp. indet., *Neoprionodus singularis*, *N. varians*, *Hibbardella ortha*, *Prioniodina montanaensis*, *Ozarkodina compressa*, *Gnathodus commutatus*, conodont bar-type, blade-type, and platform-type fragments, conodont natural assemblages, and a paleoniscoid fish scale and tooth.

Four faunal communities are recognized in the Tyler Formation (Grenda, 1977, 1978b) and names proposed for them were based on their dominant fossil constituents. Progressing from the shoreline to deeper water and open marine conditions are the *Anthraconaia-Cyzicus* (*Lioestheria*) Community, the *Lingula* Community, the *Aviculopecten* Community, and the *Eolissochonetes* Community. *Tylerocaris*

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hollandi n. gen., n. sp. is a member of the *Aviculopecten* Community. Dominant taxa in this community include *Aviculopecten eaglensis* and *A. phosphaticus*.

The following abbreviations are used in the remainder of this paper: A = University of North Dakota Accession file; NDGS = North Dakota Geological Survey; USNM = U.S. National Museum of Natural History.

SYSTEMATIC PALEONTOLOGY

Class **MALACOSTRACA** Latreille, 1806
Subclass **EUMALACOSTRACA** Grobben, 1892
Superorder **PERACARIDA** Calman, 1904
Order **MYSIDACEA** Boas, 1883
Suborder **PYGOCEPHALOMORHA** Beurlen, 1930
Family **TEALLIOCARIDIDAE** Brooks, 1962
(emend. herein)

Diagnosis.--Carapace with three to five prominent longitudinal keels, anterolateral spines, if present, small; abdominal tergites keeled to unkeeled; median process of telson lobate or absent.

Range and occurrence.--Mississippian to Pennsylvanian of France, Scotland and North America.

Genus ***Tylerocaris*** n. gen.

Type species.--*Tylerocaris hollandi* Grenda, n. sp.

Etymology.--*Tyler* (Tyler Formation) and Latin *caris* f., (shrimp).

Diagnosis.--Pygocephalomorph with smooth carapace; anterolateral spines absent; branchiostegal keels, single pair of lateral keels, and median keel well developed on carapace; anterolateral and posterolateral junctions of carapace rounded; sternal processes present; telson triangular with nodose median and nodose lateral margin keels.

Comparison.--*Tylerocaris* exhibits morphologic characters that suggest it is phylogenetically related to *Tealliocaris*, *Pseudotealliocaris* and *Anthracaris*. *Tylerocaris* has five carapace keels, keeled abdominal tergites, keeled telson, and a smooth carapace, whereas *Tealliocaris* has three carapace keels, unkeeled abdominal tergites, unkeeled telson, and a papillose or tuberculate carapace. *Pseudotealliocaris* has anterolateral spines, seven carapace keels, a posteriorly-oriented cervical groove, and a punctate carapace, whereas *Tylerocaris* lacks anterolateral spines, has five carapace keels, a transverse cervical groove, and a smooth carapace. *Tylerocaris* lacks branchiostegal serrations, hepatic spines, and anterolateral spines, whereas all these characters are present in *Anthracaris*. *Anthracaris* also has three carapace keels in contrast to five in *Tylerocaris*.

Pseudogalathea, *Tealliocaris*, and *Tylerocaris* are the three genera herein recognized in Tealliocarididae. *Pseudogalathea* has anterolateral spines and a very prominent posterolateral junction of the carapace. These characters are lacking in *Tylerocaris*.

Pseudotealliocaris, *Anthracaris*, *Pygocephalus*, *Mamayocaris* and *Bellocaris* are the five genera recognized in Pygocephalidae. *Pygocephalus* and *Mamayocaris* have anterolateral spines and branchiostegal serrations, whereas these are absent in *Tylerocaris*. *Bellocaris* has double gastric spines and anterolateral spines, both of which are absent in *Tylerocaris*.

Tylerocaris hollandi n. sp.
Figures 1, 2

Diagnosis.--By monotypy, same as genus.

Etymology.--Named in honor of Dr. F. D. Holland, Jr., Professor Emeritus of Geology at the University of North Dakota.

Description of material.--Three specimens of *Tylerocaris hollandi* were found in the Tyler Formation of North Dakota. The best preserved and most complete specimen is designated the holotype (USNM 442090). The other two specimens are designated paratypes (USNM 442091, 442092).

The holotype is nearly complete except for lacking appendages on the thorax. The specimen is oriented dorsal side upward on the bedding plane; it is flattened and has sternal features impressed upward onto the dorsal surface of the carapace. Approximately 3.0 mm of the posterior part of the right flagellum is preserved. The posterior 3.0 mm of the left flagellum is present, a portion 3.0 mm in length is missing, and the anterior 4.0 mm is present. This indicates that the flagella were approximately 10.0 mm long. Antennules are not preserved. Antennal scales are large and setate anteriorly. A round, distinct patch (approximately 1.0 mm in diameter) of darker colored material is present on each side of the rostrum and probably represents eye pigment.

The rostrum is triangular and wide (width 1.5 mm, length approximately 2.0 mm) posteriorly. The anterior edge of the carapace has a slight keel and this keel continues around the periphery of the rostrum. The anteriormost portion of the rostrum has part of a median keel preserved. The median keel was continu-

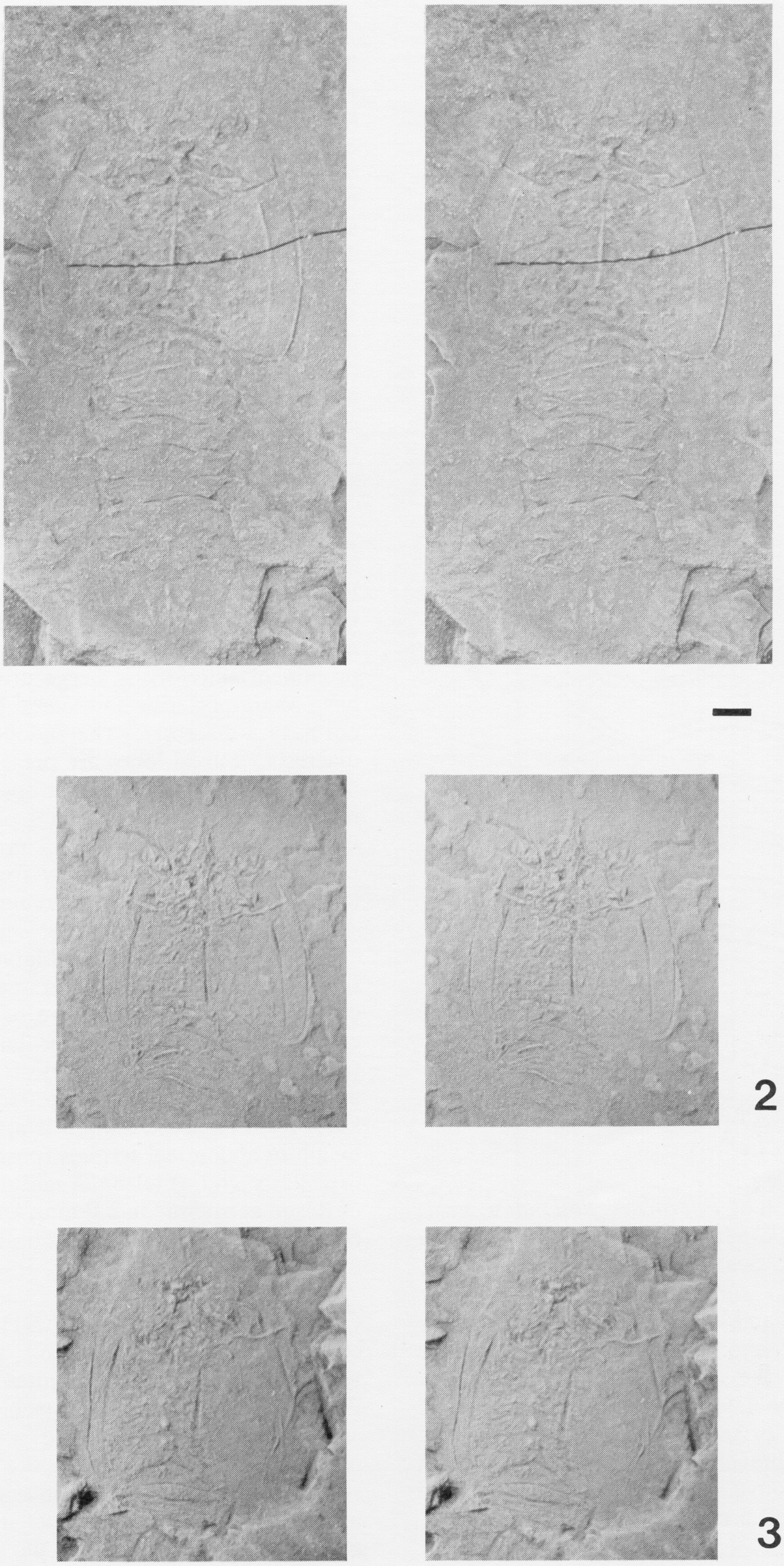

Figure 1-*Tylerocaris hollandi* n. gen., n. sp. from the Tyler Formation (Pennsylvanian), North Dakota. 1. holotype, USNM 442090, stereopair of dorsal view. 2. paratype, USNM 442091, stereopair of dorsal view of a mold of the exterior. 3. paratype, USNM 442092, stereopair of ventral view of a mold of the exterior. Scale bar equals 1 mm.

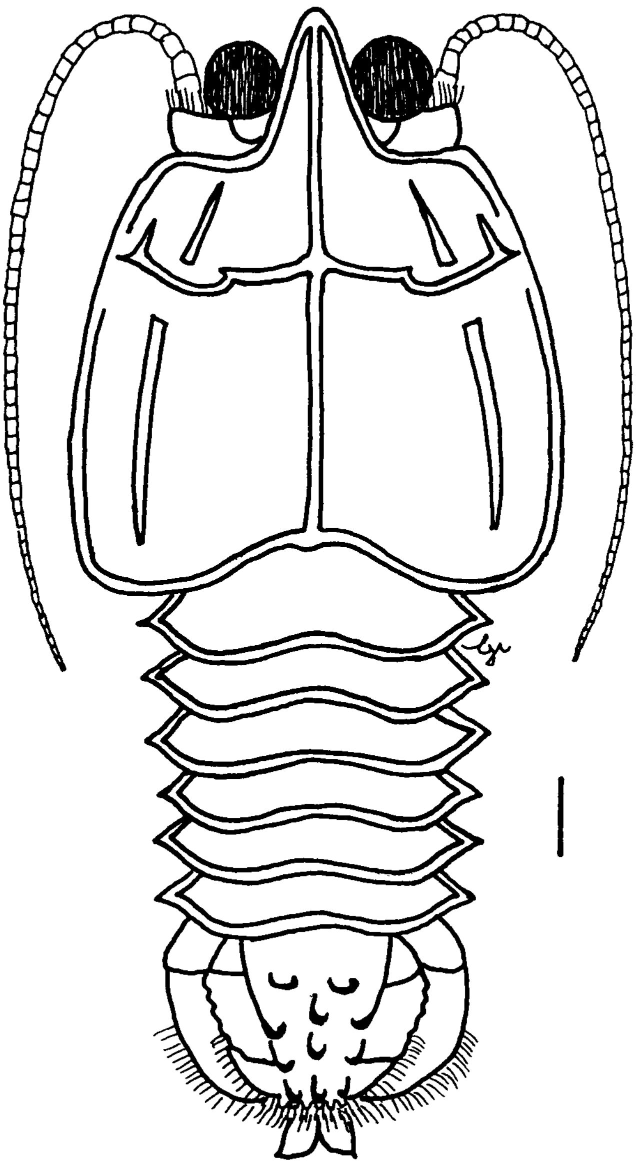

Figure 2-Reconstruction of *Tylerocaris hollandi* n. gen., n. sp. from the Tyler Formation (Pennsylvanian), North Dakota. Dorsal view. Scale bar equals 1 mm.

ous across the rostrum and is not evident because it was obscured by the impression of ventral features in the median dorsal part of the carapace. It is present and continuous on paratype USNM 442091. The cervical groove is transversely oriented across the carapace and extends almost to the branchiostegal keels. At its most lateral extent the groove bends 90° anteriorly and extends approximately 0.5 mm before it terminates.

Anterior and posterior margins of the carapace are keeled. The branchiostegal keels continue around the anterior and posterior margins of the carapace, but become less prominent along the anterior margin. The junction of the anterolateral margins of the carapace and the junction of the posterolateral margins are both smoothly curved. The lateral margins of the carapace are very gently curved. A single pair of lateral keels are parallel to the lateral margins of the carapace, become slightly more prominent anteriorly, and end approximately 0.5 mm posterior of the cervical groove. The keels are 1.0 mm from the lateral edges of the carapace. Anterior to the cervical groove, the lateral keels continue as spine-like protrusions, which I interpret as gastric spines. The median keel becomes less prominent anteriorly. It extends from the posterior margin of the carapace to the cervical groove and then continues anterior of the cervical groove to the tip of the rostrum. Lateral portions of exopods and thoracic sternites are visible in the middle area of the carapace.

Six, keeled abdominal tergites are present with the keel located around the peripheral edge of each tergite. Pleural lobes of the tergites are pointed. The telson is triangular, has a nodose median keel, and slight, nodose lateral keels. The lateral keels become more prominent anteriorly. Large uropods are present and have setate posterior and lateral borders. Exopods do not have a diaeresis. The endopods have a transverse diaeresis. Furcal lobes are present and extend beyond the posterior margin of the uropods approximately 0.5 mm. A node-like protrusion is present on each side of the telson approximately 0.5 mm behind its anterior margin and 0.5 mm laterally from the midline of the telson. The caudal fan is circular in outline.

The length of the holotype (anterior end of rostrum to posterior end of furcal lobes) is 14.0 mm; carapace length (anterior end of rostrum to posterior end at midline) is 6.0 mm; lateral carapace length (measured along left branchiostegal keel) is 6.0 mm; maximum carapace width is 6.5 mm; distance of lateral keels from carapace margin is approximately 0.9 mm; length of abdominal tergites (posterior end of carapace to anterior end of telson at midline) is 5.5 mm; length of telson at midline is 2.0 mm; telson width at anterior end 2.0 mm, and telson width at posterior end is 1.0 mm.

Paratype (USNM 442091) is a mold of the exterior of the dorsal surface. The carapace is complete and has ventral sternites impressed upon it. Pereiopods and antennae are lacking. The anterolateral areas of the carapace have a very faint veineous pattern. The rest of the carapace is smooth. Antennal scales are preserved. Depressions that seem to be molds of the eyes are present. Flagellae are not preserved. The preservation of the rostrum is better than that of the holotype. The four anteriormost abdominal tergites are present and positioned at an acute angle to the plane of symmetry. The posterior abdominal tergites and all of the caudal fan are missing.

Carapace length is 5.0 mm; lateral carapace length is 5.0 mm; maximum carapace width is 5.5 mm, and lateral keels are approximately 0.7 mm from the carapace margin.

Paratype (USNM 442092) is a mold of the ventral surface of a specimen situated close to the periphery of the core. The carapace is nearly complete. Pereiopods and antennae are lacking. The rostrum is complete and intact, although very difficult to see. Antennal scales are very faint also. The posterior 5.0 mm of the right flagellum (left flagellum as viewed on the bedding plane) is present and may have been complete were it not cut by the core barrel. Ventral features are present and are oriented to the left of midline (as viewed). The left edge of the carapace (right edge as viewed in this ventral mold) is eroded away. Sternal processes are present. Process bases are discernible on body segments seven to ten; the processes are intact on segments eleven and twelve, and a base is discernible on segment thirteen. Basal fragments of right endopods and exopods are present. The three anterior-most abdominal tergites are preserved slightly left of the midline, possibly as a relict of preservation. The posterior portion of the specimen is missing. Carapace length is 6.0 mm; lateral carapace length is 6.0 mm; maximum carapace width is 5.0 + mm, and the right lateral keel is approximately 0.5 mm from the carapace margin.

Types and repository.--The holotype, USNM 442090, and paratypes USNM 442091-442092, are deposited in the U.S. National Museum of Natural History, Washington, D.C.

Occurrence.--*Tylerocaris hollandi* was found at one locality in the Tyler Formation of North Dakota. Bedding plane A1830C (NDGS well 2667), in the interval 18.7 m (61.5 ft) to 19.2 m (63.0 ft) below the top of the Tyler Formation picked at 2467.8 m (8097 ft), contains the specimens.

Remarks.--The orientation of the three types just prior to burial with sediment was dorsal surface upward for the holotype and ventral side upward for both of the paratypes. *Tylerocaris* is believed to be phylogenetically related to *Tealliocaris* and *Anthracaris*. *Tylerocaris* may represent an evolutionary stage in between the Telliocarididae and Pygocephalidae. I believe that *Tylerocaris* and *Pseudotealliocaris* may be at the same evolutionary stage in the *Tealliocaris* to *Mamayocaris* phylogeny that Brooks (1962, text plate 16) proposed for the Pygocephalomorpha. The phylogeny envisioned implies that the Carboniferous Tealliocarididae and Pygocephalidae should be united into one family. Further study is necessary to see if this tentative hypothesis is correct. *Tylerocaris hollandi* is the first reported North American tealliocaridid. The North Dakota occurrence extends the geologic range of the family, previously reported only from the Mississippian, into the Pennsylvanian.

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SUBSURFACE STRATIGRAPHY, LITHOFACIES AND PALEOENVIRONMENTS OF THE FOX HILLS FORMATION (MAASTRICHTIAN: LATE CRETACEOUS) ADJACENT TO THE TYPE AREA, NORTH DAKOTA AND SOUTH DAKOTA - TOWARD A MORE HOLISTIC VIEW

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ABSTRACT

General sedimentologic, stratigraphic, and paleontologic relationships represented by the Fox Hills Formation (Late Cretaceous: Maastrichtian) in the type area of North Dakota and South Dakota have been described over the last half-century based upon studies by numerous workers in several loci of bedrock outcrop. The process of description of the primary Fox Hills exposures in the Missouri Valley region and lesser exposure in eastern Montana and the Fairpoint and Stoneville Quadrangles of South Dakota has created a disjunct image of the stratigraphy and deposystem of this formation. The present paper calls attention to the questions raised by this disjunct pattern of knowledge and presents some data that contribute to a more unified, or holistic, interpretation of the formation. Although most pieces of the stratigraphic puzzle are known, the whole picture has not yet been assembled, as it were. A few key pieces are still missing. Most of these must be supplied by subsurface study of the formation.

Examination of the Fox Hills and contiguous formations underlying Hettinger, Adams, Stark, Mercer, Oliver, Morton, Burleigh, Logan, Grant, and portions of Sioux and Emmons Counties, North Dakota, using structural, isopachous, and lithologic data, demonstrates that the classic member terminology and facies relationships of exposures in the Missouri Valley in North Dakota and South Dakota are not indicative of the formation in the subsurface regionally. A wide area of Hettinger, Stark and Grant Counties is underlain by organic-rich brown and green silt and shale facies indicative of interdistributary bay depositional conditions. These represent undescribed unit(s) within the Fox Hills-Hell Creek deposystem. Distributary channel facies and associated crevasse splay sandstones outline the region along its northern, western and southern margins. A particularly thick, distributary channel sand body invaded the bay from the north and now underlies Mercer and Oliver Counties. This unit has been termed "Colgate" Member in the region, but its petrologic and stratigraphic affinities with that unit are yet to be determined.

Percent sandstone isopleths define the delta front-lower delta plain deposystem well. Structural contours and first-sand maps demonstrate that Fox Hills sedimentation was partially controlled by structural highs penecontemporaneously developing on the Pierre Shale. Mild effects of Laramide tectonism continued to influence the Williston Basin during, and presumably after, Fox Hills time. Elongate patterns on isopachous maps reflect depositional responses to movements of basement blocks. In Emmons County relationships suggest that nondepositon, or erosion, may have been involved in the uneven distribution of the Linton volcanic ash in a trough-shaped, estuary-like body.

Facies patterns and paleogeography in southeastern portions of the study area were controlled by a platform related to the Transcontinental Arch which trapped sands and resulted in formation of a wide, sea level coastal marsh. Against this the Fox Hills-Hell Creek Delta prograded, coalescing to produce closure of the Fox Hills Seaway and division of the Late Cretaceous Interior Seaway into northern and southern basins. An elongate estuary, open to the northeast, was reinvaded as subsidence and/or tectonic adjustment occurred in the region, depositing tongues of marine sediment within the Hell Creek Formation. These conditions gradually migrated northeastward leaving a vegetated plain, the Dakota Isthmus, behind as the Cretaceous ended. A persistent southwest to northeast drainage pattern was established.

Proceedings of the F. D. Holland, Jr., geological symposium, 1992, J. M. Erickson and J. W. Hoganson, eds., North Dakota Geological Survey Miscellaneous Series No. 76.

DEDICATION

This paper is affectionately dedicated to John Raymond Erickson and Eleanor Virginia Christenson Erickson, my parents. They have been my loving teachers and my wisest friends, without whose guidance, care, and counsel I would never have come to know the tutelage of F.D.H., Jr., nor the Fox Hills of North Dakota.

REASONS AND ARGUMENTATION-- Being an introduction of sorts

I have prepared this paper for the Holland Symposium in a fashion that respects many of the modes of inquiry which Bud Holland practised with us as students and colleagues. In particular, it is my intention not to expound upon the known so much as it is to point out what is not known about the Fox Hills Formation in central North Dakota and adjacent South Dakota, where the historical type area is located, believing that in the recognition of our ignorance lies the beginning of wisdom. My familiarity with the formation is based upon field studies over a span of 20 or so years, but most were concentrated in the 1970's and early 1980's. I feel it provides the kind of first-hand information base that Bud would insist upon before one makes the sorts of suggestions I am about to embark upon in this paper! It is also based upon twenty years of discussion and interpretation of water well subsurface data with my stratigraphy classes at St. Lawrence. My ignorance, too, may be magnified by both of these experiences so *caveat emptor!*

It is appropriate that I introduce here the philosophical direction that has always guided my work on the Fox Hills Formation, even before that philosophy had been adequately articulated. It involves the effort toward recognizing the functional relationships between parts in geology. Following the concept of "holistic community" as used by Kauffman and Scott (1976), holistic stratigraphy is defined as a total lithostratigraphic and chronostratigrphic interpretation of an episode of sedimentation. It is carried out by describing vertical and lateral boundaries, interrelationships of lithosomes, their lithologic compositions, contact types, thicknesses, post-depositional diagenetic effects, relationships to tectonic episodes and to control by local structures, and biostratigraphy. Holistic stratigraphy leads to a complete interpretation of paleogeography and, when combined with a total description of the fossil content of the rocks and the inferences therefrom, a holistic community, it produces a holistic Earth history for a region.

Obviously, scale of investigation is of fundamental import to this concept. I would suggest that scientists presently are making far too many broad, regional interpretations based upon far too scanty knowledge of local detail. The striking study of Hell Creek depositional relationships by Butler (1980) approaches the processes involved in holistic stratigraphic analysis as closely as any I have seen applied in the Williston Basin. In many cases, the local detail is known but overlooked, an error of omission of which I, too, may be guilty. In any case, it is the holistic stratigraphy of the Fox Hills Formation in which I hope to begin to interest students by the paper that follows. There is much that could be done.

In the mid - 1960's, after some years of quiescence, a series of investigations renewed both paleontologic and stratigraphic interest in the Fox Hills Formation and its super- and subjacent units the Hell Creek Formation and Pierre Shale respectively. Principal among these are works by Waage (1968), Feldmann (1972), Speden (1970), Erickson (1974), and Klett and Erickson (1976). Previous geologic mapping of these Montana Group rocks in the Missouri Valley counties of Burleigh (Kume and Hanson, 1965), Emmons (Fisher, 1952), and Morton (Laird and Mitchell, 1942), in North Dakota and Morgan and Petsch (1945) in South Dakota, as well as more recent work in Emmons County (Bluemle, 1984) and Grant and Sioux Counties (Carlson, 1982) adjacent to the type area, provide excellent stratigraphic frameworks for raising the sorts of questions that I shall advance herein. The only extensive subsurface examination of the Fox Hills Formation in the state is that by Cvancara (1976). It, too, is thought provoking as one addresses the formation in terms of current ideas of facies modeling and sequence stratigraphy. These, and a host of earlier works extending all the way back to the original recognition of the formation by Meek and Hayden (1856), have been seminal in the emerging concept of the Fox Hills Formation.

And what are the questions I would raise about the formation? They are questions of facies distribution and interpretation, of paleoenvironmental analysis, of stratigraphic continuity, of formation thicknesses and contacts in the subsurface, of unconformities and sequence boundaries and of integrating interpretations with those of Waage and other South Dakota workers in the region of the type area. I will make some suggestions for study in the region. I suggest also that many paleontologic questions have been awaiting an holistic depositional and stratigraphic framework before they can be answered, but these are not the focus of the present paper.

The importance of this work is evident to those familiar with the resources of the region and to those geologists with interests in the latest Cretaceous events. The Fox Hills Formation contains one, or more, of the major aquifers in the counties mentioned and those adjacent. A thorough understanding of its subsurface stratigraphy and facies will be of greatest significance to those who seek groundwater in the region. The citizenry has already benefitted from preliminary subsurface study by the North Dakota Geological Survey, the faculty and students of the University of North Dakota, the North Dakota State Water Commission and United States Geological Survey; but greater mapping detail is now called for from all of these groups. An understanding of the structural and stratigraphic relationships of the formation will eventually benefit those involved in basin analysis, and a comprehensive documentation of its facies and contacts will supply sequence stratigraphers with a sound image of the final Mesozoic episode of Williston Basin infilling.

On a more practical level there are some issues to be addressed in order to make progress on the broad holistic history mentioned above. First, I wish to suggest that the formation as it is exposed and studied in the Missouri Valley is deceptive and is stratigraphically and lithologically atypical of subsurface counterparts to the west and northwest. It is also atypical of facies to the east if one may trust uneroded remnants of those facies to supply example enough for extrapolation. As evidence of this I point out the studies of Carlson (1982) in Grant and Sioux Counties and Bluemle (1984) in Emmons County each of which adopted a different, and I believe justifiable, internal stratigraphy for the formation on the east and west sides of the Missouri Valley. Which of these, if any, should be the basis for subsurface study of the formation?

Lastly, I believe that the definition of the contacts of the formation must be applied consistantly if the extent of interfingering with the overlying Hell Creek and underlying Pierre Formations is to be appreciated. The upper contact has been a source of difficulty since its first regional application because of the incomplete preservation of lithologic units between the marine and terrestrial lithotopes. An "eastern Montana-western North Dakota" concept of the contact has been repeatedly imported into the Missouri Valley region and forced to fit the stratigraphy. It is more easily applied to log data and is therefore practical, but it does not clarify paleoenvironmental relationships nor respond to the questions I raise herein.

In this model the Colgate Member of Calvert (1912), having typical development in eastern Montana, is considered of dominant importance; although its depositional origin and lateral relationships usually have not been verified, and lignite, or lignitic shales, often occur below it in logged sections, the Colgate is historically regarded as capping the formation. In the Missouri Valley the Colgate has been interpreted as a lagoonal or back-barrier beach deposit (Feldmann, 1972) often containing marine or brackish fossil organisms, whereas it is regarded as fluvial in western North Dakota (Butler, 1980). In eastern Montana it is known to overlie mapped lignites which are included within the Fox Hills Formation, apparently because the Colgate is maintained as the capping unit. Such applications continue today (Sholes, et al., 1989) although their implications for interpretation of the geologic history of the region and its sequence stratigraphy continue to be overlooked. Waage (1968) clearly pointed out the misinterpretations of age and stratigraphic position that can result from this viewpoint and his ideas should be more broadly applied.

Butler's (1980) convincing work on the Colgate, in the context of its petrology, depositional setting, and stratigraphic relation to Hell Creek sediments in the region of Glendive, Montana, contains the first thorough documentation of the lithologic properties of the Colgate. Although it was not the unit of primary interest to Butler, the Colgate was shown to be a unidirectional, tractive current deposit associated with progradation of a lower delta-plain regime into the Fox Hills marine coastline at that place. Whether that unit can be carried as a member across North Dakota, or whether it is discontinuous, making the concept of the Colgate "lithofaces" established by Waage (1968) more appropriate, is a query whose answering will result in the sort of complete stratigraphic analysis that will eventually serve residents of the region well if groundwater demands increase. When accomplished, the nomenclature applied should clarify relationships, not subvert or confuse them as seems to occur at present.

Unfortunately the stratigraphic work of Frye (1964, 1969) on the Hell Creek Formation in the Missouri Valley has also been disregarded or misinterpreted in the haste to make sweeping, regional generalizations. One such misinterpretation that mars an otherwise well-documented study appeared in the summary paper on Paleogene depositional systems of the Williston Basin (Cherven and Jacob, 1985, p. 129, 134)) in which the authors stated that Frye had observed that lower members of the Hell Creek pinch out into the Pierre Shale in the Missouri Valley region, and the stratigraphic diagram resulting from this misconception is equally confusing. Actually, Frye (1969, p.20) correctly observed that, "The Hell Creek Formation in North Dakota, South Dakota, and eastern Montana rests upon the Fox Hills Formation." Marine units within the Hell Creek in the Missouri Valley are tongues of the Fox Hills Formation (Frye, 1964) with all of the stratigraphic implications borne by that definition. If we are to have a "holistic" view of the formation, we must continually define the contacts where they have not yet been defined and redefine them where misinterpretation has led to "non-holistic" uses (that is, usage that does not lead to a coherent, plausible, regional paleogeography). Subsurface studies are particularly sensitive to this need.

One such study by Cvancara (1976) employing contacts used by Trapp (1971), Croft (1970) and Randich (1975) clearly demonstrated the difficulties of applying surficial lithologic nomenclature and contact picks to subsurface data. In one region, an alternative choice of the more traditional upper contact at the base of the first lignite would have reduced the thickness of the Fox Hills Formation by approximately 200 feet (61 meters). By not placing the contact at that point, these workers created a distinctly different interpretation of the formation than might be suggested herein. Attendant differences in all related concepts, such as isopach and lithofacies patterns, extend therefrom. When developing a concept of the formation in the subsurface, such variation in picks of the formation boundaries will be a major impediment. By presenting well-log interpretations and summaries of published literature as interpreted through the eyes of my field experience, I hope to suggest some approaches that will reduce future problems of this type.

LOCATION AND GEOLOGIC SETTING

This paper presents interpretations made from field studies, subsurface data in the form of both water and oil well logs, and published sources of several types. Coverage extends from Mercer and McClean Counties in North Dakota, on the north, to Dewey and Ziebach Counties on the south, and from eastern Dunn, Stark, Hettinger, Adams, and Perkins Counties on the west to Wells, Stutsman, Logan and McIntosh Counties on the east (Figure 1). It is traversed from north to south by the Missouri Trench, a feature which has exerted substantial impact upon geologists' perceptions of Fox Hills rocks since the formation was first recognized. The formation crops out over the east-central and southeastern portion of the area shown in Figure 1 and has a regional strike that roughly follows the southeastern margin of the Williston Basin and the Transcontinental Arch (Figure 2). Regional dip is toward the northwest. Local departures from this trend imply that more complicated structural controls have applied both pre- and post-depositionally. Several recent papers have noted regional structural controls for late Mesozoic sedimentation (Anna, 1986a, 1986b; Shurr, et al., 1989), although they have largely ignored published studies that first pointed out lineaments or their implications (Erickson, 1968; Erickson, et al., 1975). Local structural trends influence the outcrop pattern but Pleistocene glacial processes, responding to regional bedrock resistance and structure that produced successive maximum-extent ice margins in the same general position, have exerted the primary geomorphic control by erosion of poorly consolidated Cretaceous sedimentary rocks. As discussed by Bluemle (1984), these successive ice margins have altered physiographic features, such as drainage patterns, that presumably had developed in response to pre-glacial bedrock and structural regimes and therefore would be more suggestive of local subsurface structural conditions.

The importance to the outcrop pattern of the formation of glacial diversion of the established northeastward-flowing streams into a trench cut adjacent to, or controlled by, the Wisconsinan ice margin was demonstrated in excellent pioneering studies by Laird and Mitchell (1942) in Morton County, North Dakota. Others have furthered the understanding of that ancestral drainage pattern (Fisher, 1952; Clayton, 1962; Bluemle, 1972, 1984), but it has not yet been applied to structural interpretation of the basin margin as it could be.

A meltwater trench was developed where the ice margin abutted the Missouri Plateau. It appears that the present Missouri Valley in southern North Dakota was cut into and through generally unconsolidated sandstones of the Timber Lake Member of the Fox Hills Formation where that unit is thinnest. That position seems to have been structurally controlled (Bluemle, 1984). In South Dakota, Missouri River tributaries along the western valley wall are eroding headwardly into thicker Timber Lake sediments and the meltwater trench lies on the eastern margin of Timber Lake strata. A distinctly different impression of the formation is gained from the South Dakota exposures than from those of North Dakota because of the position of this glacially-induced Missouri Trench.

These relationships are of import because they result in a display of Fox Hills strata in the type area that is largely atypical of the formation in the subsurface. Twenty miles to the east or west from the Missouri Valley the character of the Fox Hills section is markedly different. Siltstones and mudstones increase at the expense of the sandstones of the Timber Lake Member. This division forms one of the demarcation lines for stratigraphic and facies nomenclature that I will address.

The other demarcation lies approximately on the state line between North Dakota and South Dakota. The varying nomenclature across that political boundary might be construed as a relict of political geography. Such is not entirely the case, however, for there are real geologic changes in both thickness and distribution of facies occurring near the state line. Differences of opinion expressed by workers regarding inter-

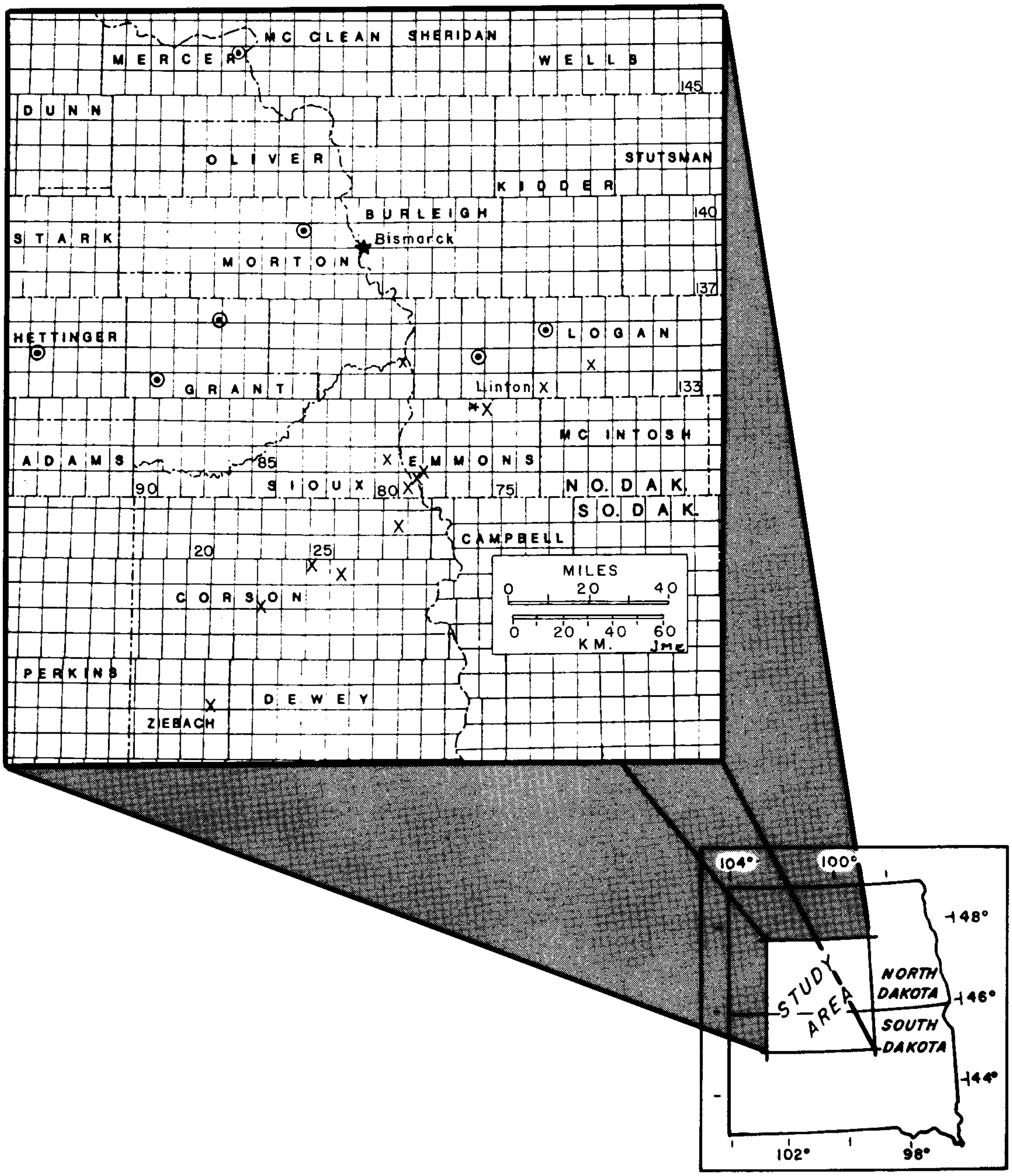

Figure 1-Index map defining the area studied and location of principal stratigraphic sections discussed in the text. X = measured outcrop sections; circles enclosing dots are North Dakota State Water Commission (NDSWC) test wells from which figured sections used herein have been derived. Data sources include Ackerman (1977, 1980), Armstrong (1975), Croft (1970, 1974), Feldmann (1972), Fisher (1952), Klausing (1979, 1982), Randich (1965, 1975), Trapp (1971), Waage (1968), and JME unpublished field data.

and intra-state member terminologies (Feldmann, 1966, 1972; Carlson, 1982; Waage,1968; Klett and Erickson,1974; Erickson; 1974, 1978; and Bluemle, 1984) are readily understood when facies distributions within the formation are examined as I begin to do herein. The terminologies used by these workers are partly summarized in Figure 3.

The thrust of this paper is to try to point out those areas where it is possible, and advisable, to carry

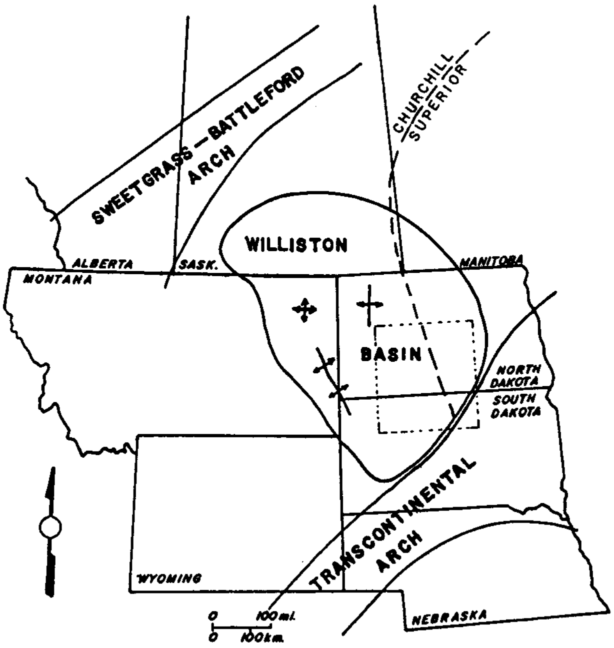

Figure 2-Primary tectonic features of the Williston Basin region surrounding the study area that is indicated by dashed square lapping from central North Dakota into north-central South Dakota. Positive structures within the basin include Poplar Dome (Montana), Nesson Anticline (North Dakota), and Cedar Creek Anticline (Montana - South Dakota). Basement provincial boundaries after Gerhard et al., 1987. Trans-Hudson orogenic belt (Green et al., 1985), a basement tectonic terrain not shown on figure, underlies the portions of North Dakota and South Dakota lying westward of the Churchill-Superior basement provincial boundary.

existing lithologic nomenclature for the formation into the subsurface. Where that seems inadvisable, I shall recommend alternatives that best serve to illustrate an approach toward holistic stratigraphy of the Fox Hills Formation. The following discussion will focus on subsurface data available in the form of water well logs of the North Dakota State Water Commission (hereafter NDSWC) appearing in various publications of the North Dakota Geological Survey. Throughout this paper references to color and properties of rocks are taken from verbal descriptions of logged cuttings as given in cited sources.

CONTACTS, MEMBERS, AND LITHOFACIES

Member terminology applied to the Fox Hills Formation is varied, but it is beginning to mature as workers attend more and more to lithologic detail of these rocks. As Figure 3 implies, names of members have been carried from Montana and South Dakota into the Missouri Valley of North Dakota, in most cases without careful study of lithologic equivalence but rather because of general lithologic similarity as well as general similarity of stratigraphic sequence and position. Subsurface studies, and knowledge of exposed sections (Butler, 1980; Waage, 1968; Klett and Erickson, 1977) are demonstrating that this approach to stratigraphy in such a complicated depositional system is unsatisfactory. More precise and appropriate packaging of strata is necessary if we are to advance further in our comprehension of the Fox Hills Formation.

There are a number of ways to accomplish this. Packaging strata using third order sequence boundaries (Vail, et al., 1977) that would portend better understanding of Maastrichtian sea level fluctuations in the Western Interior is an obvious approach. At present we do not possess sufficient data to interpret such boundaries accurately.

Waage (1968) provided an acceptable alternative by establishing regional members with local intertonguing lithofacies and associated biofacies. Both the Trail City and Iron Lightning Members are such packages. I will interpret the subsurface data in this report to suggest that three additional lithofacies complexes exist and could, or should, be recognized as members. Before discussing internal stratigraphy, mention of the choice of contacts is appropriate.

Pierre--Fox Hills Contact

In the region of the type area (*sensu* Waage, 1968) the transition from the Pierre Shale to the Fox Hills Formation is generally gradational through a distance of five to fifteen feet (0.92 to 4.52 meters) from dark gray to black, fissile shale into gray shale with silt laminae or homogeneous, gray, silty shale. Less commonly it occurs through a rapid transition into sandy siltstone or silty sandstone. Lenses or pods of yellow jarosite may mark the transition zone. Waage's (1968) discussion of conditions at the contact as well as lithologies associated with the Trail City Member is thorough, and I commend it to all who would work in the region. Based upon outcrop exposures in Emmons County, Feldmann (1966) provided an excellent discussion of similarities and differences between the units in South Dakota and those in the Missouri Valley of North Dakota. I will discuss below his suggestion that the Trail City could not be usefully recognized in North Dakota, an interpretation that was related to the Linton Municipal Park (Seeman Park) exposures.

The contact as understood in outcrop is variable and is not as readily picked from driller's samples.

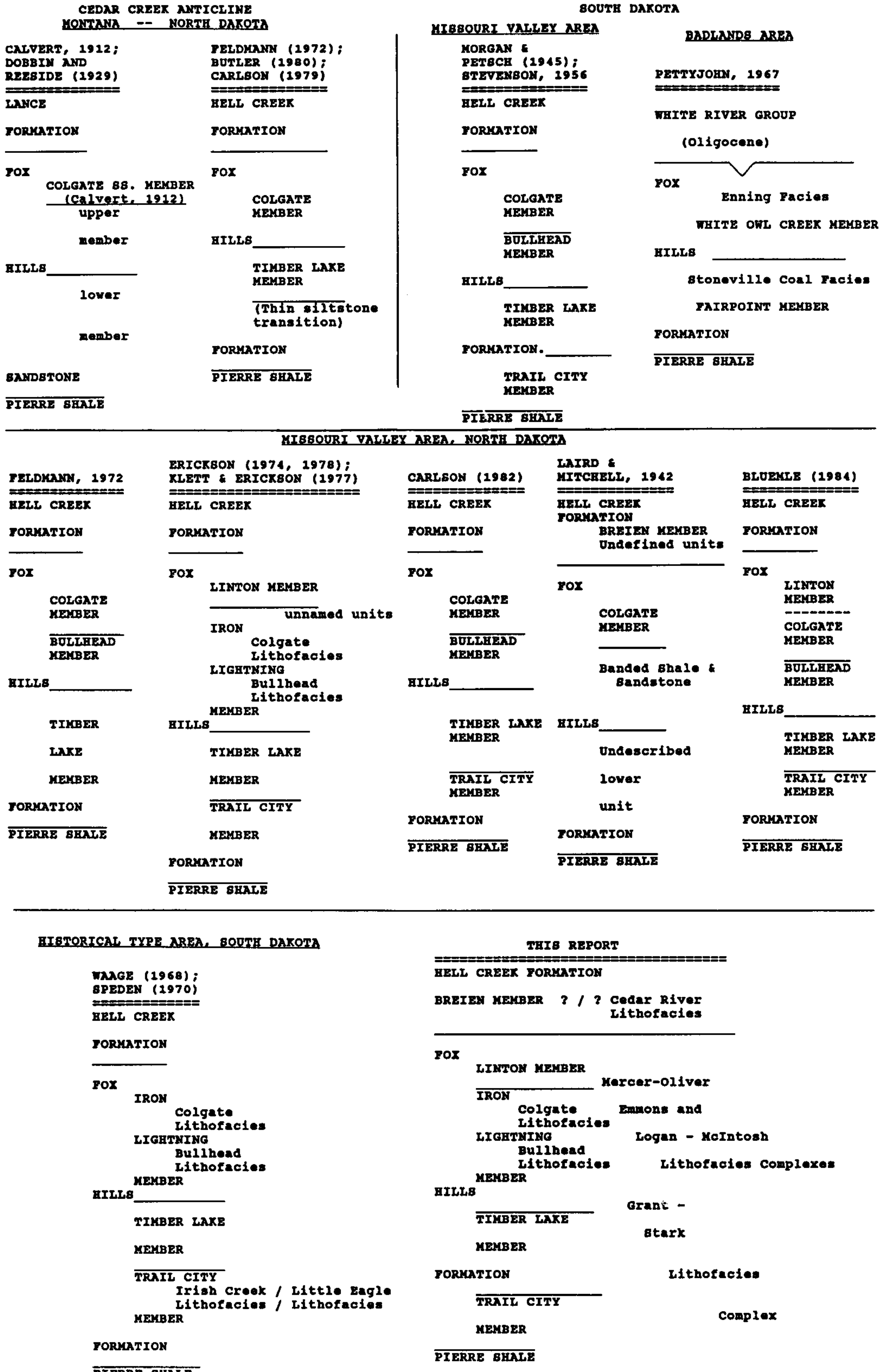

Figure 3-Stratigraphic terminology of the Fox Hills Formation as member nomenclature has been applied in and around the type area since the early part of this century. Terminology includes use of Colgate Member designated by Calvert (1912) in eastern Montana.

The contact has been chosen with laudable consistency and accuracy by geologists who have been responsible for overseeing water test holes of the North Dakota State Water Commission (NDSWC). The best picks recognize the Pierre Shale as dark, black, or grayish-black hard, siliceous shale. Occasionally the terms brittle, bentonitic, bluish, and mottled are used to describe unique attributes of the Pierre in a particular well. Jarosite, seen in outcrop and used as a marker (Waage, 1968), is never noted in descriptive logs, even when made from cuttings, and thus is not helpful. An example that serves as an index for "normal" picks of the contact is given in Figure 4 (See also Randich, 1975, p. 100, or 151). This reflects the standard pick of workers, the one I have used for the present study.

Untypical transitions from Pierre to Fox Hills deposition are noted in logs of NDSWC #3629 Hettinger County (Figure 5) and NDSWC wells #4484 (Figure 6) and #4486 (Figure 7) in Grant County (Randich, 1975). In the first, transition to sandy siltstone and sandstone occurs rapidly through a few feet of section with very little intervening silty shale lithology of the Trail City type. In outcrop such a situation occurs at the municipal park (Seeman Park) in Linton, Emmons County, North Dakota, a misleading site that is often used to characterize the contact in North Dakota. Actually, this transition is far more rapid than in most areas and should not be considered the norm for reasons to be discussed below. The section was measured and described by Feldmann (1972, plate 1). Similarly, there are areas where the contact is marked by transition upward from dark fissile Pierre Shale to green or brownish clay, often with lignitic particles in it, in the Fox Hills Formation. Such contacts occur in Grant County as logged in Figures 6 and 7. This transition to brown, green, or variegated shale characterizes the base of the formation over a wide region in Grant, western Sioux, and southern Morton Counties.

I have examined conditions at the base of the Fox Hills Formation throughout the study area. Using the criteria above, and recognizing that virtually all drilling ceased after entering the Pierre, I prepared distribution maps of lithologies occurring at the level of 25 feet (7.6 meters) and 30 feet (9.1 meters) above the base of the Fox Hills (Figures 8 & 9). These maps simply represent lithology and are likely to present time-transgressive conditions. They serve at this point to illustrate regions within the study area where one may expect the transition to be gradational into siltstones or more abrupt into sandier facies. Interpretations from these data will be made elsewhere. Important to discussions of the contact is the recognition that areas of siltstone are indicative of Trail City deposition, whereas sandstones mark Timber Lake (or comparable), shallower water deposits. Variegated shale or silty shale implies a depositional setting not described for the formation in outcrop.

Because drilling was regularly terminated at the first black shale-type lithology, documentation of intertonguing of Fox Hills with Pierre lithologies is not possible as yet even though it is to be expected in this region and may, in the future, help to define minor aquifers. In some instances (NDSWC #5435) it seems likely that the Pierre has not been reached but rather the well has bottomed in a brown or green shale facies above the Pierre as noted by Klausing (1982, p.141). In other cases the contact is in more sandy rocks and the Pierre Shale lies at an unknown depth as in Figure 15 (NDSWC #5419, Klausing, 1982, p.206). These occurrences are discussed below. For the construction of maps involving the Pierre Shale in this report such questionable contacts have not been used.

Fox Hills--Hell Creek Contact

Here I need not over emphasize that the contact with the Hell Creek Formation is unusually variable (Waage, 1961, 1968; Frye, 1969). Its stratigraphic position has been the cause of debate over many years and has influenced, and been influenced by, the thinking of stratigraphers working in regions far from the type area of the Fox Hills Formation. Waage (1968, 1975), Feldmann (1967, 1972) and Erickson (1971, 1974) each provide summaries of development of thought on the subject. In this section I will focus on local issues.

The value of locating the Fox Hills-Hell Creek contact with precision lies, as with most contacts, in the microstratigraphic tool it provides those seeking to make finely-resolved facies and paleoenvironmental interpretations. At times when laminae of a few centimeters thickness may define episodes of bolide impact or Cretaceous-Tertiary extinction events, should we approach formation contacts with any less rigor?

Theoretically, the contact must be at the junction between the last marine-dominated lithology and the first terrestrially- dominated lithology. The difficulty, then, becomes recognition of depositional environment of each potential boundary lithology.

Early on, the utility of lignite as a basal unit for the Hell Creek Formation was established (Frye, 1965; Laird and Mitchell, 1942) because of the obvious non-marine origin for the material. In the outcrop area of the Missouri Valley lignite is generally not present and alternatives must be found.

Two alternatives have been used in lieu of lignites. Because interdistributary shale is replacing

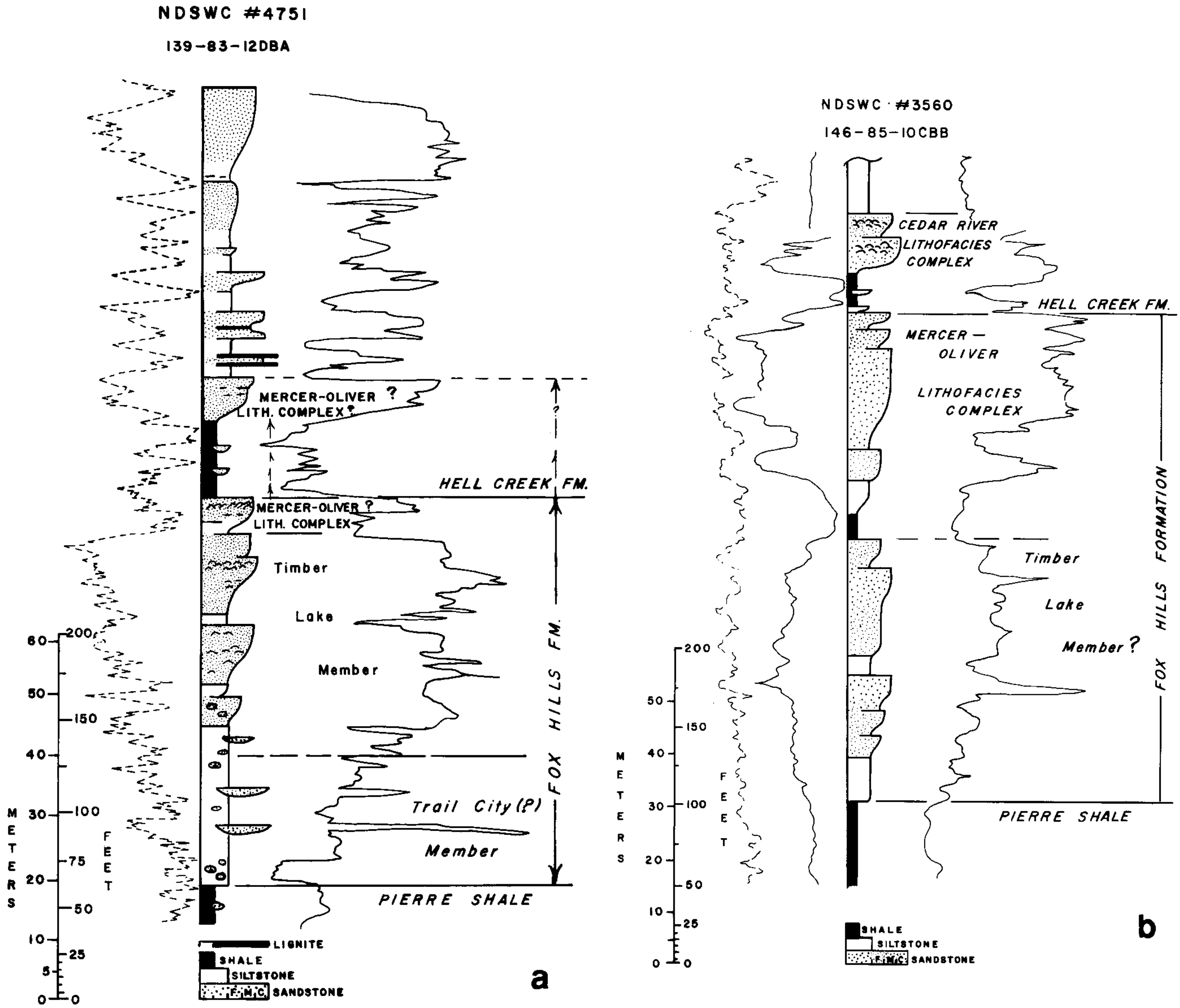

Figure 4a,b-Comparison of stratigraphic sections within the Mercer-Oliver Lithofacies Complex. **4a:** Interpretation of log section from NDSWC #4751, A,B located in Sec. 12, T. 139 N., R. 83 W., Morton Co., North Dakota (Ackerman, 1977). The transition from Pierre Shale through siltstone to sandstone is considered "normal" and representative of the transition where the Trail City Member of the Fox Hills Formation is well developed. Mercer-Oliver lithofacies are thin and interfinger with Timber Lake Member sandstones. In this instance the Fox Hills contact could easily be picked 68 feet higher than appears herein, but I have not done so, electing to follow the usage of Ackerman; **4b:** Interpretation of log section from NDSWC #3560 located in Sec. 10, T. 146 N., R. 85 W., Mercer Co., North Dakota. The Mercer-Oliver lithofacies complex is well developed, including more than 100 feet (31 m) of "Colgate" sandstone at the top of the formation (Croft, 1970). At that site the entire formation is in the Mercer-Oliver lithofacies; lower sandstones holding the position of the Timber Lake Member seem unrelated to the Timber Lake of the Missouri Valley.

sandstone the lowest lignitic shale overlying marine sandstone may define the Hell Creek. Recognition of paleosol characteristics within such a shale provides the requisite evidence for marine-terrestrial transition signifying the contact. In outcrop, over portions of northeastern Sioux and southeastern Grant Counties, the most useful placement is in a thin (4" to 10") maroon lignitic shale which marks a paleosol having some lateral extent. Tracing such a thin stratum into the subsurface in the waterwell data from which this

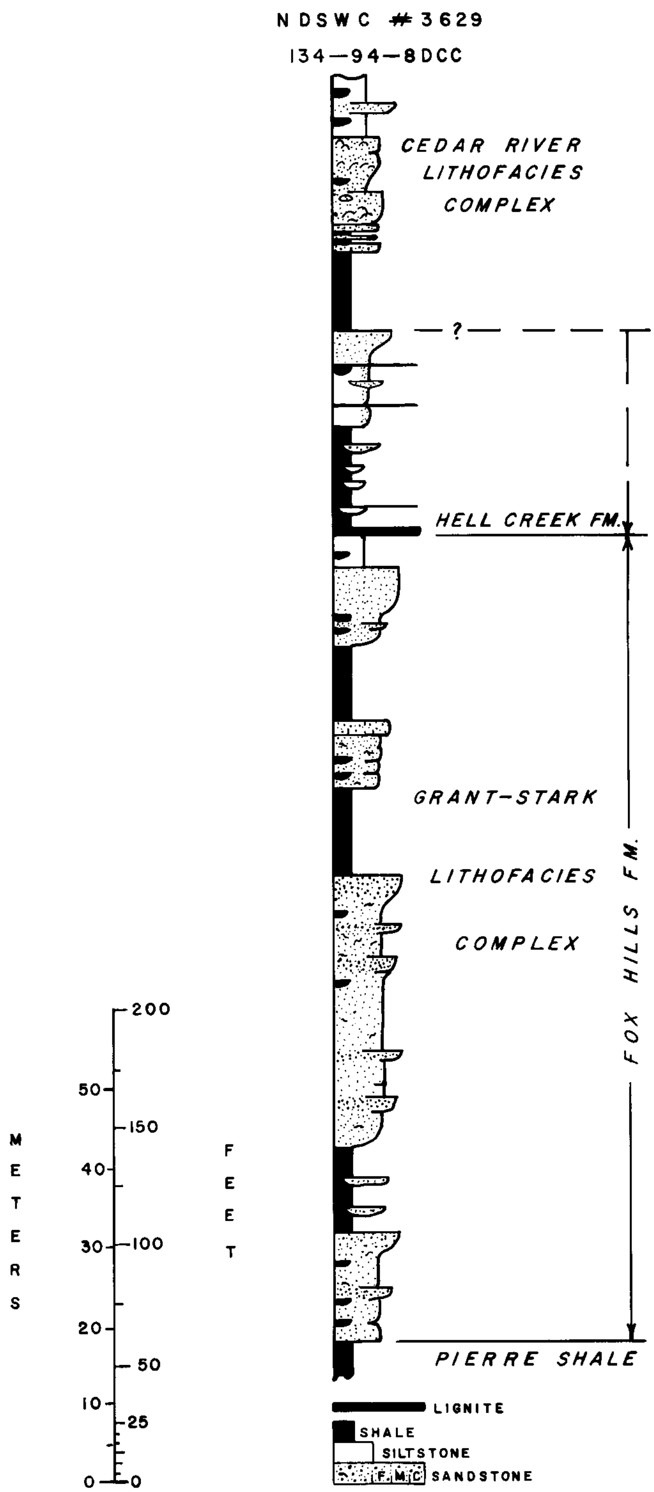

Figure 5-Interpretation of log section from NDSWC #3629 located in Sec. 8, T. 134 N., R. 94 W., Hettinger Co., North Dakota (Trapp, 1971). All sandstones in the lower 200 feet are lignite-rich rocks that interfinger with brown and green lignaceous shale; these facies are interpreted to represent back-barrier bay or lagoon deposits open periodically to marinewaters. Sandstones above 200 feet are channel and crevasse facies representing inter-distributary bay deposits that were influenced more often by freshwater conditions. It is suggested that the top of Fox Hills Formation be lowered from original NDSWC pick to the base of the lowest lignite as indicated. The formation here is represented by sandy facies of the Grant-Stark lithofacies complex which can be recognized in the subsurface by presence of lignaceous matter in red, green and brown shales and in lowest sandstones. Fox Hills-Pierre contact often is at change from black to green or brown shale.

report is generated has been difficult, and in most cases unsuccessful. Often a brown, green or variegated shale with carbonaceous matter makes a proper basal unit for the Hell Creek in a position such as that marked by one of the indicators in Figure 4 and 5. Choice of the lowest brown, carbonaceous shale is appropriate as it stands in Figure 4a from Grant County well #4751.

Under a wide area of central Sioux, Grant, and Morton Counties all shales in the Fox Hills Formation have notable volumes of lignitic debris and high iron content, and choice of contact can't be based solely upon shale lithologies. In well #4486 (Figure 7) "brown carbonaceous shale" (Randich, 1975) lies directly upon the Pierre suggesting either that no Fox Hills exist in this region or that another combination of lithologic factors must be considered during contact choice. The Fox Hills is unusually thin in this region but it is not absent. The first lignite makes an appropriate upper contact in this particular example.

Some workers have adopted a second approach, one based upon the concept of the Colgate Sandstone Member of the Fox Hills Formation which is treated conceptually as a tabular sandstone after interpretations developed by Thom and Dobbin (1924) in western North Dakota and employed by Fisher (1952) and Feldmann (1967, 1972) in Emmons County where it was assigned a lagoonal beach facies origin as noted previously. Feldmann (1972) demonstrated presence of such a sandstone on Whitehorse Butte in northeastern Sioux County where it caps the section. Rocks are a fine to medium-grained, very thin-bedded, white and very light green, salt and pepper sandstone in close proximity to a bed of perlite that Feldmann has correlated with the Linton volcanic ash bed. Exact position of this sandstone with respect to the Fox Hills-Hell Creek contact is not known due to absence of Hell Creek sediments, although it is assumed to lie at the top of the Fox Hills (Feldmann, 1972, Plate 1).

Perhaps following Feldmann's usage, geologists working across parts of Stark, Dunn, Mercer,

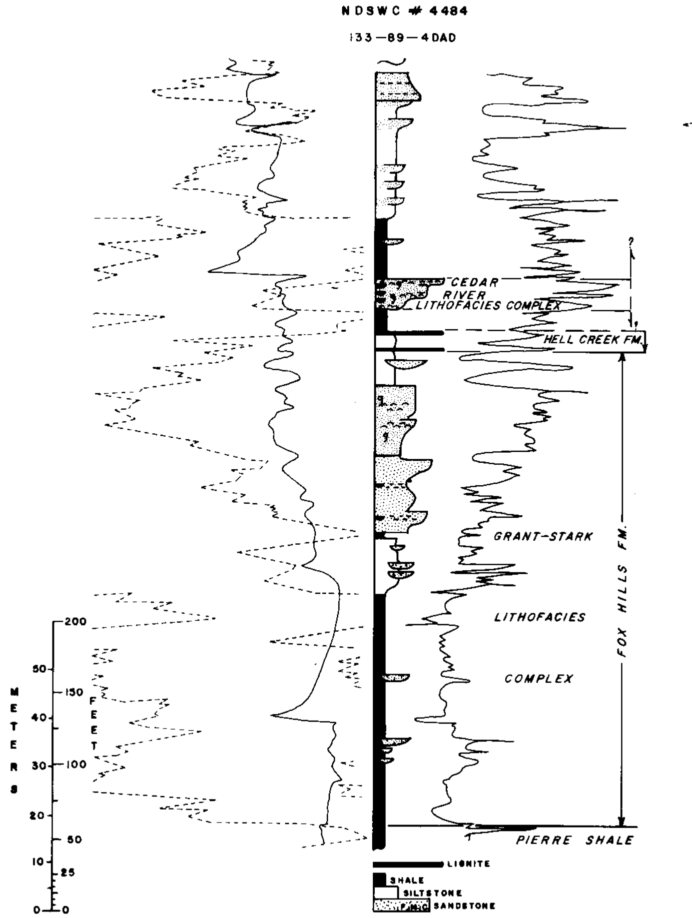

Figure 6-Interpretation of log section from NDSWC #4484 located in Sec. 4, T. 133 N., R. 89 W., Grant Co., North Dakota (Randich, 1975). Upper contact of the Fox Hills should be lowered 10 feet (3.1 m) from NDSWC pick to the base of the lowest recorded lignite. The Pierre-Fox Hills transition in this section is from black shale of the Pierre upward into brown and green shales of the Grant-Stark lithofacies complex of the Fox Hills Formation. Fossiliferous sandstones occurring in the interval approximately 25 to 75 feet below the Hell Creek Formation are interpreted as fingers of the Timber Lake Member. Fossiliferous sandstones logged above the Fox Hills-Hell Creek contact are part of the Cedar River lithofacies complex within the Hell Creek Formation.

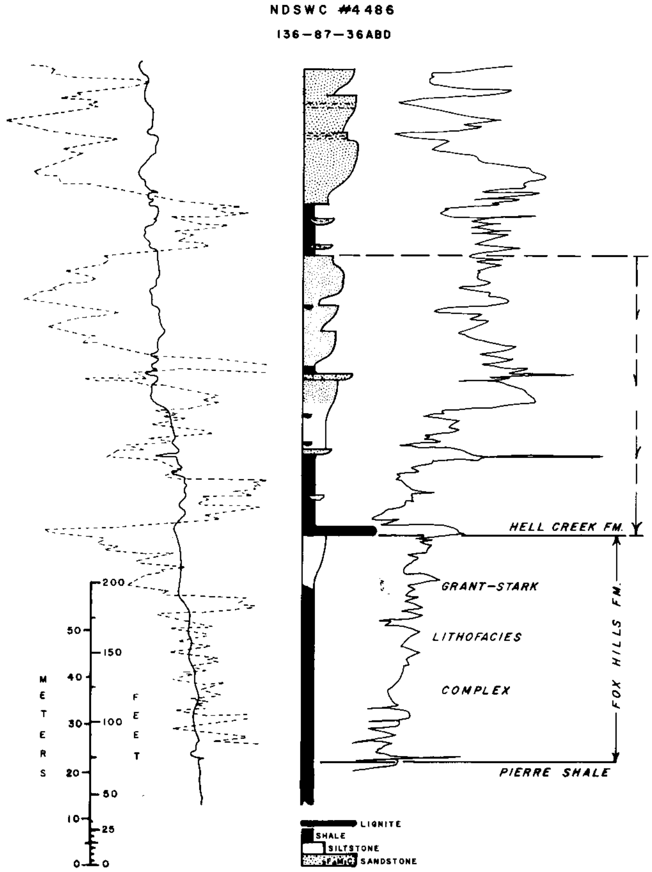

Figure 7-Interpretation of log section from NDSWC #4486 located in Sec. 36, T. 136 N., R. 87 W., northwestern Grant Co., North Dakota (Randich, 1975). Choice of Fox Hills-Hell Creek contact at this site should be at first lignite (755-foot depth) rather than at 565 -foot depth as given by Randich (1975) and applied by Cvancara (1976, section #6). All facies in this section are interpreted to represent back-barrier bay deposits overtopped by those of an interdistributary bay lithotope. Shoreface and barrier island sandstones representative of the Timber Lake Member are entirely absent from this site. Variegated shales of the Grant-Stark lithofacies complex overlie black shales of the Pierre Shale.

Oliver, McLean and northern Morton Counties (Trapp, 1971; Croft, 1970) have consistently used a thick, very fine-to-fine grained, clean sandstone or a fine-to-medium grained, silty sandstone, sometimes identified as "Colgate Member" as the top unit of the Fox Hills Formation. Cvancara (1976, plate 2) also followed this usage when studying the thickness of the formation in the region. I have generally accepted a contact at the top of this sandstone in these counties unless there has been reason to place it lower in the section. It is characteristic of the Mercer-Oliver lithofacies complex and makes up the top 102 feet (31.1 m) of sandstone in Figure 4b.

This subsurface "Colgate" contrasts with outcrop relationships in eastern Sioux, western Emmons, Corson and Ziebach Counties where Colgate sandstones are poorly-indurated, poorly-sorted, buff to white channel-filling sediments of intertidal lagoon origin. These channel sands occur randomly in the

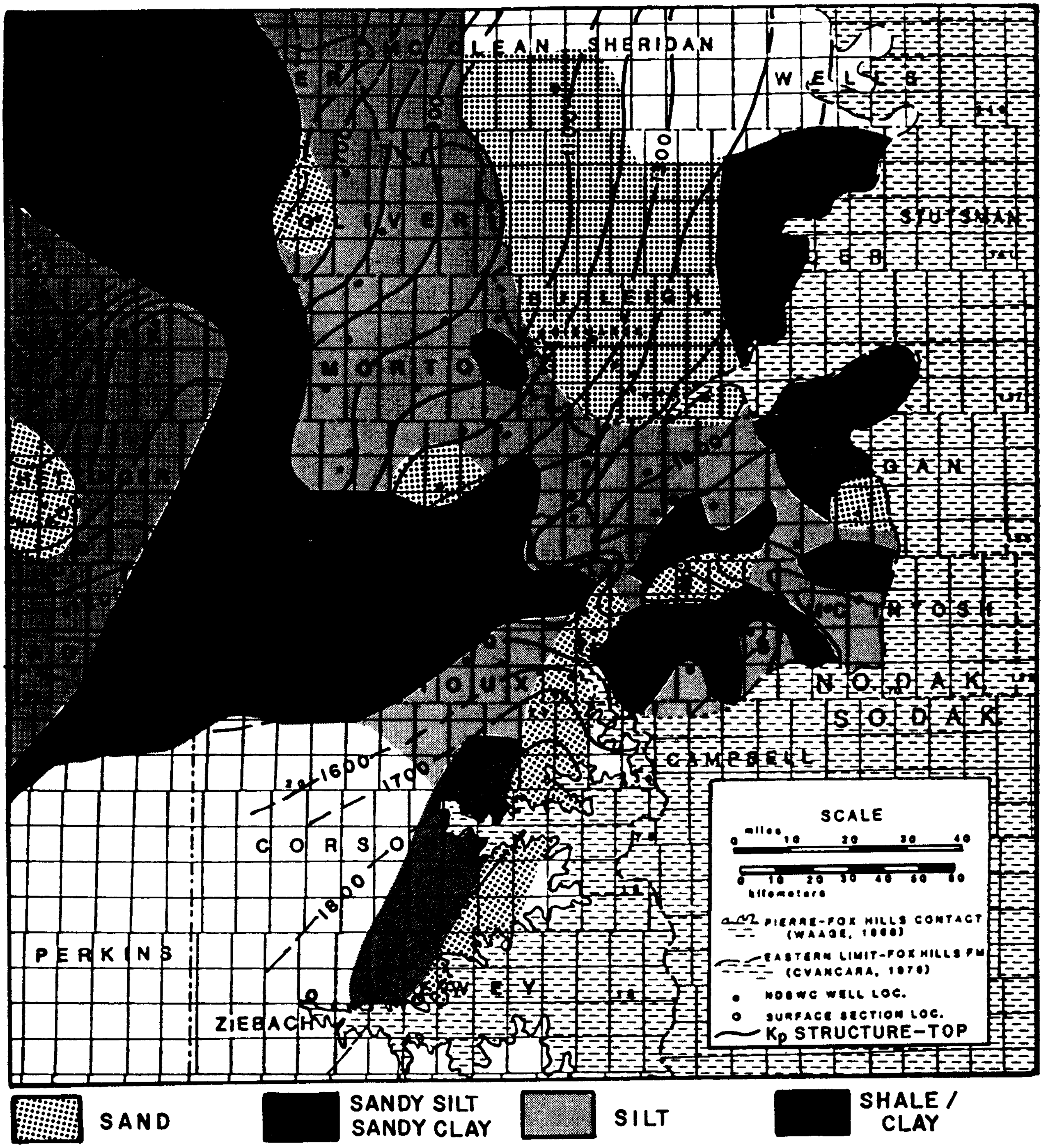

Figure 8-Isolith map drawn on a horizon 25 feet (7.6 m) above the base of the Fox Hills Formation using data points as indicated. Unpatterned regions have insufficient data. Base map is structure contour map of the top of the Pierre Shale; note apparent structural influence upon facies, particularly in Emmons, Logan, McIntosh, eastern Sioux and northeastern Corson Counties. Compare with Figure 9. Compiled from Croft, 1970; Trapp, 1971; Randich, 1975; Ackerman, 1977, 1980; Armstrong, 1975; Feldmann, 1972; Waage, 1968. Area of shale pattern lies beyond the eroded margin of the Fox Hills Formation.

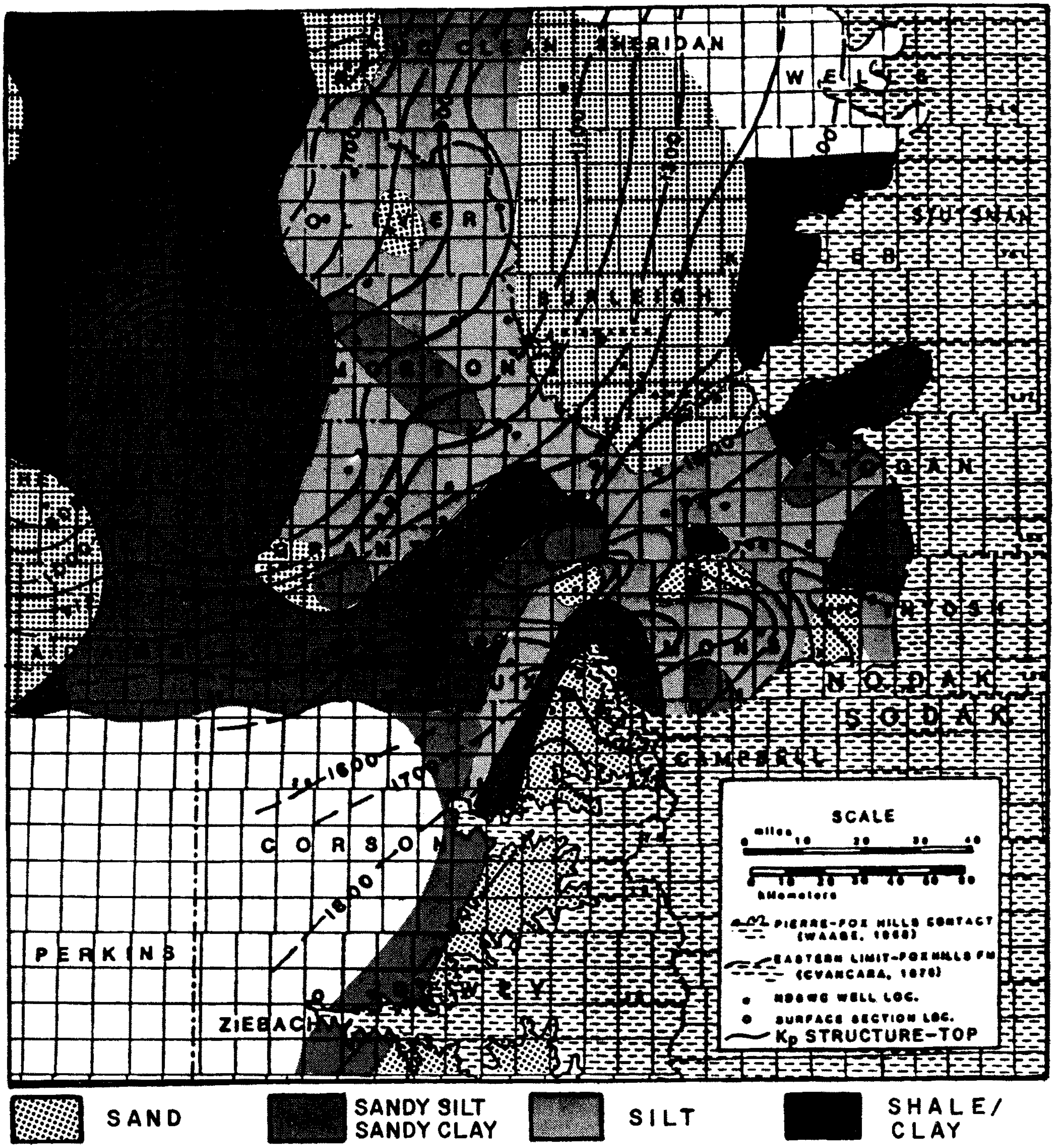

Figure 9-Isolith map of a horizon 35 feet (10.7 m) above the base of the Fox Hills Formation drawn on Pierre Shale structure contour base map. Comparison with Figure 8 demonstrates lithofacies development as Fox Hills lithotopes entered the area during regression. Grant-Stark variegated shale lithotope was already isolated by sandstones on the east at this early stratigraphic position (and early age) in the formation in the area. Data sources as in Figure 8.

upper portion of the formation (Iron Lightning Member), frequently well below the top (Waage 1968; Erickson, 1974).

East of the Missouri Valley, where the formation is thoroughly dissected, outcrop stratigraphy is based upon poor exposures in buttes. These contain rocks that are generally siltstone or very fine, brown-to-orange uncemented sandstone with one, two, or three cemented, fine to medium grained, thin-bedded, fossiliferous, green sandstones that formed the basis for physical correlations and structural interpretations made by Fisher, (1952). As has been noted elsewhere (Erickson and Klett, 1975; Klett and Erickson, 1977) these strata are not definable in exposures west and northwest of Linton in Emmons County (Figure 1).

South and east of Linton the Colgate lithofacies is also reduced or absent and the contact is placed above an indurated, fine-to-medium-grained, cross-stratified, brown to gray-green, porous sandstone that contains large specimens of the trace fossil *Ophiomorpha* and plant root traces. This unit represents the Linton Member of the formation as used by Klett and Erickson (1977) and Bluemle (1984). It is interpreted to lie just below the Hell Creek contact in NDSWC #8126 (Armstrong, 1975) as shown in Figure 10. This unit is difficult to trace in the subsurface.

In summary, it is most appropriate to place the Fox Hills- Hell Creek contact at the base of the lowest lignite; in the absence of lignite, at base of the lowest significant brown, green, or maroon lignitic shale or lignitic siltstone; or at the top of a fine-to-medium grained, greenish-gray to olive-gray sandstone. Based upon this concept I have used the following corrected picks in the present study. In North Dakota Highway Department composite log for Sec. 11, T. 139 N., R. 91 W. (Trapp, 1971, p. 304-7) I have lowered the base of the Hell Creek to the "dark brown shale with probable thin lignitic seams" which thins the Fox Hills by 83 feet (25.3 m) at this location. Furthermore, in columns 4, 5, 6, 12, and 18 of Cvancara (1976) I suggest that the top of the Fox Hills should be picked at the lowest recognized lignite. When one makes this choice the contact can be lowered by as much as 190 feet (58.2 m) as indicated in Figures 5 and 7. This choice has obvious effects upon isopachous, structure contour, and lithofacies mapping. In the sections to follow I have made interpretations using each choice of contact.

In one instance, test hole #3575 (Trapp, 1971, p. 239), there is reason to elevate the pick for the top of the Fox Hills Formation to the top of a fine-to-medium--grained, light olive- gray sandstone logged as the basal unit of the Hell Creek Formation. This choice adds an

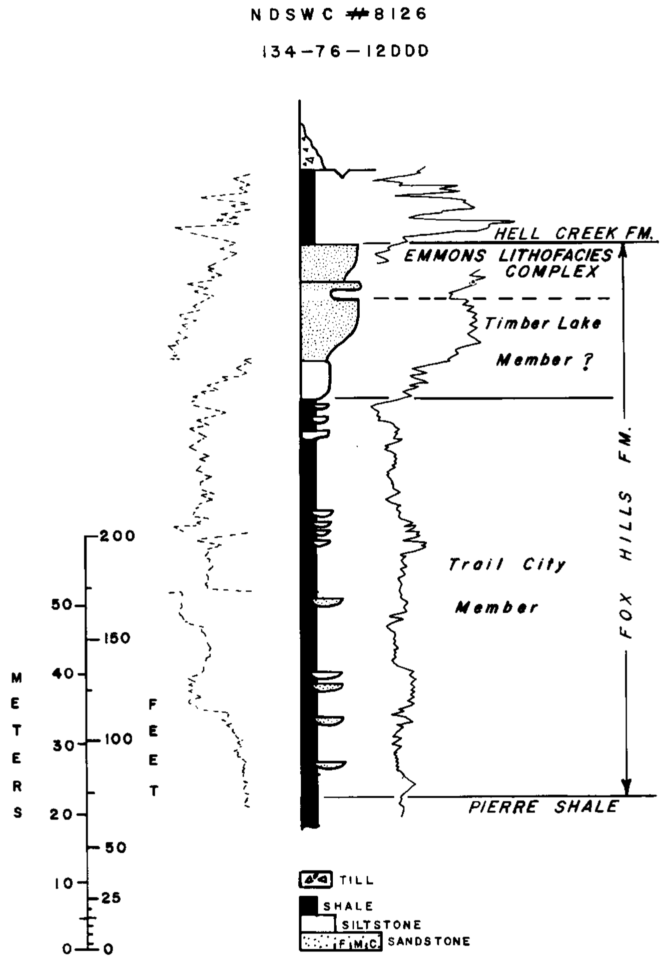

Figure 10-Interpretation of log section from NDSWC test well #8126, Sec. 12, T. 134 N, R. 76 W, Emmons Co. (Armstrong, 1975). In this section the Pierre-Fox Hills contact appears as it is generally seen in a "normal" transition situation in the type area in the Missouri Valley near the North Dakota-South Dakota border. Section illustrates some of the relationships in the Emmons lithofacies complex. Timber Lake Members sandstones are questionably present at this site; This facies complex is highly variable stratigraphically, sometimes including a prominent volcanic ash bed and a well-defined sandstone (Linton Member) representing estuarine channel and point bar lithotopes respectively. The Trail City Member is unusually thick at this site.

additional 56 feet (17.1 m) to the Fox Hills and yields a total thickness of 320 feet (97.5 m) for the formation. This contact was not used in the majority of mapping reported herein, but it is likely a better choice for paleoenvironmental and paleogeographic interpretive purposes at this one location; therefore it has been applied in constructing Figure 11 in the following section.

MEMBERS AND LITHOFACIES COMPLEXES

Across the portions of North and South Dakota presently under examination, several areas possessing characteristic, distinctive lithologic and stratigraphic identities can be recognized. Waage (1968, Figure 5) was careful to demonstrate and document both the interfingering relationships as well as the partial heterochroneity of Fox Hills rocks in the type area; and, as noted elsewhere, he established a terminology of lithofacies to best represent the sedimentary record he found (Figure 3). An essentially continuous, cross-strike exposure of Fox Hills rocks in the Grand, Moreau and Cheyenne River drainages allowed accurate mapping which, in turn, demonstrated the complexity of facies. This same type of activity has not been done in North Dakota, in part because such cross-strike exposures are absent making detailed stratigraphic work more difficult.

In North Dakota such detail is unavailable at present, yet subsurface data show, unmistakably, that an equal complexity of facies exists. To discuss the formation it is appropriate herein to give informal names to some of these lithofacies complexes. I will designate five regionally-restricted facies complexes, some of which include sub-facies. As here discussed, these include the Grant-Stark, Mercer-Oliver, Missouri Valley, Emmons, and Logan-McIntosh complexes in the Fox Hills Formation and the Cedar River complex in the Hell Creek Formation. Distribution of these lithologic packages is illustrated in Figure 11. It must be understood that I am defining suites of similar sediment and stratigraphy that have restricted areal extent; these need not be mutually exclusive, but instead, are likely to contain intertonguing facies from adjacent regions.

Grant-Stark Lithofacies Complex

The Grant-Stark lithofacies complex underlies much of Stark, Grant, and eastern Hettinger Counties of North Dakota, perhaps with extensions reaching into Sioux County. It is recognized by transition from typical Pierre lithology into thick brownish or greenish shale that is often carbonaceous, passes upward into variegated, carbonaceous siltstone which contains, or is capped by, lignite one to five feet (0.3 to 1.5 m) thick. As logged by NDSWC geologists and as used by other workers (Cvancara, 1976; Daly, 1989) the formation includes as much as 200 feet (61 m) of additional shale and fine sandstone above the lowest lignite (see Figures 6 and 7). I recommend lowering the Fox Hills-Hell Creek contact in NDSWC well #3629 (Trapp, 1971) approximately 83 feet (25.3 m) to the base of the first lignitic sandstone in accord with my previous discussion of contact preference (Figure 5). This choice is in keeping with regional lignites that occur in NDSWC #3627 lowering the contact by 87 feet (26.8 m) and NDSWC #3628 lowering the contact by 218 feet (66.2 m) (Trapp, 1971). Using this same contact choice (Figure 6) drops the contact by about 10 feet (3.1 m) in Grant County well NDSWC #4484 (Randich, 1975).

I have chosen to place the upper Fox Hills contact at the base of the lowest lignite resulting in a markedly thinner Fox Hills section dominated by brown or green shale and siltstone. Those lithologies generally characterize the Grant-Stark complex which is noteably reduced in sandstone content. Grant-Stark facies interfinger into sandier facies quaquaversally from the center of the complex in Twps 134 and 135 N., R. 89 W. (Figure 11). There is no development of the typical transition from marine black and gray Pierre Shale into fine- and medium-grained sandstones of the Timber Lake Member in the central region of this complex although intertonguing with the Timber Lake Member is demonstrable southeastward in central Sioux County.

Several lithologic logs from the region make reference to thin "limestone" beds at various positions in the section. In southeastern Grant County, where lignite is absent in the base of the Hell Creek, thin "limestone" beds within variegated shales, silts and increasingly prevalent sandstones are used to define a subset of this regional lithofacies complex (Figure 11). Inspection of cuttings from NDSWC wells #4491, and #8083, indicate these "limestones" to be hard, very fine-grained, gray, calcite-cemented sandstones (personal observations, and communication from F. D. Holland, Jr.). Logs containing "limestones" occur throughout Grant County with possible extensions across Sioux County. Eastward these well-cemented beds interfinger with increasingly sandy rocks of the typical Missouri Valley facies.

Figure 12 indicates that the variegated facies thins to zero rather abruptly along a northwest-southeast trend through the region. Where present, it is not unusual to find more than 120 feet (36.6 m) of brown or green shale. Reference to Figures 8 and 9 permits another means of demonstrating the extent of this Grant-Stark complex as it is found within 30 feet (9.2 m) of the Pierre contact. The sequence extends into Hettinger County (Figure 5) where the Pierre-Fox Hills transition is quite sandstone-rich, unfossiliferous, and lignitic.

Rocks of the Grant-Stark complex become sandier and more marine eastward and sandier but more fluvial westward. Nonetheless they represent a coherent suite of facies that are not seen in outcrop, nor do they correspond to any published formal lithostratigraphic unit in the type area. My suggestion here is that the Grant-Stark lithofacies be described as

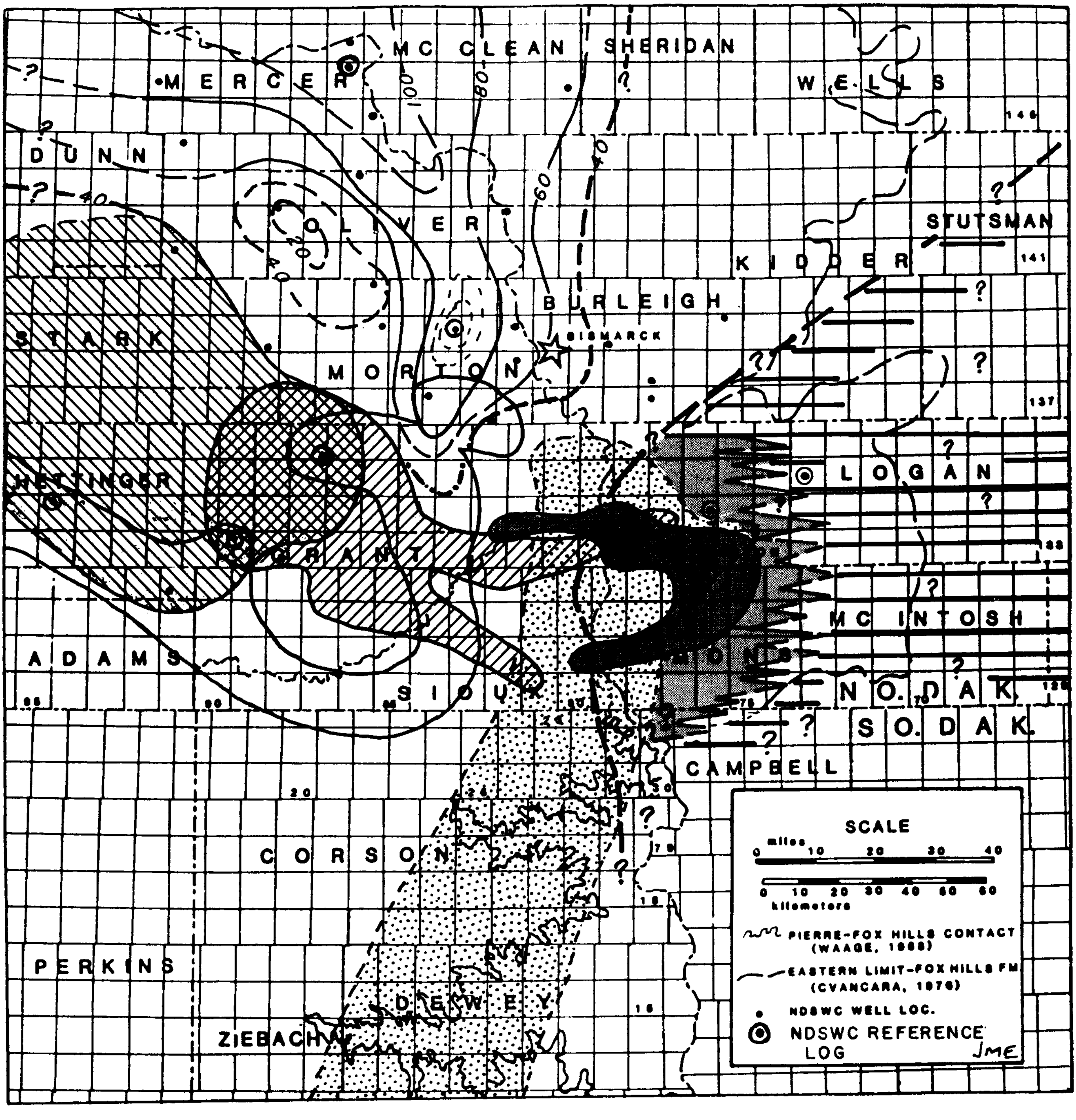

Figure 11-Map illustrating geographic distribution of lithofacies complexes described in text or recognized in literature. These facies packages document basic deposystems of the formation, albeit schematically. Mercer-Oliver complex indicated by 20-foot (6.1-m) isopachous contours; Grant-Stark complex by diagonal lines - lignite phase NW-SE -oriented diagonals, phase bearing calcite-cemented sandstones by NE-SW-oriented diagonals; Missouri Valley complex by stippled area (dominated be sandstone of the Timber Lake Member) and unpatterned area westward from it where Iron Lightning Member rocks are prominent; Emmons complex indicated by two tones of shading in the area eastward from Missouri Valley lithofacies complex (includes darker pattern showing Linton ash deposits); Logan and McIntosh complex by horizontal rule pattern east of facies boundary with Emmons complex. Lithofacies are undefined in the unpatterned areas of Burleigh, Kidder, Sheridan and Wells Cos.

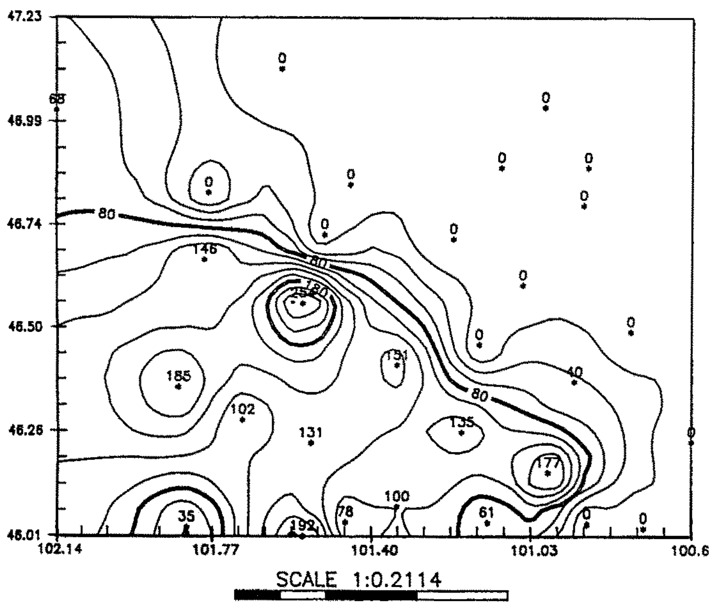

Figure 12-Isopachous map of variegated green and brown shale and siltstone of the Grant-Stark lithofacies complex in the North Dakota portion of the study area generated from computer-stored data taken from sources given in Figure 1. Note absence of variegated shale and siltstone from the northeastern portion of the map. Coordinates are latitude and longitude.

a new member of the Fox Hills Formation when subsurface relationships are more perfectly known.

Mercer-Oliver Lithofacies Complex

Fewer wells have penetrated the formation in the northwestern quadrant of the study region due to its increasing depth down the regional dip. Although control is weak, it is sufficient to show a distinctive facies pattern in the upper portion of the formation in Mercer and Oliver Counties (Figure 11). Examination of facies in the base of the formation (Figures 8 and 9) indicates a "normal" gradational transition from the Pierre Shale in most of this area. The top of the Fox Hills Formation is characterized by a fine-to-medium-grained, sometimes silty, dark greenish-gray sandstone that commonly ranges from 70 feet (21.5 m) to 150 feet (46 m) in these counties. Added thicknesses could be included if higher contacts were chosen. As noted previously, this sandstone has been referred to as the "Colgate Member" and the Fox Hills-Hell Creek contact has been placed at its top regionally (Croft, 1970).

A means of delimiting the Mercer-Oliver facies complex is taken arbitrary to include those Fox Hills rocks within the greater-than-forty-foot (12.3 m) isopach of the upper sandstone as demonstrated by the isopachous map of this unit included on Figure 11. In northeastern Mercer County it is more than 100 feet (30.5 m) thick, therefore making up more than one third of the total thickness of the Fox Hills Formation. Examples of this facies are recorded in NDSWC wells #3557, #3558, and #3560 as reported by Croft (1970). I have used NDSWC #3560 (Figure 4b) and Cvancara's (1976, Pl. 2) section 14, which is from NDSWC well #3557 (Croft, 1970, p. 106- 107), as the reference sections for this lithofacies complex.

Transition to the Hell Creek does not involve lignite in this region. Carbonaceous shale or siltstone is generally the basal unit of that formation above the thick "Colgate" sandstone.

Missouri Valley Lithofacies Complex

For purposes of this discussion it is necessary to provide a descriptor for the members and lithofacies of the formation that I have alluded to as "normal" and "characteristic of the type area" of the formation in the Missouri Valley region. This part of the formation is most adequately described (Waage, 1968; Speden, 1970; Feldmann, 1972; Bluemle, 1984; Bluemle, et al., 1980; Carlson, 1982). It includes the Trail City, Timber Lake, and Iron Lightning Members (= Colgate and Bullhead Members as used in North Dakota) and a number of litho- and biofacies carefully detailed by Waage (1968). On the schematic facies distribution map in Figure 11, the Missouri Valley complex includes the stippled pattern extending from the Missouri Valley in Morton County, North Dakota, southward into Dewey and Ziebach Counties, South Dakota. In South Dakots it also includes units of the Fox Hills Formation that lie westward of this, particularly in the Iron Lightning Badlands, but are unpatterned on the map in Figure 11.

Rocks of the Missouri Valley facies complex form a transition from marine siltstone into marine shoreface sandstone, succeeded by brown and grey, laminated shale representing brackish water deposition, incised by channels filled by buff, silty sandstones. Most outcrop exposures of Fox Hills rocks in the type area expose one, or more, of these units which, therefore, have produced the stereotype of the formation.

Emmons Lithofacies Complex

Emmons County holds one key to interpretation of the complicated depositional system of the Fox Hills. Several lithologies may be diagnostic of this complex as determined from both outcrop study and well log examination. Transition from Pierre to Fox Hills deposition is from black, tight, siliceous shale to gray, glauconitic shale except in the area of Linton where change is rapid into sandstone (Feldmann, 1972, Pl. 1, Section 6). Glauconitic shale or siltstone are unusual lithologies that are found distinctively in the basal portions of the Emmons and Logan-McIntosh lithofacies complexes. Siltstone facies underlying much of this region contain fossiliferous concretions from two or more zones of the Trail City Member, but it is rare to find these in outcrop. Presence of the Trail City siltstone was noted by Fisher (1952), and Erickson (1978) described the occurrence of the characteristic Lower *Hoploscaphites nicolleti* Zone (Waage, 1968) in the county.

Siltstones, sandstones and, in some sections, volcanic ash overlie Timber Lake or Trail City facies. Fisher (1952) documented some of these overlying rocks in his sections (Plate 3). The ash bed at Linton, a water-lain perlite, figured prominently as a datum in his interpretations. It was proven marine in the area south of Linton (Artzner, 1973), from which it rises in the section westward until it occupies a position within a broad estuarine or fluvial channel of the lower Hell Creek Formation near Breien, North Dakota (Feldmann, 1972; JME field observations, 1972).

In the Linton area, the ash bed, exposed in Sec. 33, T. 132 N., R. 76 W., appears to rest unconformably on undefined rocks (probably Trail City Member) at a topographic elevation below that of the top of the Pierre at Seeman Park based on a hand- leveled survey. Bluemle (1984) believed the ash at this location to lie about 60 feet (18.5 m) above the Pierre Shale. I have not examined the ash contact at this location, but isopachous mapping (Figure 13) of the ash using well and outcrop data has led to a computer reconstruction of the ash body filling a narrow basin having an uneven floor configuration (Figure 14) that suggests a cross-section of a river or estuary channel with terraced sides that was overwhelmed by ash deposition. The preserved portion of this basin is reconstructed in Figure 11 documenting where ash is preserved today. The shape of the deposit supports interpretation that ash filled a distributary channel and portions of an estuarine embayment associated with it. Incomplete preservation of ash is further indication of the lateral complexity of these facies and supports the presence of disconformities within the formation in this region.

Fisher's mapping (1952) further described the Emmons County lithologic sequence. A series of flaggy, green, fine-to-medium grained, indurated marine sandstones containing distinctive fossil assemblage, generally molds of mollusks, provide markers in outcrop that are sometimes recognizable in the subsurface.

Capping many buttes in the county is another

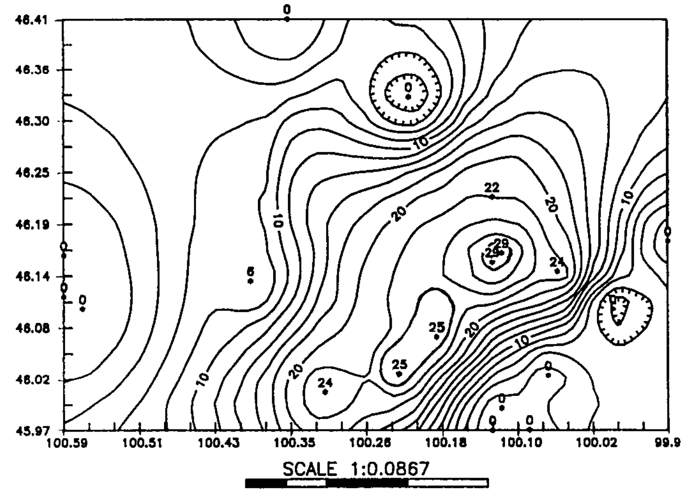

Figure 13-Isopachous map of "Linton" volcanic ash bed as distributed in log sections and as recorded in literature for the area around Linton, Emmons Co., North Dakota. Note elongated shape of the deposit. References are latitude and longitude. (Data sources as in Figure 1 with the addition of Artzner, 1973). Coordinates are latitude and longitude.

sandstone, green-gray, brown-weathering and containing plant roots and fragments believed to belong to *Pandanus* sp.(H. A. Leffingwell, 1991, personal communication). This distinctive unit, used as a datum by Fisher (1952), is the Linton Member (Klett and Erickson, 1975). It is lithologically distinct from both the Colgate lithofacies and from the fine-grained glauconitic sandstones of the Breien Member of the Hell Creek Formation (Frye, 1969, p.35).

The log section in Figure 10, although somewhat sandier in the upper portion than is usual, is representative of the Emmons sequence in areas where ash is absent. Fisher's sections at NW1/4, Sec. 3, T. 130 N., R. 77 W. and SW1/4 Sec. 9 and SE1/4 Sec. 17, T. 132 N., R. 76 W. (1952, Pl. 3) are appropriate reference sections where ash is present. Local absence of ash throughout the circumscribed area (Figure 11) of deposition is reflected by its absence from the type section of the Linton Member in N1/2, Secs. 8 and 9, T. 132 N., R. 76 W. within the same butte system as measured by Fisher. In ranges west of R. 77 W. this sequence is replaced in undefined fashion by the sand stones of the upper part of the Timber Lake Member and the Iron Lightning Member. In part, the Emmons complex probably overlies the lower Timber Lake disconformably above bed "B" in NW1/4 Sec. 12, T. 129 N., R. 79 W. as used by Fisher (1952, Pl. 3). Eastward, also in undefined fashion (intergrading? - see Figure 11), the facies of the Logan-McIntosh sequence occur in place of the Emmons complex. Much remains

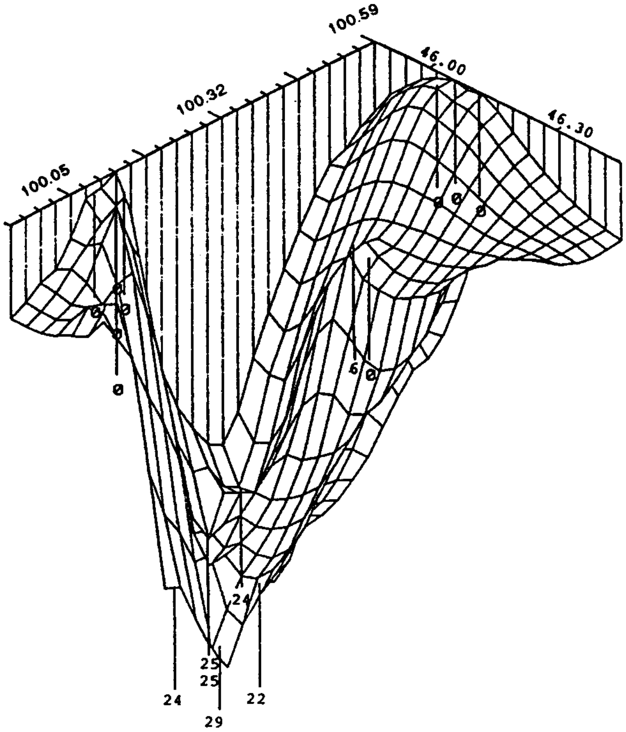

Figure 14-Inverted surface representation of the isopach data of the "Linton" volcanic ash bed as mapped in Figure 13. Diagram is presented as if the ash top were a datum. Shape of the deposit suggests deposition on an erosional surface within the Fox Hills Formation. No ash records from the Hell Creek Formation (Feldmann, 1972) are included.

to be understood about the lateral relationships of these rocks.

Logan--McIntosh Lithofacies Complex

Eastward from central Emmons County across Logan and McIntosh counties there occurs a consistent series of siltstones and brownish sandstones that are lateral equivalents of the strata described by Fisher (1952) in central Emmons County. These are characterized by increased glauconite content, eastwardly diminishing claystone and shale content, very scarce fossils, prominent siltstones, and sandstones containing cemented intervals -- often three in number -- which coarsen eastwardly, becoming medium-grained upward in the section. In restricted beds, sandstones are coarser here than in any area except, perhaps, in the subcrop of "Colgate Member" in the Mercer-Oliver facies. The log in Figure 15 exemplifies the lithofacies included in this complex. Further logs descriptive of these rocks are NDSWC #5434 and #5419 (Klausing, 1982, p. 145 and 206).

Due to erosional and depositional effects of glaciation, outcrops of this facies complex are scarce; most are roadcuts revealing 10 or 20 feet of section at best. Fox Hills rocks have been eroded east of a north-south line roughly through the centers of Logan and McIntosh Counties. The erosional remnant known as Shell Buttes (Sec. 26, T. 133 N., R. 73 W.) is an outlier that provides important insight into regional depositional patterns. The outcrop is a fine-to-very fine- grained, brown sandstone encompassing a massive oyster bank preserving large *Crassostrea glabra* clumped in living position with dead shells current-

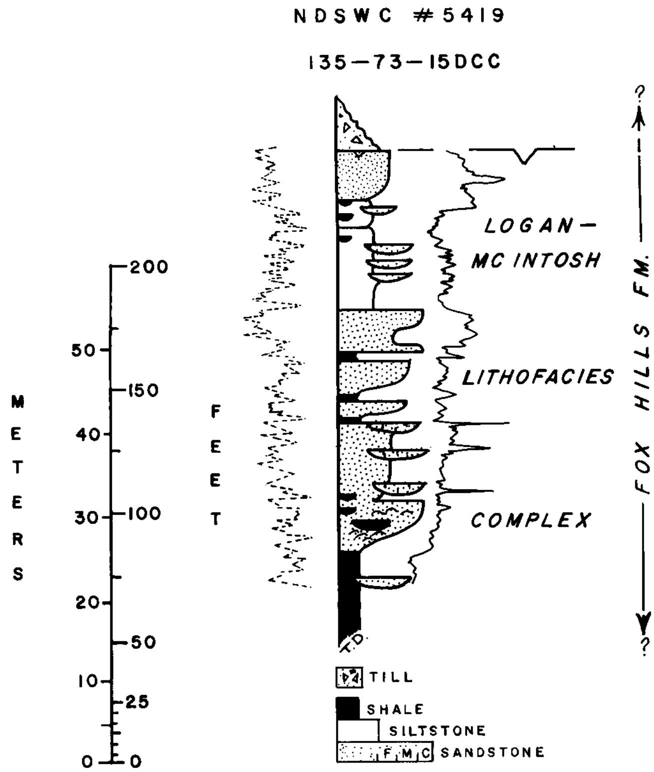

Figure 15-Log section of NDSWC test well #5419, Sec. 15, T. 135 N., R. 73 W., Logan Co., North Dakota (Klausing, 1982, p. 206-7). Sandstone and siltstone dominate the Logan-McIntosh lithofacies complex. Sections are often erosionally truncated; base of this well is in glauconitic shale, an unusual lithology not normally characteristic of the Pierre, which is perhaps more correctly associated with Trail City lithotopes. Approximately the first 25 feet (7.6 m) of fossiliferous sandstone may be the only evidence of the Timber Lake Member in this area. Three prominent spikes on resistivity log are likely calcite-cemented sandstone beds corresponding to the green sandstone beds used as datums by Fisher (1952) in Emmons Co., North Dakota. There they contain an unusual marine fauna, frequent large clay galls, unique mineralogy and flaggy bedding not seen in the Timber Lake Member.

bedded on the flanks of the estuarine tidal channel in which they dwelt (Feldmann and Palubniack, 1975). Orientation of valves in life position provides an index of the direction of tidal currents (Lawrence, 1971) which was 4 degrees west of north (N=27) at this location (Erickson and Hickey, unpublished data). Although no record of the tidal flat sediment remains, it may reasonably be assumed to have been a muddier facies of the same very fine, indurated sandstone that now surrounds the oysters. This outcrop is consistent with upper facies of the Logan-McIntosh complex across these counties, the significance of which will be interpreted elsewhere.

Cedar River Lithofacies Complex of the Hell Creek Formation

In the previous discussion of the upper contact of the Fox Hills Formation I redefined the top by lowering it over a portion of Stark, Hettinger, Morton and Grant Counties compared to usage of others (e.g. Cvancara, 1976; Trapp, 1971). In doing so, the corresponding thickness accrues to the Hell Creek Formation. This region contains one, sometimes more, units logged as "fossiliferous" sandstone alternating with green lignitic shale, or lignite, in composite thicknesses that reach 370 feet (114 m) above the base of the Hell Creek Formation. Some of these rocks are represented on Figures 4b and 5.

Examination of well cuttings, though generally inconclusive as to fossil content, has provided some proof of the marine origin of these fossiliferous sandstones. In samples from NDSWC well #3628 (1160-70 feet) in Hettinger County, the fossil fragments belong to a marine gastropod, probably *Drepanochilus* sp. All NDSWC test wells logged with fossiliferous sandstones in the Hell Creek Formation were noted and have been encompassed on Figure 11. The "fish-hook-shaped" pattern thus produced lies parallel to the north interfluve of the Cedar River in Adams and Hettinger Counties of North Dakota, and I have borrowed that geographic term to describe this "complex" of lithofacies facies.

Proximity of these sediments to the type section of the Breien Member of the Hell Creek suggests they may be related to that marine tongue of the Fox Hills that penetrates the Hell Creek Formation (Laird and Mitchell, 1942; Frye, 1964). Physical correlation based upon descriptions of drilled lithologies is not convincing, however, and further study is needed to be certain of lateral relationships among these sandstones.

Questions of Facies

I raise questions regarding the interpretation of Fox Hills lithofacies relationships with the hope that they will be fruitfully explored by future workers. First, are the units termed "Colgate Member" by various workers in fact equivalent to the Colgate as originally defined in Montana, and, if they are not, why do we persist in using the name (and concept) inappropriately? Secondly, how is the "Colgate" of the Mercer- Oliver lithofacies complex related in time, space, and depositional origin to the "Colgate lithofacies" defined by Waage (1968) very convincingly as a tidal-channel sandstone facies developed in back-bar, intertidal lagoons? Thirdly, how may facies west of the Missouri Valley be related to those associated with the Linton Member in the Emmons lithofacies complex to the east. Lastly, how do the subsurface Fox Hills facies relate spatially to the Hell Creek Formation? As I stated earlier, it is not my goal to answer these questions but to raise them and to note that thorough petrographic, stratigraphic, and structural studies must form the criteria for their answers.

PIERRE AND FOX HILLS STRUCTURE

The Missouri Valley region of Fox Hills deposition lies on the southeastern margin of the Williston Basin including its transition onto the "stable," positive northwestern flank of the Transcontinental Arch (Figure 2). Studies of Paleozoic subcrops have verified that the Missouri Valley region has repeatedly served as a hingement area of this basin margin (Petersen, 1984; Anna, 1986a, 1986b; Moore, et al., 1987), and that fracture- enhanced trends of porosity and permeability in Paleozoic units are related to basement controls (Freisatz, 1991) It was suggested some time ago (Erickson, 1968, 1970) that tectonism, evidenced by earthquake epicenters, reflected presence of shifting basement blocks that have influenced both erosion and deposition patterns throughout the existence of the basin.

Orientation of systemic unconformities summarized by Shurr, et al. (1989) indicates a general north-south strike of those boundaries through the study area suggesting consistency of tectonic control upon the location and orientation of the erosional margin of the basin through much of the middle and late Phanerozoic. This is in agreement with interpretations that place the Churchill-Superior basement province boundary parallel with the Missouri River valley underlying the area between Bismarck and the southern border of North Dakota (Laird, 1964; Gerhard, et al., 1990, recognizing the region as one of orogenic activity (Green, et al., 1985).

The first documentation of linears in the Williston Basin made from Landsat data was by Munsell (1975) and O'Brien (1975). They demonstrated northwest-southeast and northeast-southwest patterns through much of the region (Erickson, et al., 1975) which have since been verified over a wider area by Anna (1986a). Linear patterns portend either direct, or indirect, control of both deposition and subsequent erosion by periodic displacement of Precambrian basement blocks along pre-existing faults (Erickson, 1968; Erickson, et al., 1975; Shurr, 1976). This was recently summarized by examination of isopach trends of several Cretaceous units in four chronostratigraphic intervals throughout the northern Great Plains (Anna, 1986a). Three paleo-lineament zones, the NE-SW oriented Mondak, Kaycee and Sybille and the NW- SE oriented Des Moines, have had potential to influence structural conditions in the region of study (Maughan and Perry, 1986; Anna, 1986b). Another set of lineament zones has been recognized by Brown and Brown (1987). A third pattern, essentially that of Erickson (1970) who first described the structural origin of the Nesson Anticline, was outlined by Gerhard, et al., 1987. Discussion of relationships between Cretaceous depositional patterns and linears from Landsat images was provided by Shurr and Rice (1986) in Montana and South Dakota.

The strongest independent evidence for basement reactivation lies in the separate, stepwise onlap of formations against the Transcontinental Arch (Cobbin & Merewether, 1983). The Colorado Lineament (Warner, 1978) is the most obvious surficial expression of an ancient basement fault pattern related to the southeastern margin of the Williston Basin. Gerhard et al. (1987) have suggested shear couples along this lineament when it functioned as a wrench fault system.

Sediments of the Zuni Sequence in the Williston Basin (Shurr, et al., 1989) were shown to reflect, in part, the NW-SE basement influence. A series of broad "paleotectonic elements" was defined on the southern and western rim of the basin. A synform with southern closure was interpreted to have influenced the Missouri Valley region. Fox Hills and younger rocks were not included in the Zuni study. On a "macro" scale, it is important to recognize that the Transcontinental Arch (Figure 2) has defined and produced the erosional limits of strata by its successive subsequent tectonism as the basin subsided, but it has seldom restricted deposition to the southeast entirely. Facies patterns have been modified by the shelf environment that was repeatedly produced by this positive structure through the Phanerozoic (Cobbin and Merewether, 1983; Witzke, et al., 1983; Shurr, et al., 1990). I suggest that the Fox Hills was no exception.

Fisher (1952), Laird and Mitchell (1942), Carlson, (1982), and Howells, (1982) have demonstrated structural deformation of the top of the Pierre Shale. Figure 16 is a compilation of data from these sources plus all published NDSWC test wells which have reached Pierre Shale. Deformation is greatest in Emmons and northeastern Sioux Counties where there is more than 300 ft (91.8 m) of structural relief on the surface. Cause and timing of deformation have not been previously discussed.

Depositional patterns of basal Fox Hills sediments described earlier (Figures 8 and 9) indicate structural highs through central Emmons County and southward through Sioux County into Corson and Ziebach Counties of South Dakota. These features seem to have trapped coarser clastics as coastal facies prograded into the region. This pattern is not uniform, however, indicating that source-controlled effects are also reflected in the basal Fox Hills sedimentation patterns.

Examination of the Pierre structural surface suggests the existence of both compression-and tension-related deformation in areas of Morton, Grant, Sioux and Emmons Counties where control is sufficient to define structures. Simple axial constructions in the Emmons-Sioux region suggest that basement shear along a NW-SE zone may have been involved in the deformation process.

Two prominent structural conditions on the Pierre that have had controlling influences upon Fox Hills sedimentation are the apparent folds in Emmons County and a monoclinal platform in NE Grant County that is manifest by a greatly reduced regional dip (Figure 16). Interpreted paleo-lineaments and Pierre-related structures are included on Figure 17.

Two iterations of structural interpretation on the top of the Fox Hills reflecting different choices for the upper contact have been prepared. Figure 18 is based upon the higher pick of the Fox Hills-Hell Creek contact shown on Figures 5, 6, and 7 as picked on published NDSWC logs and as used by Cvancara (1976). Figure 19 is based upon the lower pick, generally the first lignite, as illustrated in the same figures. In the area mapped in South Dakota contact choice is based upon my interpretation of published data (Stevenson, 1956; Waage, 1968) and the same picks are used in each figure. Structure in the Emmons and eastern Sioux County region is subdued. Although control is a bit weak, the maps suggest continuing deformation during and following Fox Hills deposition. Specifics of the two maps differ, yet both reflect a shift of deformation into western Sioux, Grant and eastern Hettinger Counties after Fox Hills deposition. A broad region of gentle dip has migrated from Morton County to the northern portion of Sioux County during the interval of Fox Hills deposition. NW-SE oriented paleostructures are suggested on both Figures 18 and 19 as a series of fold axes. Presumably the Pierre had

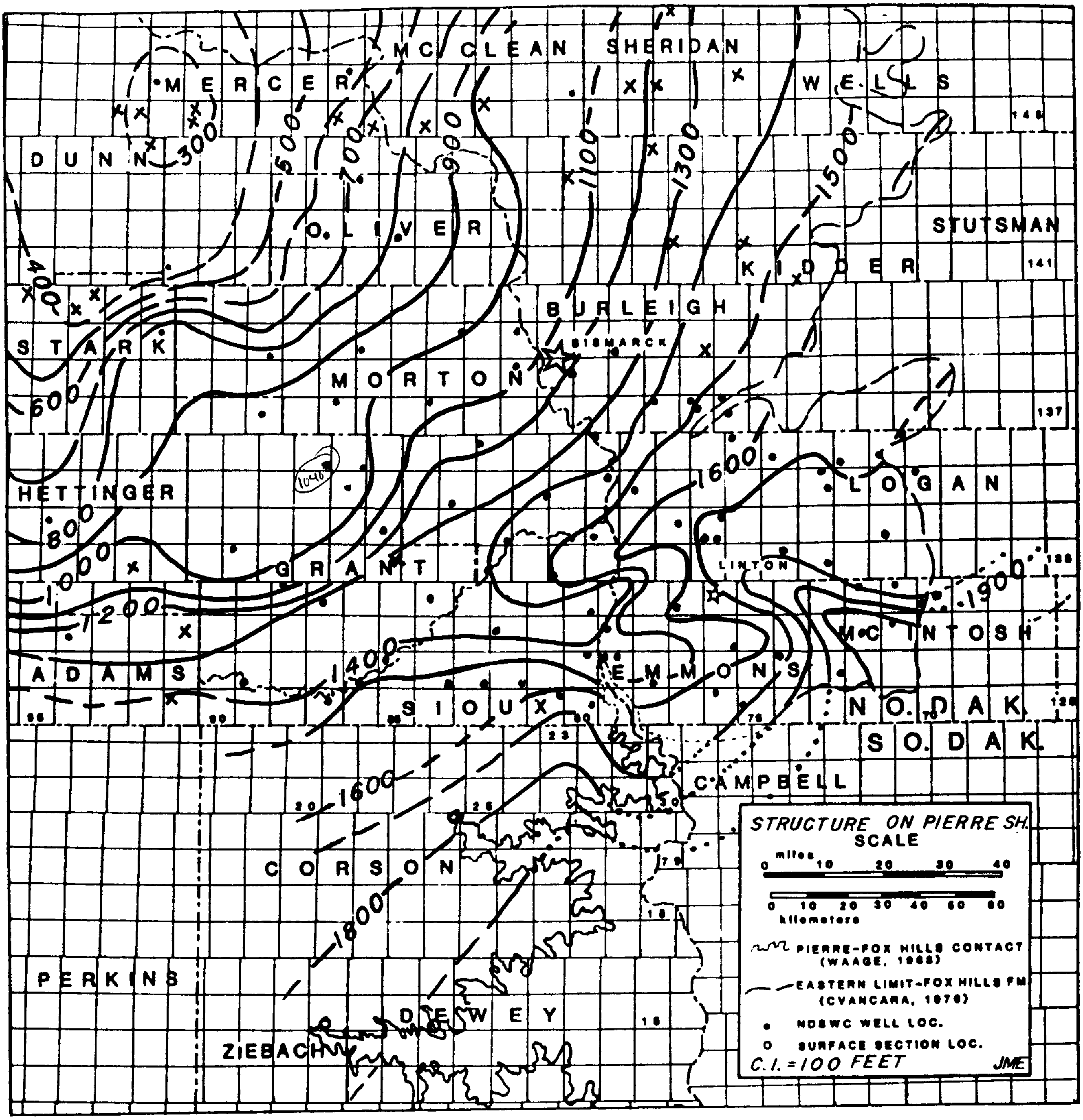

Figure 16-Simple interpretation of structural configuration of the top of the Pierre Shale. Data from NDSWC logs (see Figure 1); Carlson, 1982; Howells, 1982; Waage, 1968; JME unpubl. field records.

been partially deformed before Fox Hills sedimentation began and further movement continued that deformation process during Fox Hills time.

Control is sufficient to demonstrate post-Fox Hills deformation in the subsurface similar in degree to that suggested by Fisher (1952) based upon field studies of exposed Fox Hills strata. More control would be desirable for thorough analysis of structural influence on Fox Hills deposition, but I believe sub-

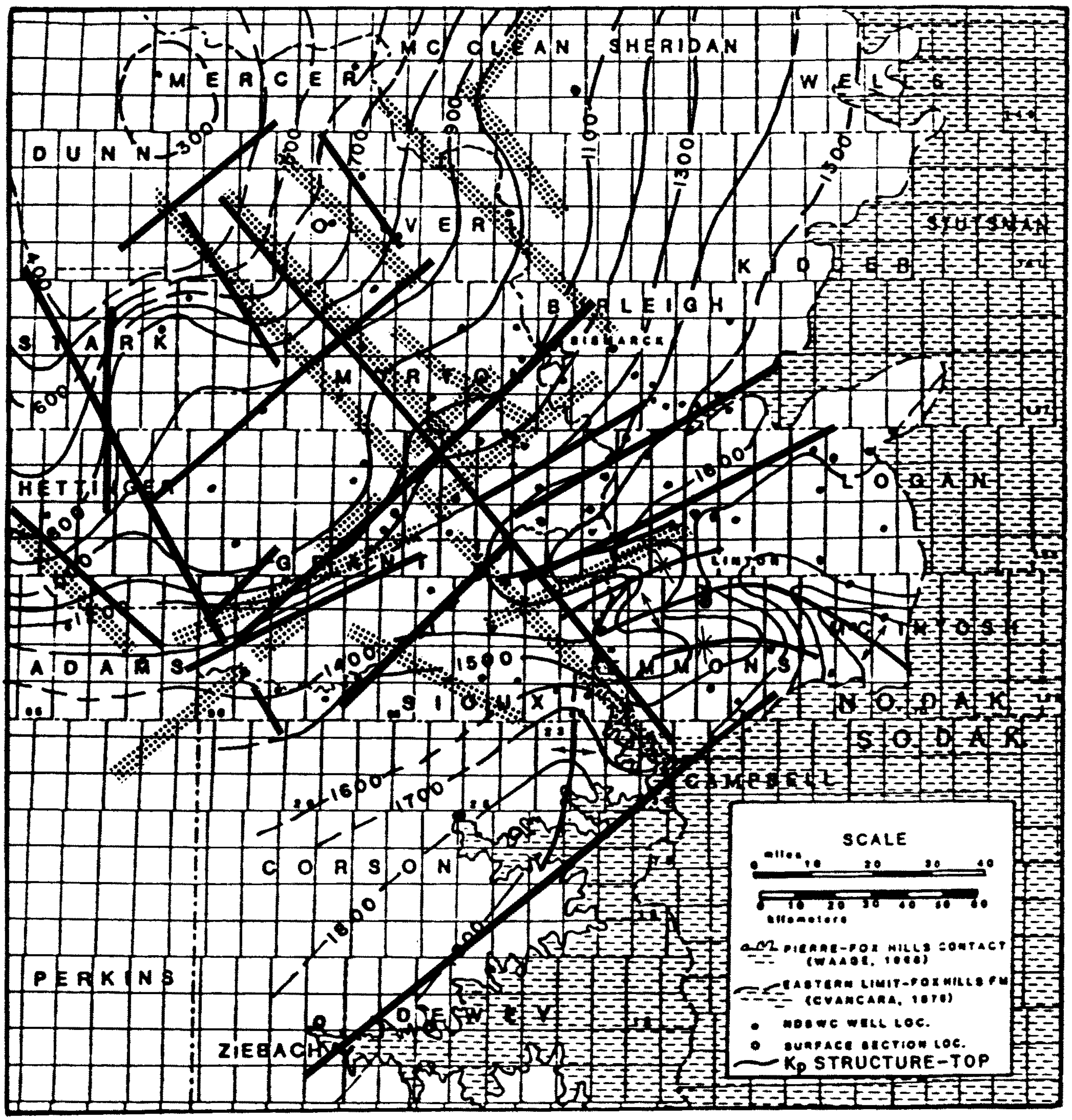

Figure 17-Simple Pierre structure as in Figure 16 onto which linears interpreted from maps in this study have been superimposed. Solid lines interpreted from Figures 16, 18, 19 and 22; linears represented as dotted patterns are interpreted from Figures 11, 20, and 21.

stantial structural influence on some Fox Hills sedimentation patterns can be demonstrated. Close analysis of the thickness and distribution of individual units within the formation will be required to resolve timing and extent of the influence of particular structures on sedimentation patterns during Fox Hills deposition. While future study might indicate timing and influence of structures, we are left with the following questions

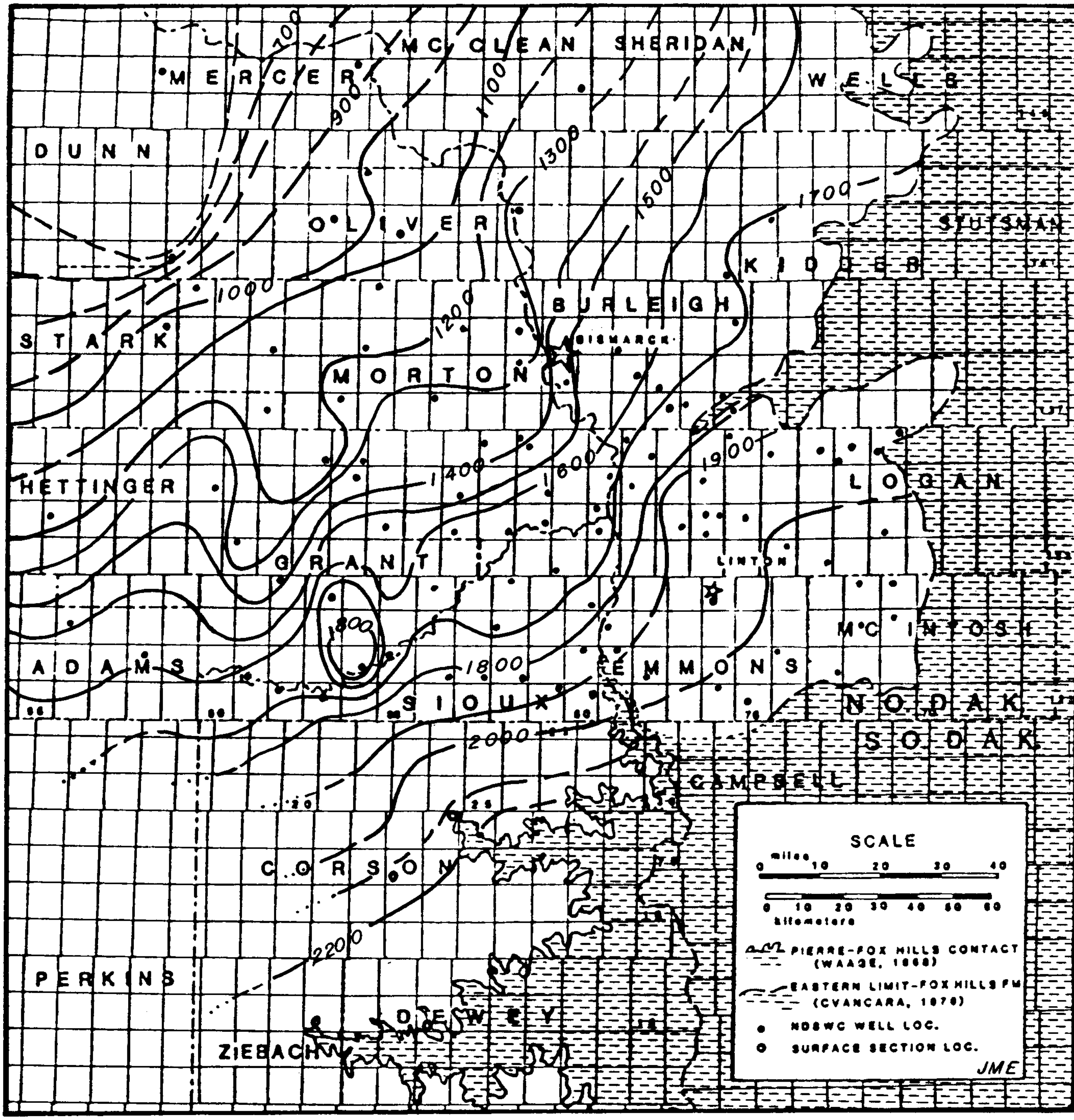

Figure 18-Simple structure contour map drawn on top of the Fox Hills Formation using higher picks of the Fox Hills-Hell Creek contact as described in text. Deformation of the Fox Hills in Hettinger, Grant and Sioux Counties suggests a westward shift of deformation during Fox Hills deposition. Data from NDSWC studies cited in Figure 1, also from Kume and Hansen, 1965; Stevenson, 1956; Cvancara, 1976; Waage, 1968.

now.

Questions of Structure

What is the real structural condition of the Fox Hills Formation in the region? What motions have produced this structure? When, and at what rates, has

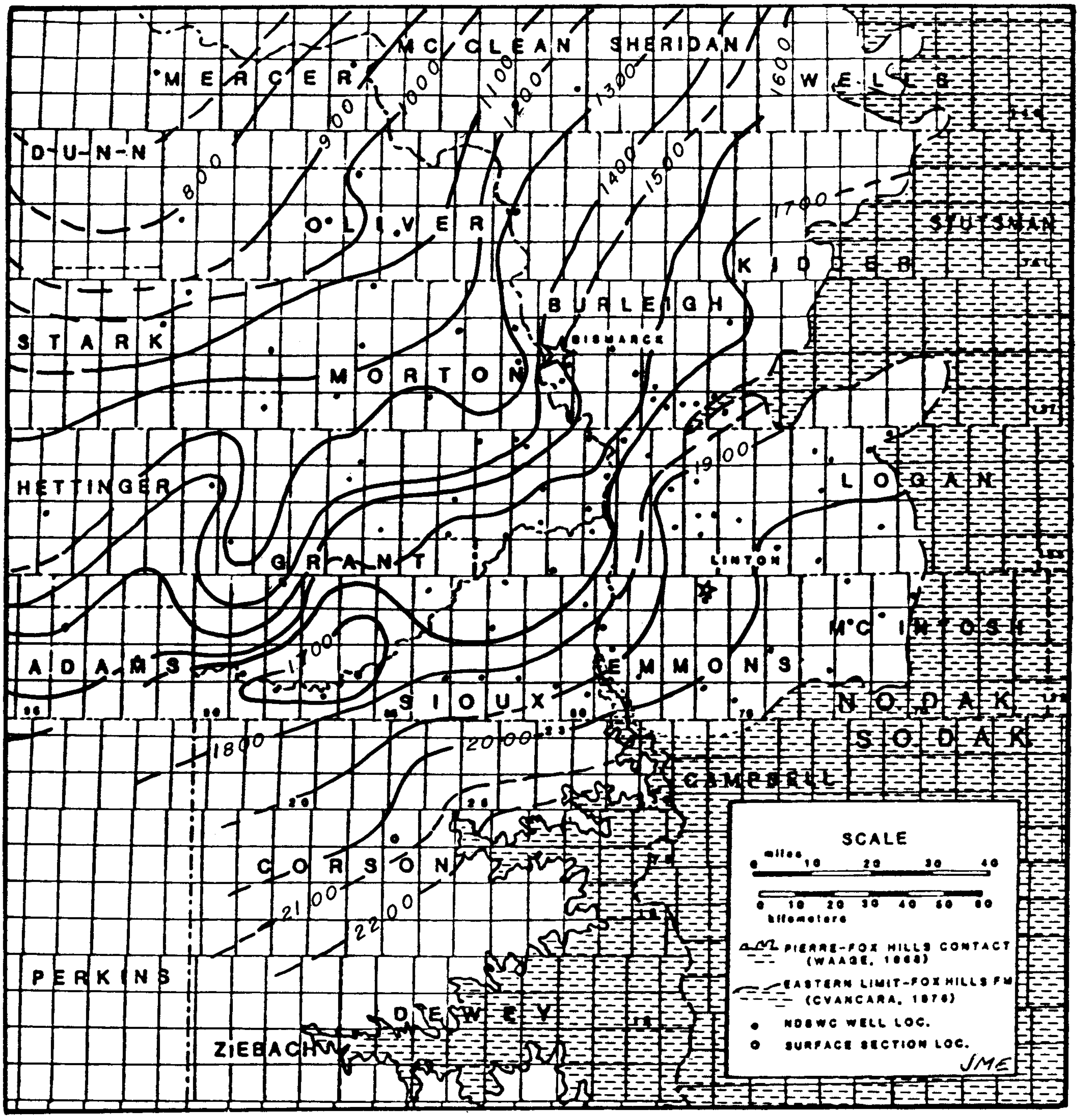

Figure 19-Simple structure contour map drawn on top of the Fox Hills Formation using lower picks as described in text. This choice of Fox Hills-Hell Creek contact de-emphasizes structural anomaly in Sioux County and reduces structural dip in northwestern portion of the study area. Regional trends are maintained. Data from NDSWC studies cited in Figure 1, also from Kume and Hansen, 1965; Stevenson, 1956; Waage, 1968.

deformation occurred? How closely have structural elements controlled facies distributions in both the Fox Hills and Hell Creek Formations? What are the local and regional groundwater patterns resulting from structural conditions? Have fossil distributions been controlled by structural elements? Numerous questions related to the structural geology of the area require investigation as part of this holistic stratigraphic investigation.

FOX HILLS DEPOSITION

My discussion of various lithofacies "complexes" introduced the idea of heterogeneity of lithology and of stratigraphic sequence previously in this paper while presenting logs that support the observations. Here it is appropriate to present data that integrate those patterns with the formation as a regional lithostratigraphic unit.

Patterns of Thickness and Distribution

Cvancara (1976) constructed an isopach map of the formation throughout North Dakota using, in most cases, tops chosen by geologists for NDSWC test well data. The isopachous map presented in Figure 20 is constructed from similar picks which result in a total thickness of the Fox Hills Formation in excess of 350 feet (107 m) in southeastern Grant County thinning rapidly until it is less than 200 feet thick (61 m) in adjacent southeastern Morton County. Adjusting thickness according to a Fox Hills top consistent with my previous discussion produced a maximum thickness of 325 feet (99 m) and generated an additional NW-SE elongate thin region in Stark and Morton Counties (Figure 21).

In each solution the Missouri Valley exposures and the type area in North and South Dakota fall within a thick portion of the formation that lies along depositional strike. Complete sections are scarce here because the formation is exposed, and often partially eroded, throughout much of Emmons, Logan, Sioux, and Corson Counties. Nevertheless, buttes, and interfluves preserve a sufficient number of complete sections to create a consistent image of Fox Hills thickness.

The isopachous maps offer more emphatic linear, or orthogonal, patterns than do the structure maps of either the Pierre or Fox Hills. Elongate thick and thin conditions parallel paleo-lineaments in both prevailing directions defined by O'Brien (1975) and suggested by structure contours. There appears to be a strong relationship between the regional patterns of linears and lineaments and the accumulation of coastal sediments represented by the Fox Hills Formation.

One emphasis of the present study is to call attention to the fact that the formation, as exposed in the Missouri Valley, is not typical of other nearby regions either in outcrop or subcrop. Although Figures 20 and 21 do not record lithology, both demonstrate that thickness of the formation varies widely northwest of the Emmons-Sioux-Corson County region of outcrop. Comparisons with Figure 11 emphasize that lithofacies described in this paper, particularly the Grant-Stark, Mercer-Oliver, and Missouri Valley complexes, are geographically distributed in patterns that correspond to thickness patterns on the isopachs within limits of control available to me. There is also strong agreement between isopachous trends and linear trends that have been noted on structure maps (Figures 17, 18, and 19) herein. This agreement supports the suggestion that structural trends strongly influenced Fox Hills depositional patterns. Cross sections presented by Armstrong (1978) and unpublished fence diagrams of my own further support structural control of Fox Hills paleogeomorphology and sedimentation patterns. Precise relationships should be the subject of additional studies for they will likely influence groundwater distribution in the region in the general manner discussed by Anna (1968a).

Patterns of Sandstone Accumulation

Using the data contoured in Figures 19 and 21 based upon the "thin" interpretation of published logs I have mapped percent sandstone across the region (Figure 22). Unlike interpretations based upon cross sections that imply a blanket of Timber Lake- type sandstones underlying much of the south-western Williston Basin (e.g., Feldmann, 1972, Pl. 1), the patterns reflect distinctly discontinuous sandstone concentrations within the Fox Hills. As Figure 22 readily indicates, the sandstone-dominated units that characterize the formation in its outcrop belt along the Missouri Valley are not represented far westward from the Emmons-Sioux County border. This again supports my contention that the exposed Fox Hills section should not be used to model its deposition throughout the basin. In fact it may make a poor model for the complex facies relationships contained in the subsurface.

Three areas in which the formation is exceptionally sandy (greater than 80% sandstone) are noted in Figure 22. A northeast-southwest-trending sandstone body extending from Sioux County into Corson County, South Dakota, contains the type Timber Lake Member of the formation. Note that areas of 80 percent concentration in Kidder and eastern Burleigh County, and in Mercer and Oliver Counties are isolated from the type Timber Lake Member by intervening regions of much reduced sand content.

Sandstone concentration in Mercer and western Oliver Counties is associated with the Mercer-Oliver complex defined by thick "Colgate" sandstone (Figure 11), but this unit in the top of the formation is only partially responsible for high sandstone percentages there. As Figures 8 and 9 demonstrate, sand was deposited in this area, low in the Fox Hills section, presumably early in Fox Hills time, well before "Colgate" deposition prograded into the area. In T. 142 N., R. 86 and 87 W., "Colgate" sandstone capping the

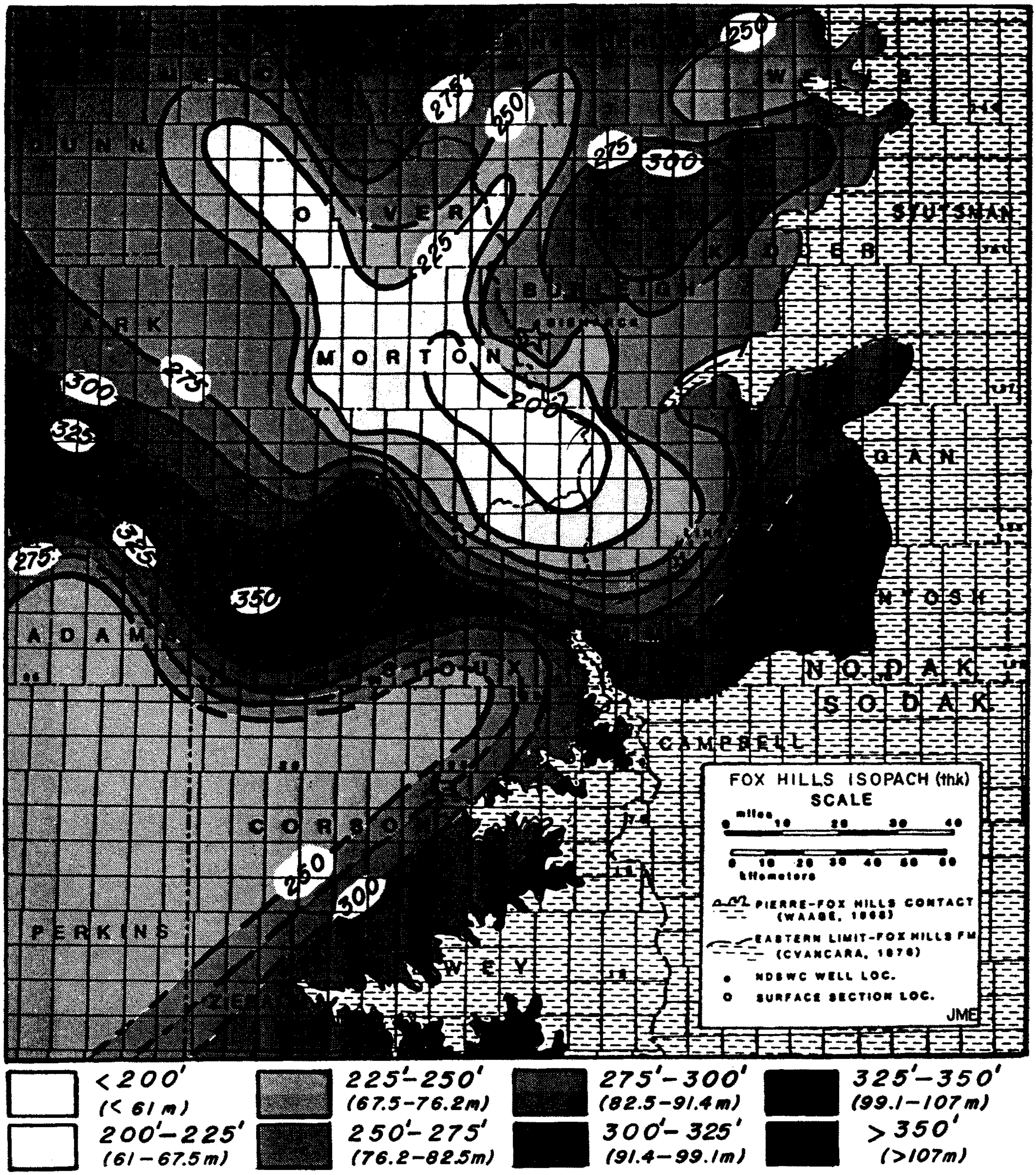

Figure 20-Isopachous map of the Fox Hills Formation using higher picks of the top as discussed in text. In this and the succeeding figure thinner areas of the formation coincide with areas where lignite and carbonaceous sediments are prevalent in the formation. These patterns emphasize those areas where Hell Creek deposition began earliest. Shale pattern on eastern portion of this and succeeding maps represents area where Fox Hills Formation is absent by erosion. Data from sources noted in Figure 18.

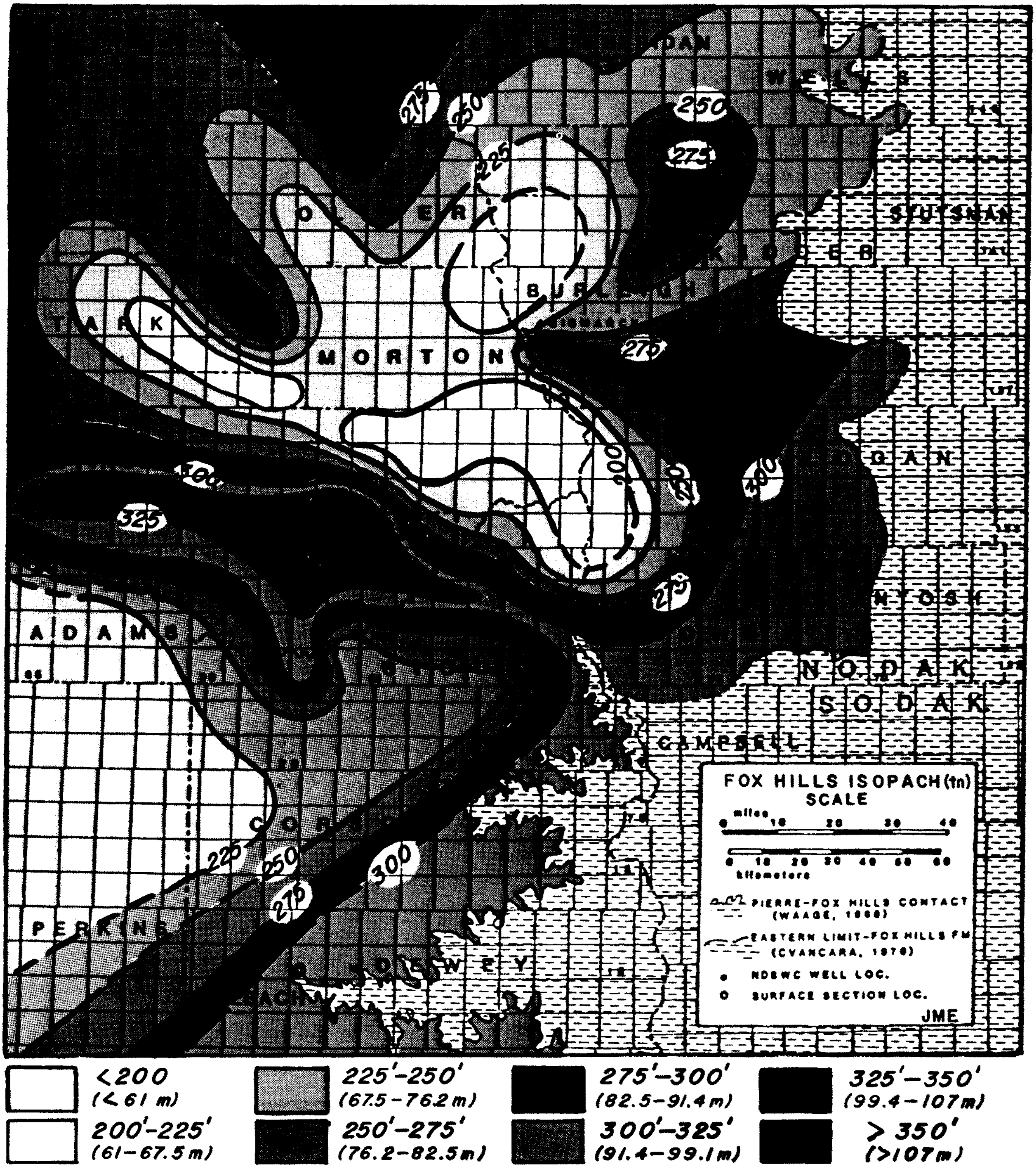

Figure 21-Isopachous map of the Fox Hills Formation using lower choice of the Fox Hills-Hell Creek contact (= thinner Fox Hills sections) discussed in text. Area over which Hell Creek deposition occurred earlier is enlarged by this interpretation and more accurately portrays the relationships between Fox Hills and Hell Creek lithotopes. Data sources as in Figure 19.

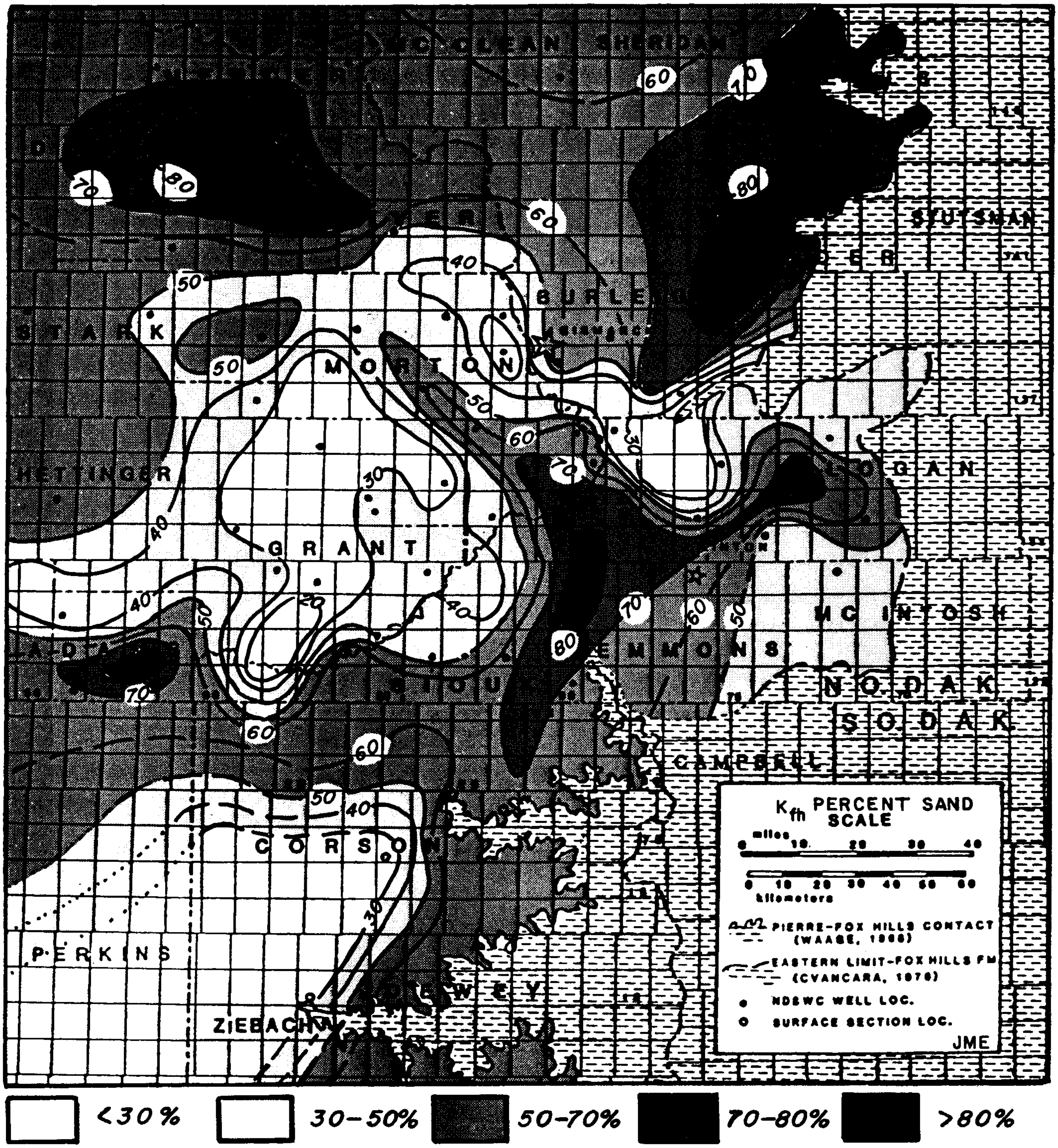

Figure 22-Percent sandstone (isopleth) map of Fox Hills Formation using lower (thin) picks of the top. Note the general correspondence of the Grant-Stark lithofacies complex with the area in which the formation contains less than 50 percent sandstone in North Dakota. Sandstone concentrations belonging to the Missouri Valley lithofacies complex which includes the Timber Lake Member are emphasized by the 70 percent isopleth. Data sources as in Figures 19 and 21.

formation is less than 20 feet (6.2 m) thick; yet the formation, which is 250-275 feet thick (76 to 82 m), still carries more than 80 percent sandstone at these points (Figures 20, 21, 22).

Two sand-poor regions, one centered in Grant County, the other in Perkins, Corson, and western Ziebach Counties, are obvious features of the sandstone percentage map (Figure 22). In South Dakota the sand-poor region includes the type section of the Iron Lightning Member dominated by Bullhead and Colgate lithofacies. Waage (1968) considered these facies to have been deltaic in origin, pointing out that they overtopped barrier island sands of the Timber Lake Member as the coast prograded northeastward. In Grant County, an area generally having less than 30 percent sand, and in places less than 20 percent, corresponds to the locus of the Grant-Stark complex (Figure 11) which also seems to overtop, or is incised into, the Timber Lake Member. Comparison of this with Figures 18 - 21 suggests that both Pierre structure and structurally-controlled subsidence during Fox Hills deposition have contributed to these depositional patterns, providing many avenues for future study. Reconstructions of depositional environment will be suggested in the following section of this paper.

INTERPRETATION POTENTIAL

As I pointed out initially, the purpose of this report is not to present the ultimate interpretation of the Fox Hills in the region of the type area; rather it is intended to point out what is not yet understood as thoroughly as it ought to be. Having presented simple structural, thickness, and lithologic summaries of original and published data, I would conclude here with a series of interpretations and mention some issues arising therefrom.

Structure

Although generally considered within the larger structural setting of the Williston Basin, the fact is that basin margin, or more correctly, Transcontinental Arch (and Trans-Hudson Orogen), tectonics dominate the style of deformation and penecontemporaneous deposition in the type area of the formation as noted previously. Depositional strike lay parallel to a positive shelf margin that reflected relative stability of the Arch and hingement of the basin margin.

Figures 23 and 24 summarize the rectilinear orientations for two bands of ERTS-1 imagery over the Williston Basin (Munsell, 1975: O'Brien, 1975). In Figure 25 I present a composite of the baseline ERTS-1 linears data (Erickson, et al., 1975), overlain by linear features interpreted from Fox Hills isopach and facies maps presented in this study (Figures 11, 20, 21, 22) and the major linears defined by Maughn and Perry (1986) and by Brown and Brown (1987). Interpretation of Fox Hills structural data based upon the prevailing lineament patterns and northeast-southwest regional depositional strike suggests a structural solution for the top of the Fox Hills like that presented in Figure 26. In this solution the Fox Hills was reduced to datum before contouring.

There is very little field evidence to support such an interpretation although structural contouring by both Laird and Mitchell (1942) and Fisher (1952) suggested post-Fox Hills deformation in the region. In Sec. 21, T. 129 N., R. 79 W., Sioux County, the stratigraphic section at the base of the Fox Hills is repeated. Bedrock in this area adjacent to the Missouri trench is frequently displaced by slump toward the river. I have discussed water table conditions with local ranchers one of whom pointed out existence of a 90-foot (27.6 m) displacement of the top of the Pierre (my interpretation of formation) between two wells that lay only 300 feet (91 m) apart. Although it is tempting to ascribe each such offset to mass-wasting phenomena, geologists who do so will never recognize wider structural attributes of the region.

A second example of subtle structure occurs in Sec. 33, T. 134 N., R. 80 W., where coarse sandstones are well-indurated and dissected by a proglacial drainage now holding an underfit stream. The valley walls expose a very cross-stratified portion of the Timber Lake Member that suggests a gentle anticlinal fold, but dip measurement is complicated by cross-stratification coupled with weathering phenomena. I have recorded dips as great as 11 degrees here, yet those seem too steep given the appearance of the structure, and may simply be very large-scale cross-strata. The structure itself may even be an illusion resulting from a change in direction of the valley proper. Nevertheless, I am left with the firm impression of anticlinal structure each time I visit the site, and the structural interpretation in Figure 26 supports that possibility. It seems that most structure to be observed in Fox Hills outcrops will be equally subtle.

Sandstone bodies (former barrier islands) parallel a prevailing lineament pattern in the region, also one lying parallel to the margin of the Williston Basin and Transcontinental Arch (Anna, 1986b). An orthogonal pattern is suggested by the locations, shapes, and orientations of the sand concentrations. Positions at which the formation possesses 70 percent, or more, sandstone indicate loci of positive structures active at one or more instances during Fox Hills

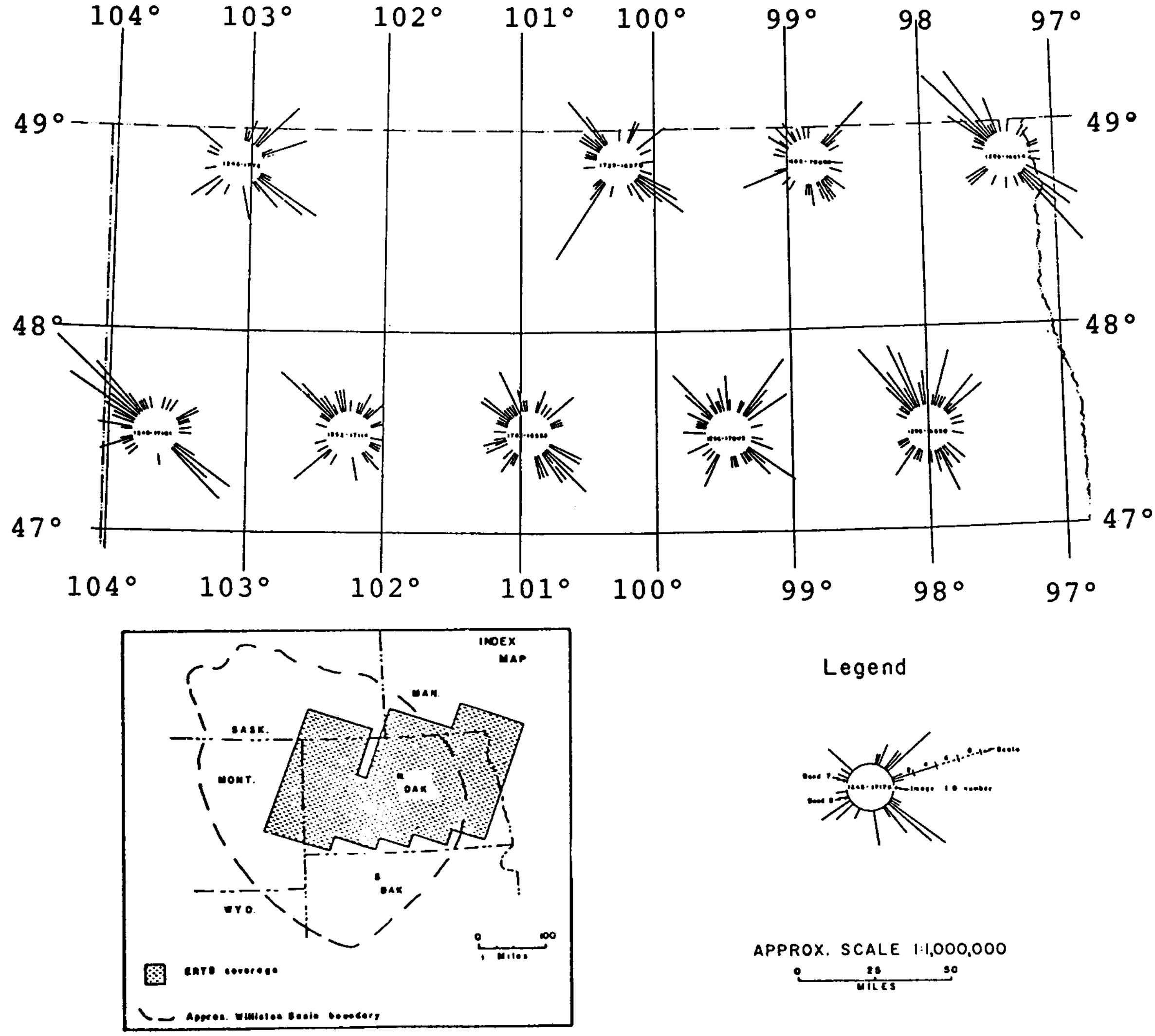

Figure 23-Orientations of linears mapped from bands 5 & 7 ERTS-1 imagery with frequency roses arrayed on image centers located north of latitude 47 degrees N. (Munsell, 1975).

deposition. Positions and longevity of inlets and distributaries, too, ought to have been influenced to some degree by this subtle tectonic "underprint."

Examination of isopach, first sand, and percent sandstone maps reinforces the impression that sediment distributions and lithofacies patterns in the Fox Hills Formation have developed in response to tectonic control of local structural elements. As might be expected, lithologies low in the formation reflect depocenters best recognized from Pierre configurations (Figures 16 and 17). Timber Lake sandstones overly Pierre highs and are relatively thin whereas silt-rich facies of the Grant-Stark complex lie in thicknesses in excess of 300 feet (92 m) on an undeformed block of Pierre Shale. Depositional patterns become decoupled from Pierre structural control after the strandline related to the Timber Lake Member passed through the region. The Mercer-Oliver and Logan-McIntosh complexes are examples of accumulations more influenced by penecontemporaneous tectonic and sealevel controls than by pre-existing Pierre structure.

New Stratigraphic Units (Members and/or Lithofacies)

Nomenclature currently employed for stratigraphic units in the formation is only appropriate for some of the areas examined herein. The exceptions are notable. The thick sandstone at the top of the Mercer-Oliver complex (Figure 4b) is not demonstrably Colgate. Over the region of its extent (Figure 11) its continuity and description suggest a unique, unnamed stratigraphic unit.

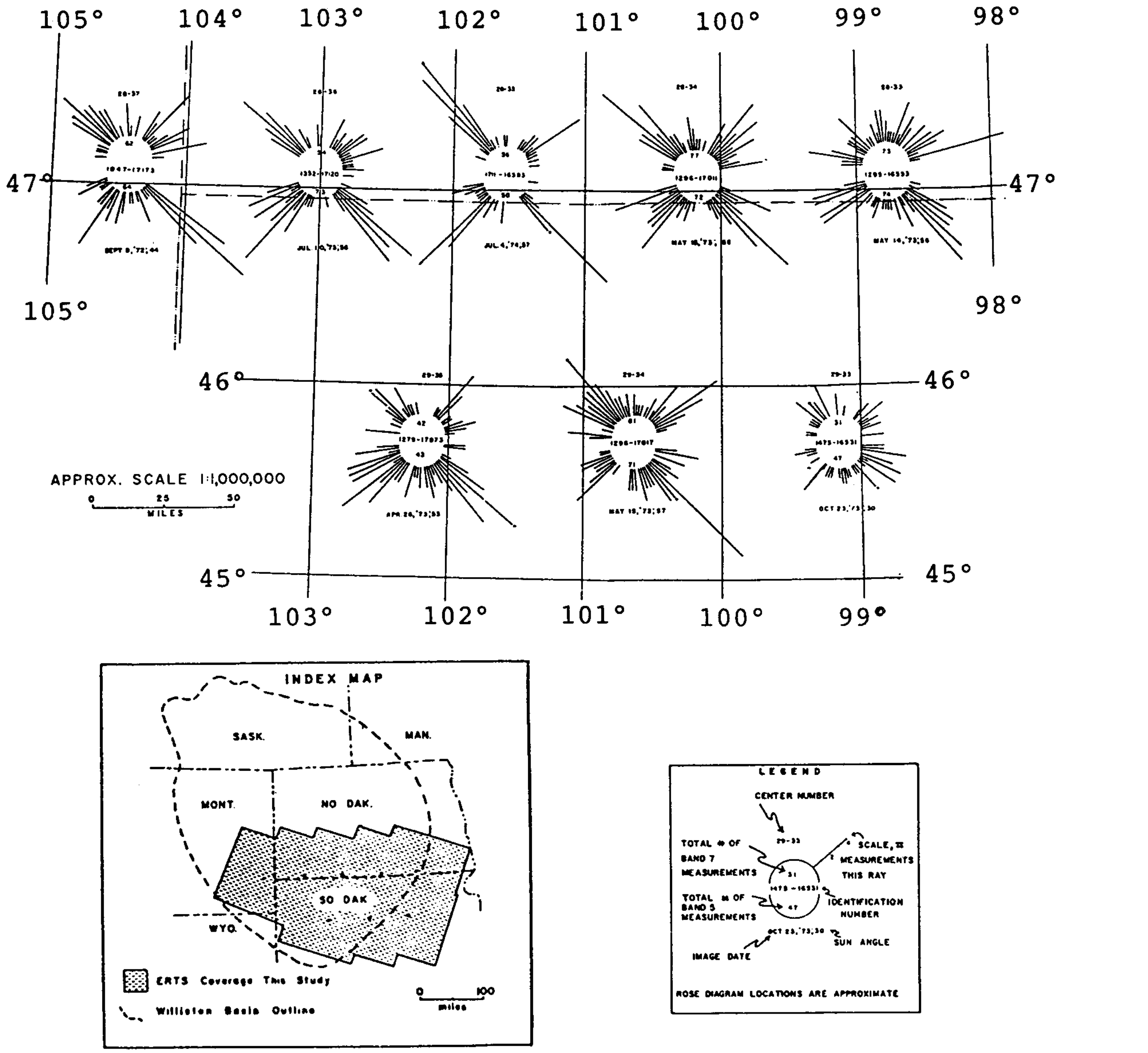

Figure 24-Orientation of linears mapped from bands 5 & 7 ERTS-1 imagery with rose diagrams arrayed on image centers south of latitude 47 degrees N.(O'Brien, 1975).

The Grant-Stark complex of facies includes thick variegated siltstone and shales at the base that may belong to an undesignated lithofacies of the Trail City Member. Alternatively, the entire complex might be viewed as formally undescribed, in which case the logs in Figures 5, 6 and 7 provide likely stratotypes for new members. Figures 5 and 6 includes sandstones that inter-tongue with variegated silts. These are absent from the section shown in Figure 7 because the site was likely distal from the source of these sands, which are interpreted as washover fan deposits originating from the southeast in Figure 6 and as crevasse splays and distributory channels in Figure 5. The percent sandstone map (Figure 22) suggests that a new name might well be applied throughout the area in which there is less than 50 percent sandstone in the formation and coincidentally where it is less than 250 (76.2 m) feet thick (Figures 21 and 22). In this same area the formation contains a large amount of carbonaceous matter that also provides a distinguishing property to the sediments. If this course of action were followed, the discussion by Pettyjohn (1967) and the data from Butler (1980) should be reviewed and incorporated as applicable.

Sandstones and siltstones of the Logan -

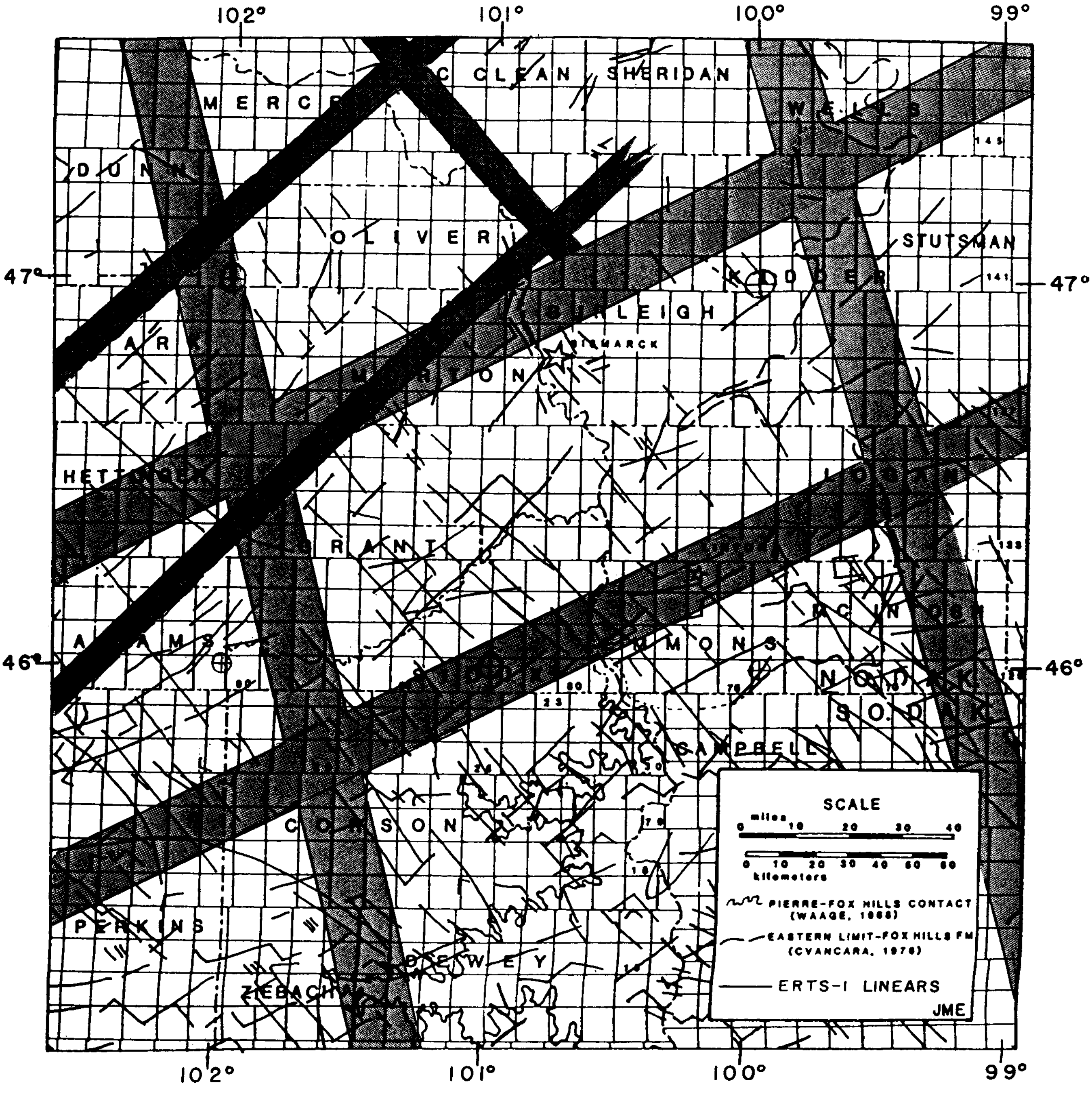

Figure 25-Linears mapped from ERTS-1 imagery for the study area (Erickson et al., 1975). Superimposed are lineaments defined by Brown and Brown (1987, p. 65) - darker gray pattern; lighter gray pattern are lineaments recognized by Maughan and Perry (1982) from various types of subsurface and surficial evidence.

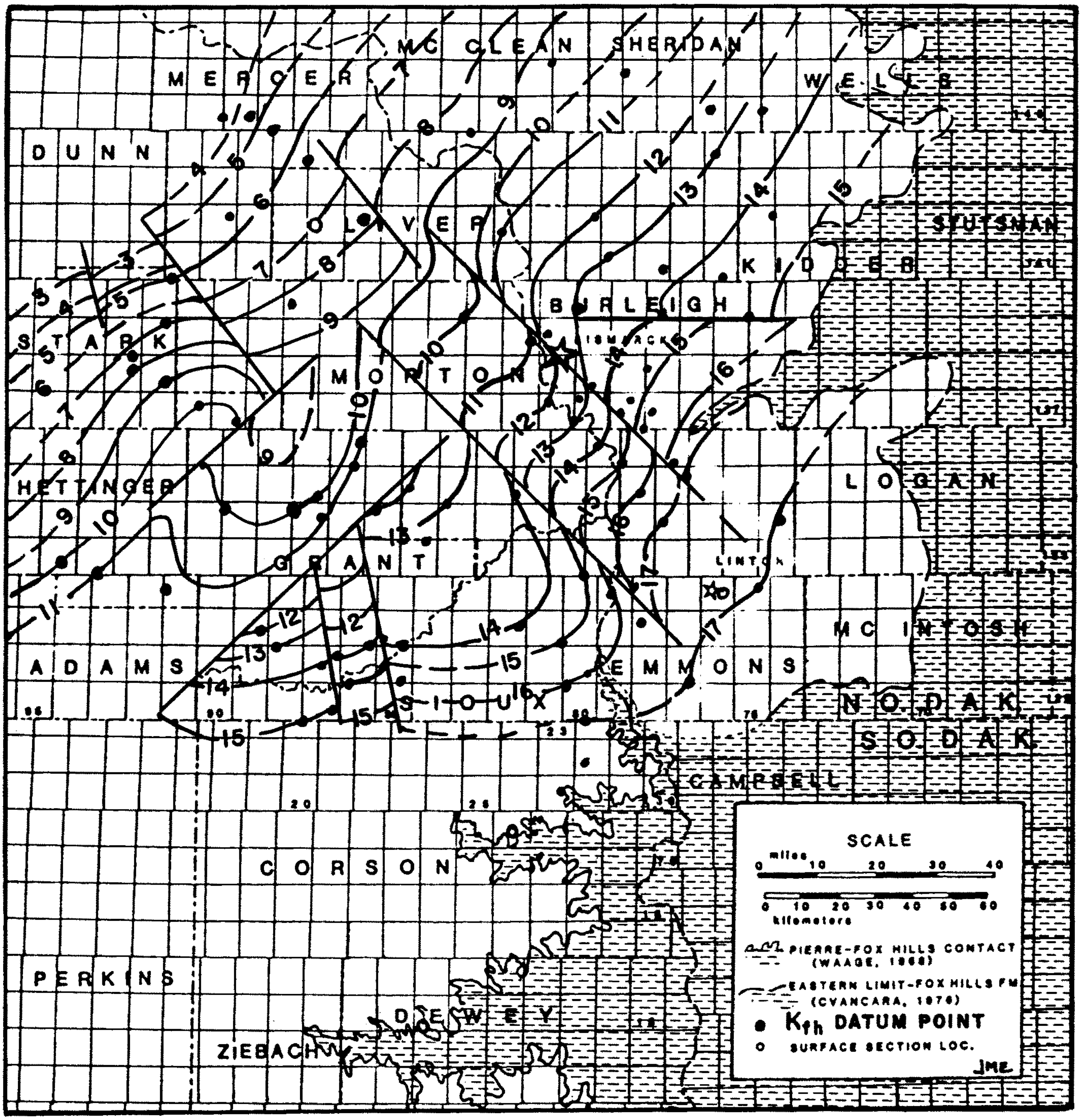

Figure 26-Interpretive structural solution drawn on top of Fox Hills Formation reduced to Pierre datum based upon Fox Hills thicknesses in Figure 21; faults are inferred from Figures 16 - 22, and 25; structure contours are in hundreds of feet.

MacIntosh complex seem to be unique. Facies are sand-dominated in Logan County, but the sandstone does not appear lithologically similar to the Timber Lake Member. Basal shale tends to be glauconitic, an unusual and characteristic attribute. Although glauconite persists in sandstones in the western portion of this region, most of the sedimentation described previously seems to have eastern or southeastern source areas and these are non-glauconitic. Coarse, moderately-sorted, gravelly sandstones, noted earlier, have not been winnowed or reworked in the barrier-type, active-marine coastal environment ascribed to the Timber Lake. Also significant for this facies complex throughout the eastern region, is the absence of carbonaceous debris in the rocks. The section in Figure 10 demonstrates the sandy nature of this complex, and it shows three indurated sands useful for stratigraphic positioning (Fisher, 1952) in the region east of Linton.

PALEOGEOMORPHOLOGY AND PALEOGEOGRAPHY

Because the Fox Hills Formation is recognized as the final significant marine deposition in the Cretaceous seaway of the Williston Basin the withdrawal of that sea is, of itself, an important event - one to be carefully examined. Understanding the paleogeography of the region as the seaway closed would seem to be of primary importance to many interpretations, including those of both marine and terrestrial biotic distributions and extinctions and of continent-wide paleoclimatic and paleo- oceanographic conditions, as well as setting the paleogeomorphic stage for re-invasion of the Williston Basin by the Cannonball Sea during the middle Paleocene.

Recognized and Unrecognized Depositional Relationships

At the time of withdrawal of the Fox Hills seaway from the Williston Basin a plexus of marine and non-marine depositional systems lay within the study region. These are summarized in Figure 28. The evidence for their origins and distributions are discussed below.

Delta Platform.--Gill and Cobban (1972) outlined the timing of regression and the strandlines associated with migration of the Sheridan Delta across the heart of the Williston Basin. The youngest strandline recognizable by fossil control was that of *Baculites clinolobatus* which those authors projected into the study area as indicated in Figure 27. Thickest deposits of this feature probably correspond with Cretaceous depocenters in western North Dakota discussed by Butler (1980) and delineated by Shurr, et al. (1989). The type area is marginal to the thickest accumulation of this deltaic wedge.

The margin of this delta, which should be distinguished as the Fox Hills-Hell Creek Delta, was distinctly lobate where it prograded into the study region. It was sediment-dominated and constructional throughout its early history. Pathways followed by major distributaries were controlled by structural features, such as the Cedar Creek Anticline and various lineaments, which, though not always above sealevel, were positive submarine features that deflected sediment distribution and eventually controlled distributary systems that prograded through the region. By the time of *B. clinolobatus* the Black Hills region in South Dakota was likewise influencing distribution patterns regionally.

Barrier Islands.--Primary sedimentary structures (Chayes and Erickson, 1973) in outcrop, coarsening-upward facies models applied by Waage (1968) and Feldmann (1972), and reiterated by Daly (1989), support interpretation of the sandstone concentration in excess of 80 percent in eastern Sioux and western Emmons Counties as the axis of a barrier island-barrier bar complex (Figure 22). Waage (1968) suggested that this feature originated in the Sioux-Emmons area and prograded southward into Corson and Dewey Counties, South Dakota, an interpretation based heavily upon absence of most of the Trail City Member from the exposed section at Linton Municipal Park.

Erickson (1978) demonstrated the occurrence of typical Trail City faunas in silty shale lithologies in nearby portions of Emmons County suggesting that its absence from the Linton Park section is atypical of regional conditions. Indeed, if one considers the Pierre Shale to have been structurally elevated at onset of sandstone deposition, there exists the probability of a disconformable contact, or of sediment bypassing, at Linton, a situation which may invalidate Waage's conclusion. Isopach trends (Figures 20 and 21) indicate that the Linton area is on one margin of a thin portion of the Fox Hills, but map control is not sufficient to detail the relationship as yet. The section exposed at Linton Municipal Park gives the definite impression that the Pierre-Fox Hills transition there is, at least, condensed as many workers have noted (Fisher, 1952; Feldmann, 1966, 1972; Waage, 1961).

Regardless of the migration direction of the Timber Lake sands, another concentration, in excess 80 percent sand (Figure 22), implies that a second barrier underlies parts of Burleigh and Kidder Counties along the same northeast-southwest depositional strike. Alter natively, this may represent a large distributary--mouth bar complex, but at present I favor the barrier island interpretation because of alignment. Regression occurred rapidly across the region and the coarsening--upward facies of the barrier bar sequence represented by the Timber Lake Member in Dewey, Corson and Sioux Counties (Figure 11, 17) and the second barrier underlying Kidder and Burleigh Counties, delineate the final fully-marine Fox Hills strand in the study area.

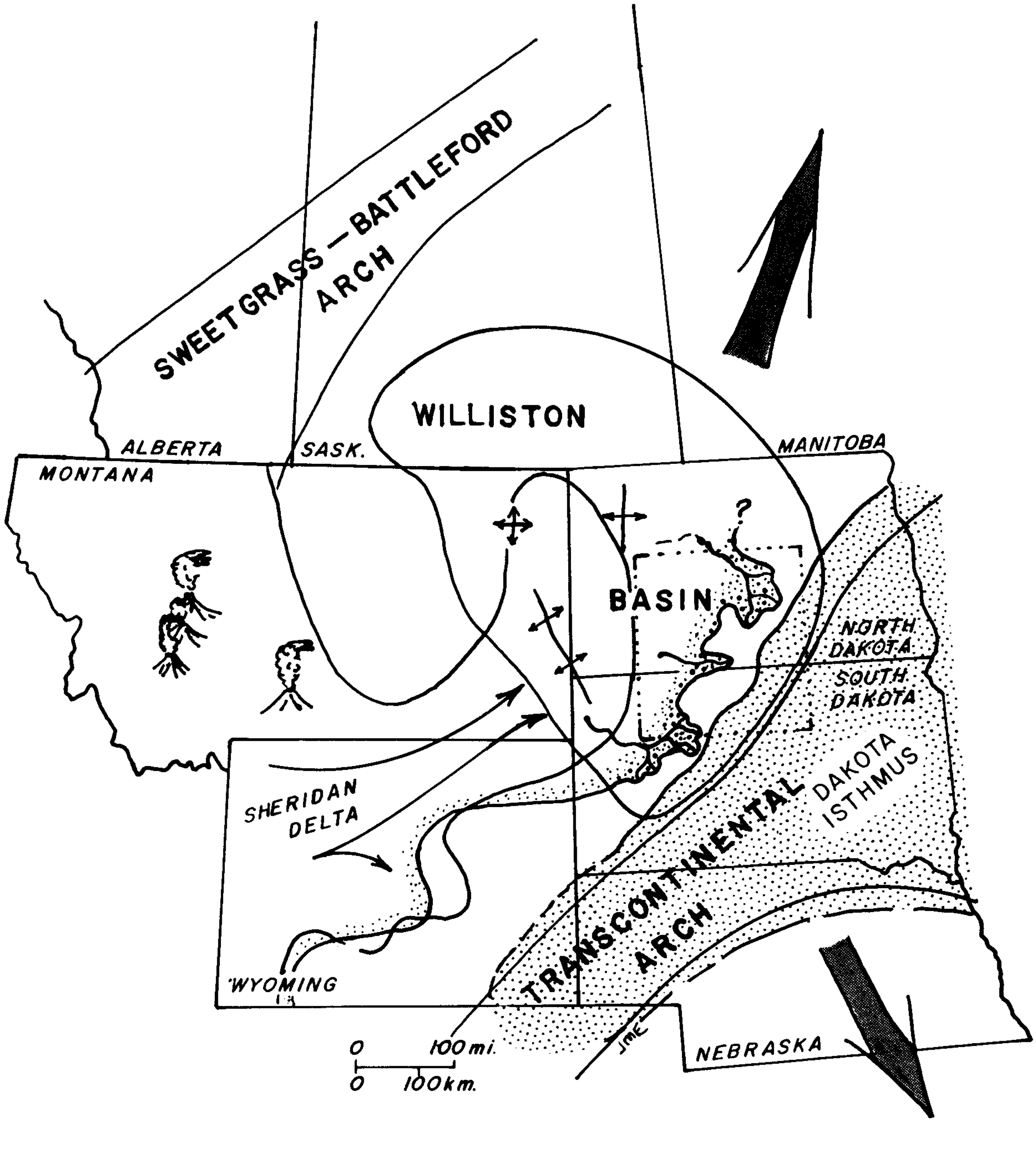

Figure 27-Map summarizing very large scale tectonic and paleogeographic features that impacted Fox Hills deposition in the study area (defined by box). The Dakota Isthmus (Erickson, 1978) generally overlay the Transcontinental Arch. Arrows indicate directions of seaway regression from the region; margins of the Sheridan Delta (Gill and Cobban, 1973) modified in the study area to show distributaries of the Fox Hills-Hell Creek Delta suggested by this study. Large shaded arrows indicate directions of regression of Late Cretaceous Interior Seaway (Fox Hills Sea) from the midcontinent.

Tidal Inlets.-- This Burleigh-Kidder barrier is separated from the Timber Lake barrier by an area of silt-and-clay- dominated deposits crossing from Morton through southern Burleigh into Logan Counties in Townships 136 and 137 North (Figure 22). It is appropriate to interpret this siltstone and shale as indicating an inlet or passageway between barriers into a lagoonal depositional setting to the west. However, lithologically the region seems more representative of a drowned estuary, implying a minor transgressive episode within the retreat of the Fox Hills sea.

A second tidal inlet crossed the Timber Lake barrier in an east-west direction, nearly parallel with the course of Fourmile Creek in southern Sioux County. This feature was of lesser magnitude than the former (actual width and depth are unknown), and, although it seems to have cut through the Timber Lake, it has not been penetrated by any of the test wells used to produce Figure 22 and therefore it is not represented therein. Where it can be seen in the field (Sections 33 and 34, T. 130 N., R. 80 W.), this inlet, too, seems to have been choked by silt and clay rather than being filled by tidal channel sands.

Distributaries.--The surface of the Fox Hills-Hell Creek Delta platform was nourished by distributaries from the west and southwest representing distal elements of the Sheridan Delta of Gill and Cobban (1973). One major distributary apparently discharged temporarily southeastward across Mercer and Oliver Counties late in Fox Hills time serving as a source for the thick "Colgate" sandstone that characterizes the upper Mercer-Oliver complex (Figure 11). This evulsion was not long-lived, and the distributary returned to its probable "normal" flow direction generally toward the northeast as implied by Butler's (1980) studies in eastern Montana.

Sandstone concentrations that lie along the North Dakota- South Dakota border of Adams and Sioux Counties suggest another distributary route, perhaps one that supplied sand to the South Dakota portions of the Timber Lake barrier system. It is represented by a region of thick Fox Hills rocks having sandstone concentrations ranging from 60 to 70 percent (Figures 20, 21, 22).

Interdistributary Bays.--Between these distributaries lay an interdistributary bay and swamp system represented by the Grant-Stark facies complex. The facies occurring in Stark and Hettinger Counties contain greater amounts of lignite at lower positions in the section. These interfinger with lagoonal or bay sediments in the Grant County portion of the complex as represented on Figure 11. The presence of the bay is suggested in the area having less than 40 percent sandstone in the Fox Hills Formation on Figure 22.

Sedimentary rocks in this area show a pattern of lignite, carbonaceous shale, brown and green shale, concretions and calcite-cemented sandstone beds that very closely resembles the distribution of sediment types ranging from the landward to seaward reaches of the interdistributary bay complex as described by Klosters (1989) for the Barataria region of the Mississippi Delta. The lignite in the section was likely a marsh on the

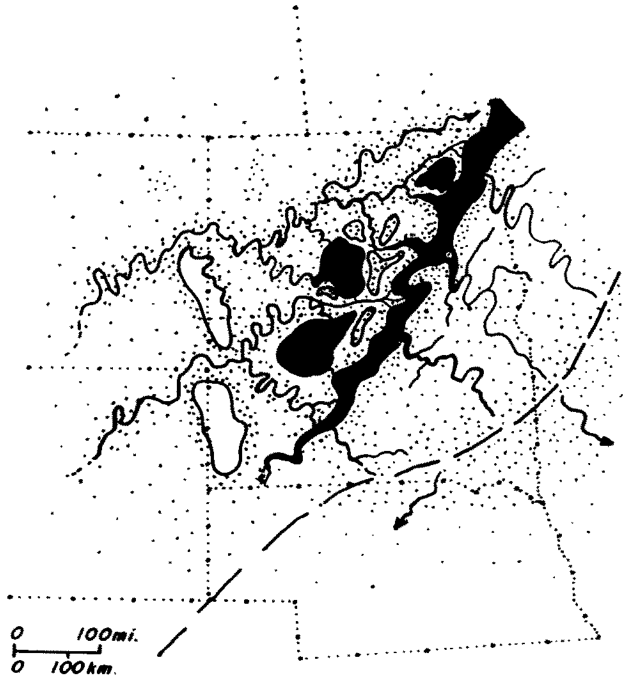

Figure 28-Paleogeomorphic map depicting conditions in the Williston Basin at the close of Fox Hills time. Interdistributary bay and lakes contained brackish-to-freshwater whereas an elongate estuary, formed by coalescing of Fox Hills-Hell Creek Delta and Dakota Isthmus, contained marine-to-brackish water. Drainage divide between Gulf Coast and Hudson Bay-Artic Ocean latest Cretaceous (Late Maastrichtian) seas developed along axis of Transcontinental Arch.

upper delta plain dominated by freshwater conditions. Periodically, lacustrine deposition prevailed. That paludal system intertongued with a brackish lagoon environment comprising the portion of the complex underlying most of Grant County with fingers into Sioux County as shown in Figure 11. Salinities in these waters were not high enough to support brackish organisms such as oysters (Feldmann and Palubniak, 1975), but marine connections were proven by discovery of the limulid xiphosuran *Casterolimulus kletti* Holland, Erickson, and O'Brien (1975) in these rocks.

Deposition in this part of the system is laminated shale and siltstone, typical of the Iron Lightning Member of the formation, interfingering with washover fan sandstones that are more fossiliferous. Fresh groundwater (meteoric water) percolated seaward through lagoonal distributary sandstone bodies and washover fan sandstones that, in some places, became cemented by calcite as demonstrated by the work of

Carpenter, et al. (1988).

Although data are incomplete, a similar lagoon or interdistributary bay seems to have been present over parts of Corson, Perkins and western Ziebach Counties, South Dakota. Facies similar to those in the Stark County area were described from South Dakota by Pettyjohn (1967) as the Fairpoint and White Owl Creek Members of the Formation. Lignite, dirty sandstones, varicolored shales, and large concretions were important constituents of those units.

It seems clear that migration of distributaries and compaction of delta platform sediments resulted in periodic abandonment of portions of the delta. Subsidence then permitted marine reinvasion of these features. The White Owl Creek Member of Pettyjohn and the Breien Member (Hell Creek Fm.) of Laird and Mitchell (1942) and Frye (1964) each represent marine transgression over the Fox Hills delta platform. Distinction of deposits produced by this type of marine incursion over the delta from those that may have resulted from eustatic sealevel rise of a T3 type, as is known from Maastrichtian sections elsewhere (Vail, et al., 1977), will pose a challenge in as much as they will both appear in logs as shale-bottomed sequences.

Such a package occurs in the "fish-hook"-shaped body of the Cedar River complex in the Hell Creek Formation as seen on Figure 11. These facies pass from Hettinger southwestward across Sioux and curve northward into Grant Counties. They are spatially related to the Grant-Stark Complex of the Fox Hills and thus to the interdistributary bay deposystem. They are proven to be marine though stratigraphically they lie within the Hell Creek Formation. Their distribution suggests a recurved spit geomorphic feature built as sand was trapped on a strand formed by the southern margin of the Grant-Stark interdistributary bay complex after abandonment of the Mercer-Oliver distributary and subsequent compaction of the bay and lagoon silts, clays, and peats. It marks one of the destructive phases of the Fox Hills- Hell Creek Delta that are, as yet, poorly documented.

The delta became wave-dominated after it reached the Missouri Valley region of North Dakota. First the Timber Lake barrier island system was established and overridden by brackish facies (Missouri Valley complex). Sedimentation westward of the barrier system was deposited in an inner delta platform setting that was restricted and predominantly fresh water, or periodically weakly brackish, as noted. Outer platform lagoons were more strongly brackish Subsequently, marine tongues of Fox Hills were introduced into the Hell Creek (Cedar River complex) upper delta plain as wave dominance of the platform took place.

Dakota Isthmus.--A second geomorphic and sedimentologic feature played a significant role in the facies patterns of the region. It is indicated by sediments of the Logan-McIntosh complex (Figures 11 and. 15) which contain muddy sandstones with a distinctive brackish water fauna dominated by the oyster *Crassostrea glabra* and several associates. The character of this assemblage was noted by Feldmann (1972), Erickson (1974), and Feldmann and Palubniak (1975). In its more saline portions *Nucula* sp., *Tancredia americana*, *Corbicula cytheriformis*, *Anomia micronema*, *Euspira subcrassa*, *Piestochilus feldmanni*, and *Neritina loganensis* are present (Erickson, 1974) whereas *Crassostrea glabra*, *Corbula cytheriformis*, *Pachymelania insculpta*, and *Pachymelania wyomingensis* signify lower salinity conditions within this lithotope (Palubniak, 1972). Deposition occurred over a broad very shallow, mud flat, essentially at mean sea-level. The shoreward margins were covered by vegetation that included palmetto and Pandanus sp., root systems of which trapped coarser sediments in a manner similar to modern mangroves, interspersed with slightly brackish tidal channels. Point bars and levees of these channel systems were vegetated by species of *Equisetum*. As sea levels dropped, this mud flat migrated northwestward into the Williston Basin. It is distinguished most easily by its fauna rather than its sediments. Where it interfingers with Emmons complex sediments it tends to be less glauconitic and more poorly sorted.

The influence of this feature ought not be underestimated during future work on the formation. It represents the southeastern margin of the Late Cretaceous seaway that developed on the more stable shelf produced by the Transcontinental Arch. As such it replicated a pattern of deposition that occurred several times in the same region (Cobban and Merewether, 1983). Erickson (1978) recognized that this feature divided the seaway into north and south portions. He called it the Dakota Isthmus. It separated the Interior Cretaceous Seaway into two water bodies having different temperatures, oceanographic conditions and, eventually, different faunas. It is likely also to have served as the earliest east-west land bridge across the Maastrichtian Fox Hills Sea.

SUMMARY

I began by saying that there is yet much to know about the Fox Hills Formation if we are to have a truly holistic understanding of the deposystem, its biota and its historical implications. This paper raises some of the more salient questions and attempts to point out that, although geologists assume an understanding of the "big picture" at the close of this Cretaceous seaway, much of the detail remains to be discovered. Upon close examination that detail can provide interpretations that significantly alter general interpretations.

Each of the lithofacies "complexes" denoted herein deserves study in detail. When this has been accomplished, geologists will have a substantial tool for understanding several things including: 1) the detailed tectonic behavior of the southern margin of the Williston Basin through the Cretaceous-Tertiary boundary interval (and perhaps throughout much of the Phanerozoic by inference); 2) the precise timing and sequencing of events that occurred at the Cretaceous-Tertiary boundary; 3) the terrestrial paleoenvironments and paleoceanographic setting of those Cretaceous-Tertiary extinctions that were taking place in the "endemic" faunas of the Western Interior of North America; 4) a precise ecosystem model for the interpretation of vertebrate and invertebrate remains and their paleobiology in the region and: 5) accurate surface and subsurface maps of lithofacies and members for precise control of groundwater exploration, allocation, and, if necessary, decontamination programs.

I have presented a series of structural, isopachous, and lithofacies interpretations that, by the questions they imply, support my contention that there is much to do before stratigraphic knowledge of the Fox Hills Formation can be considered "holistic". In essence mine is another voice saying that detailed field study of geological resources is still required and is still an extremely worthy investment of public funds and of geologists' labors. There is much to be understood about this already very well-studied geologic unit.

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VERTEBRATE FOSSIL RECORD, AGE, AND PALEOENVIRONMENTAL SETTING OF THE BRULE FORMATION (OLIGOCENE) IN NORTH DAKOTA

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ABSTRACT

Five classes of vertebrates, Osteichthyes, Amphibia, Reptilia, Aves, and Mammalia, are represented by fossils from the Brule Formation in southwestern North Dakota. Mammalia, by far the largest group, contains at least 60 taxa from 28 families in 10 orders. Freshwater and land gastropod, ostracod, trace, and sparse plant fossils were found associated with the vertebrates. Vertebrate fossils were widely distributed in the lower Brule but few were recovered from the upper Brule. No significant stratigraphic change was detected in species composition throughout the lower Brule. Collectively, the vertebrate taxa indicate an Orellan North American Land Mammal Age for the lower Brule in North Dakota. The age of the upper Brule could not be determined because of the sparsity of fossils.

Lithologies characterizing the Brule Formation in North Dakota represent deposition by a dynamic fluvial system where sluggish, loosely-sinuous, aggrading streams transected a broad floodplain that contained small ponds. The fauna that inhabited North Dakota during Orellan time was savanna-adapted. Some of the animals apparently preferred living in the stream-marginal gallery woodlands while others preferred the open savanna. A shallow-pond community was also identified.

INTRODUCTION

Although isolated occurrences of several vertebrate taxa have been reported from the Brule Formation in North Dakota, the fauna has not received comprehensive treatment compared to equivalent-age faunas from other areas of the mid-continent. This is partly because of the limited number of fossil-bearing outcrops in North Dakota compared to, for example, the Big Badlands of South Dakota. Consideration of the North Dakota Brule fossil record is important, however, because southwestern North Dakota is the furthest northeast occurrence of Brule faunas in North America. Our objectives are to: 1) identify the vertebrate fauna from the Brule Formation in North Dakota and provide a comprehensive list of known taxa, 2) determine the biochronologic age of the Brule Formation in North Dakota, and 3) define the paleoenvironmental setting in which the North Dakota fauna lived.

Edward Drinker Cope was apparently first to collect fossils from the Brule Formation in North Dakota and, based on those fossils, assigned an Oligocene age to the unit (Cope, 1883). He referred to these fossiliferous rocks as the "White River Formation" because of the similarity of the North Dakota fossils to those from the Big Badlands of South Dakota. For many years it was unclear where in North Dakota Cope had collected the fossils. Leonard (1922) concluded that the collection was made at White Butte (Slope County). Skinner (1951) confirmed Leonard's conclusion after examining Cope's field notes.

As part of a geological reconnaissance of North Dakota, Montana, and Idaho for the Carnegie Museum of Pittsburgh, Earl Douglass collected vertebrate fossils from White Butte (Slope County) in 1905. In addition, he extended the known geographic range of Brule faunas to the Little Badlands area southwest of

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Dickinson, Stark County, North Dakota. Douglass described the fossils from those areas in a series of articles (Douglass, 1908a,b, 1909). Leonard (1922), State Geologist of North Dakota from 1902 to 1932, conducted a major study of the "White River Formation" in North Dakota and listed several vertebrate taxa that he collected from the Brule Formation in the Little Badlands.

An important Brule fossil site (Fitterer Ranch, southwest of Dickinson, Stark County) was discovered in 1944 by a party from the Frick Laboratory of the American Museum of Natural History led by Morris Skinner. Skinner collected Brule fossils at the Fitterer Ranch site and other localities in southwestern North Dakota sporadically from 1944 to 1964. Approximately two thousand vertebrate fossil specimens, mostly from the Brule, were collected in North Dakota by Skinner and his associates over that time (Tedford, pers. comm.). Although Skinner did not describe his North Dakota Brule fossils, many of the specimens that he collected have been examined for taxonomic studies (e.g., Schultz and Falkenbach, 1956, 1968; Prothero and Shubin, 1989). Denson and Gill (1965) also reported the occurrence of a few vertebrate taxa from the Brule Formation in North Dakota but the primary objective of their study was to determine the uranium content of the Oligocene units.

Most reports of North Dakota Brule fossils have dealt only with isolated occurrences of unique individuals; e.g., *Subhyracodon*, Chinburg and Holland (1965); *Oligoscalops galbreathi* Reed and Turnbull (1965); *Scaphiopus skinneri* Estes (1970); or have been cited in taxonomic studies of specific groups; e.g., horses, Prothero and Shubin (1989); oreodonts, Schlultz and Falkenbach (1956,1968). Hoganson and Lammers (1985) presented a list of vertebrate genera that they recovered from the lower Brule in Stark County, North Dakota and discussed the biochronologic and paleoecological implications of that fauna. They later presented additions to that faunal list (Lammers and Hoganson, 1988). Kihm and Lammers (1986) summarized the known vertebrate fossil record of the Brule and other White River Group formations in North Dakota and reviewed the biochronology of the White River vertebrate faunas.

STUDY AREA

Outcrops of the Brule Formation in North Dakota are the furthest northeast exposures of that formation in North America. These outcrops are few, isolated and laterally restricted and occur in the eastern Little Badlands (South Heart Badlands) and outlying buttes in Stark County and the Chalky Buttes including White Butte in Slope County (Fig. 1). Vertebrate fossils were recovered primarily from the Brule Formation exposed in the Little Badlands proper (Sec. 23, T. 138 N., R. 98 W.), Obritsch Ranch (Secs. 28 and 29, T. 138 N., R. 97 W.), and Fitterer Ranch (Secs. 7, 17, and 18, T. 137 N., R. 97 W.) (Fig. 2), all in Stark County. A few collections were also made from the Brule at White Butte, (Sec. 30, T. 134 N., R. 100 W.), and part of Chalky Buttes, (Sec. 31, T. 134 N., R. 100 W.), in Slope County.

METHODS

Fossils recovered for this study were collected over a span of several years. One of us (GEL) collected fossils from the North Dakota Brule Formation, with several assistants, from 1975 to 1983. Both of us conducted field studies and collected fossils from the Brule, assisted by several volunteers, from 1983 to 1991. The greatest diversity of taxa were collected during these times by examining outcrop faces at various stratigraphic levels within the Brule. Fossils reported here were either collected *in situ* just beginning to weather out of the formation or were found as float but unquestionably weathering out of the Brule. A concentration of bones was discovered in a channel sandstone ("Fitterer bed") at the Fitterer Ranch locality (Fig. 3), and an excavation of that bone bed was conducted for a total of 1 month during 1984 and 1985. No complete skeletons were recovered during this study but several hundred identifiable specimens were collected. These specimens are either housed at the Manitoba Museum of Man and Nature, Winnipeg or in the North Dakota State Fossil Collection, Heritage Center, Bismarck.

STRATIGRAPHY AND SEDIMENTOLOGY

The Oligocene age Brule Formation is the uppermost formation in the White River Group (Fig. 4). Meek and Hayden (1861) applied the name White River to rock exposures along the White River in Nebraska. That terminology was first used for outcrops in North Dakota (Chalky Buttes) by Cope (1883). The known occurrence of White River rocks in North Dakota was extended to include exposures in the Little Badlands, Stark County, by Douglass (1909). Leonard (1922) divided the "White River Formation" in North Dakota into basal sand, middle clay, and upper limestone and clay members. The division of the "White River Formation" into three unnamed members in North Dakota was continued by Holland (1957). The lithostratigraphic terminology of the White River Group was formalized by Darton (1899a, 1899b) for Nebraska and South Dakota where he divided the White River into two formations; the lower Chadron

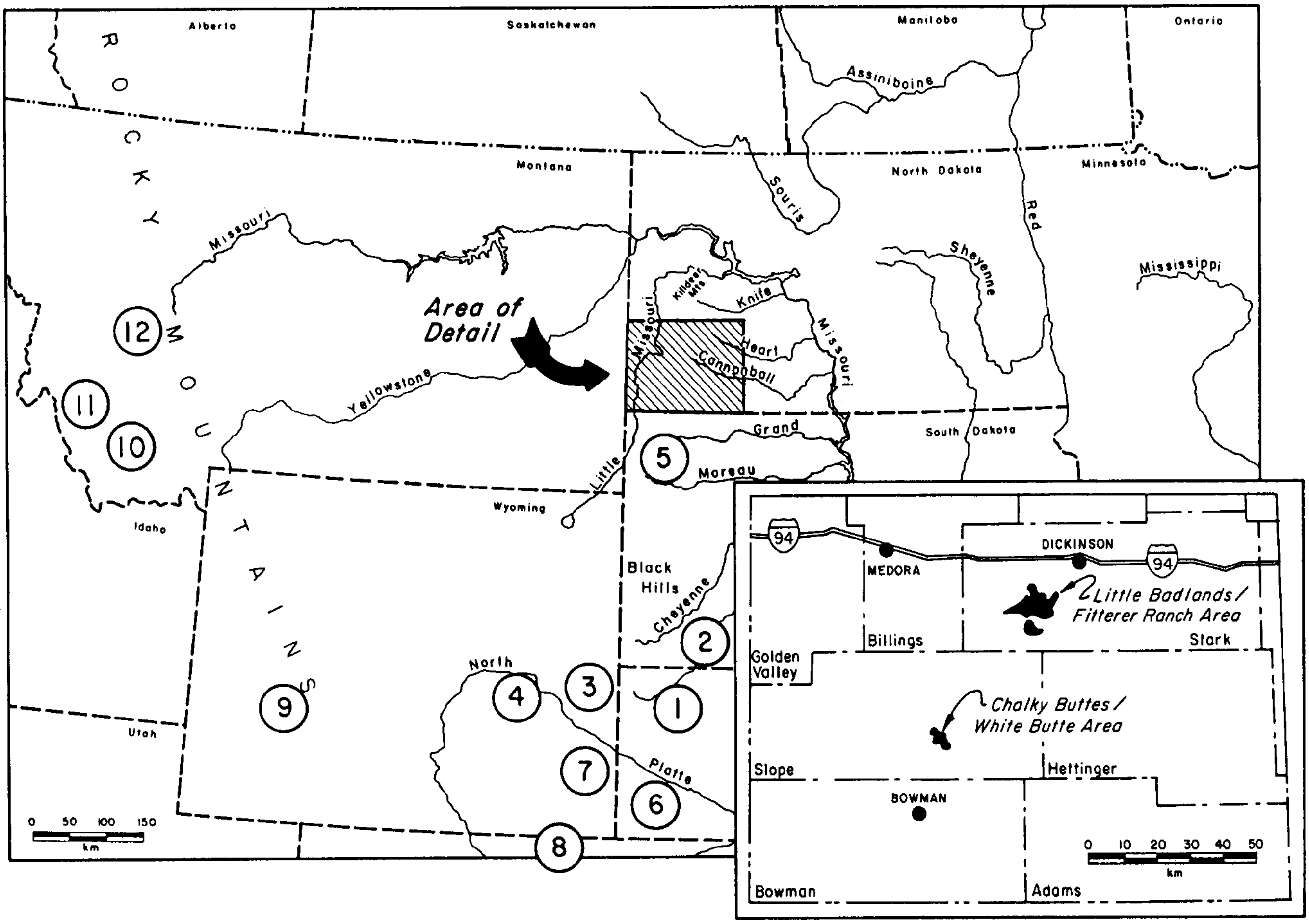

Figure 1-Location of the Little Badlands (including the Fitterer and Obritsch Ranch sites) and Chalky Buttes (including White Butte) vertebrate fossil localities. The map also shows locations of other Orellan age sites (after, Savage and Russell, 1983). 1) Badland Creek, Brecht Ranch (Stock Dam), Meng Ranch, and Toadstool Park--Nebraska; 2) Battle Creek Breaks, Canyon, Draw and Big Badlands--South Dakota; 3) Bald Butte (Hat Creek Basin)--Wyoming; 4) Douglas Southeast (Orin Junction)--Wyoming; 5) Slim Buttes--South Dakota; 6) Scotts Bluff Monument District--Nebraska; 7) Goshen Hole District and Harvard Fossil Reserve--Wyoming; 8) Cedar Creek Member Sites--Colorado; 9) Devils Gap (Beaver Divide)--Wyoming; 10) Cook Ranch Formation Sites--Montana; 11) Big Hole River--Montana; and 12) Palisades Section and Toston (Dry Creek)--Montana.

Formation (previously called the "Titanotherium beds") and the upper Brule Formation (previously called the "turtle or oreodon beds"). That terminology was not, however, used in North Dakota until 1965 by Denson and Gill (1965) but is now the standard terminology used for Oligocene formations in North Dakota.

Denson and Gill (1965) determined that the Brule is unconformably underlain by the Chadron Formation and unconformably overlain by the Arikaree Formation. Stone (1972, 1973), in a study to determine the age and stratigraphy of middle Cenozoic deposits in North Dakota, informally divided the Brule Formation into two members, a lower, "Dickinson member" and upper, "Schefield member." Hoganson (1986) pointed out that Stone's Brule members were never formally named in accordance with the rules established in the North American Stratigraphic Code and must, therefore, remain informal stratigraphic names. Stone (1972) stated that the Brule unconformably overlies the Chadron Formation and Stone (1973) and Hoganson (1986) both noted that the Brule, although the contact is rarely observable, is overlain disconformably by the Arikaree Formation (called the "Killdeer formation" by Stone).

The Brule Formation consists of complexly interbedded lithologies of claystone, mudstone, siltstone, and sandstone, intercalated with tuffaceous siltstones and freshwater limestones in some areas (Figs. 2 and 4). It unconformably overlies the massive, gray claystones of the Chadron Formation. The Chadron clay

Figure 2-South-facing butte exposure of the Brule Formation at Fitterer Ranch (NE1/4, SW1/4, Sec. 7, T. 137 N., R. 97 W.), Stark County showing the mudstone dominated, fluted slopes of the lower Brule overlain by the cliff-forming upper Brule. Arrows point to tuffaceous siltstone (1 meter thick), Skinner's "White marker zone".

stones are characteristically capped by thin marl or limestone beds, caliche zones, or radially fibrous, calcareous nodules (Hoganson, 1986). The contact between the two formations is usually placed above the uppermost limestone. Pink to gray, poorly-laminated to massive, nodular mudstone, which exhibits pitted weathering resulting from the weathering of small (usually no larger than 3 cm in diameter) claystone clasts in the mudstone matrix, is the dominant lithology in the lower Brule (called the "Dickinson member" by Stone). Pedogenic structures and root casts, at times observed in the mudstones, suggest periods of subareal exposure and soil development.

Locally, up to 3 meters thick, green, cross-bedded, generally very fossiliferous sandstones occur in the lower Brule. These sandstones are moderately to poorly sorted, medium to coarse grained, and are sometimes conglomeratic. They primarily contain grains of quartz and feldspar, rocks of mixed igneous lithologies and clasts of claystone. One of these sandstones was called the "Fitterer Channel" by Skinner (1951), the "Fitterer sandstone facies" by Stone (1972), and the "Fitterer bed" by Stone (1973) (Figs. 3 and 4). These channel sandstones vary in lithology and thickness and occur at different stratigraphic positions within the lower Brule at different localities. It is uncertain whether or not they represent the same channel deposit because outcrops are not continuous making correlation difficult. A 0.5 to 2-meter-thick white, calcareous, tuffaceous siltstone occurs about 21 m above the Brule\Chadron contact (Figs. 2 and 4). Skinner (1951) called this siltstone the "White marker zone". It is exposed at similar stratigraphic positions at the Little Badlands, Fitterer Ranch and Obritsch Ranch localities and appears to be an important stratigraphic marker. The lower Brule is approximately 30 m thick at the Fitterer Ranch locality and approximately 45 m thick at the Little Badlands locality.

The upper Brule (in part the "Schefield member" of Stone, 1973) consists of gray to grayish brown, interbedded claystones, mudstones, siltstones and sandstones that, in some areas, weathers to horizontal, banded layers. Where banded, it is cliff forming in contrast to the fluted slopes of the lower Brule (Fig. 2). The cliff-forming beds, which occur in the lower part of the upper Brule section, are thin (up to 15 cm), even and sharp, but they become more massive and blocky higher in section. The cliff-forming beds contain spherical (2.5 to 5 cm in diameter)-to-elongate (up to 15 cm long) calcareous concretions. However, this cliff-forming unit is laterally discontinuous even in the areas where best exposed at the Fitterer Ranch and

Figure 3-Excavation of vertebrate fossils from a channel sandstone ("Fitterer bed") at the Fitterer Ranch locality (NW 1/4, NW 1/4, Sec. 17, T. 137 N., R. 97 W.), Stark County. Most of the exposed bones are from the rhinoceros, *Subhyracodon*.

White Butte localities. Where it is not present, mudstone lithologies dominate as in the lower Brule. Therefore, giving the cliff-forming unit member rank, as proposed by Stone (1973), may not be warranted.

Stone (1973) suggested that, at the Fitterer Ranch locality, the top of the Brule should be placed at the top of the cliff-forming unit. At the same locality, Skinner (1951) considered the Brule to extend to the top of the section, and Denson and Gill (1965) mapped all but the uppermost 3 m of the Fitterer section as Brule. They considered the upper 3 m of sandstone to be Arikaree Formation. Because the cliff-forming unit is laterally discontinuous, it seems reasonable to conform with Denson and Gill (1965) and place the upper contact of the Brule Formation at the base of the butte-capping sandstone. Therefore, the upper Brule attains a maximum thickness of about 42 m at the Fitterer Ranch locality, but is mostly covered. It is only about 3 m thick and is the capping, resistant unit at the highest point (SW1/4, NE1/4, Sec. 23, T. 138 N., R. 98 W.) in the Little Badlands. In the Chalky Buttes the entire Brule Formation is only about 3.5 to 21 m thick (Denson and Gill, 1965).

THE VERTEBRATE FAUNA

Five classes of vertebrates, Osteichthyes, Amphibia, Reptilia, Aves, and Mammalia, are represented by fossils in the Brule Formation in North Dakota. Mammalia, by far the largest group, contains at least 60 taxa from 28 families in 10 orders (Table 1). Table 1 lists all reported vertebrate taxa from the North Dakota Brule. Some of the taxonomic names used by earlier workers are obsolete but are included for historic perspective. Most of the vertebrate fossils were found as isolated specimens, and were widely distributed throughout the lower Brule. Some were collected from areas of high concentration in fluvial sandstone facies, such as the "Fitterer bed" (Fig. 3). Few fossils were found in the upper Brule. No significant stratigraphic change was detected in species composition of the fauna throughout the lower Brule section, and fossils in the upper Brule were too sparse to determine if there is any significant difference between the faunas of the upper and lower Brule.

Plant fossils found associated with the vertebrate remains in North Dakota are: *Celtis hatcheri* (endocarps, "pits" of hackberry trees), root traces, charophyte oogonia, and algal mats. Invertebrate fossils from the North Dakota Brule include freshwater gastropods (Lymnaeidae, Planorbidae and Physidae), terrestrial gastropods (Pupillidae, and the helicid, *Pseudolisinoe leidyi*), and freshwater ostracods. The trace fossils *Pallichnus dakotensis* (beetle pupal cells), *Celliforma ficoides* (bee larval cells) and mammal coprolites were also collected.

BIOCHRONOLOGY OF THE BRULE FORMATION IN NORTH DAKOTA

Skinner (1951) was first to suggest, based on lithologic and faunal similarities to exposures and faunas in South Dakota and Nebraska, an Orellan North American Land Mammal Age for the Brule Formation in North Dakota. Skinner, however, considered his interpretation to be preliminary because the mammal fossils that he collected from North Dakota had not been adequately studied. Most subsequent workers have concurred, without providing much biochronologic evidence, that at least the lower part of the Brule Formation in North Dakota is Orellan in age (e.g., Stone, 1972, 1973; Estes, 1970; Hoganson and Lammers, 1985; Hoganson, 1986; and Kihm and Lammers, 1986).

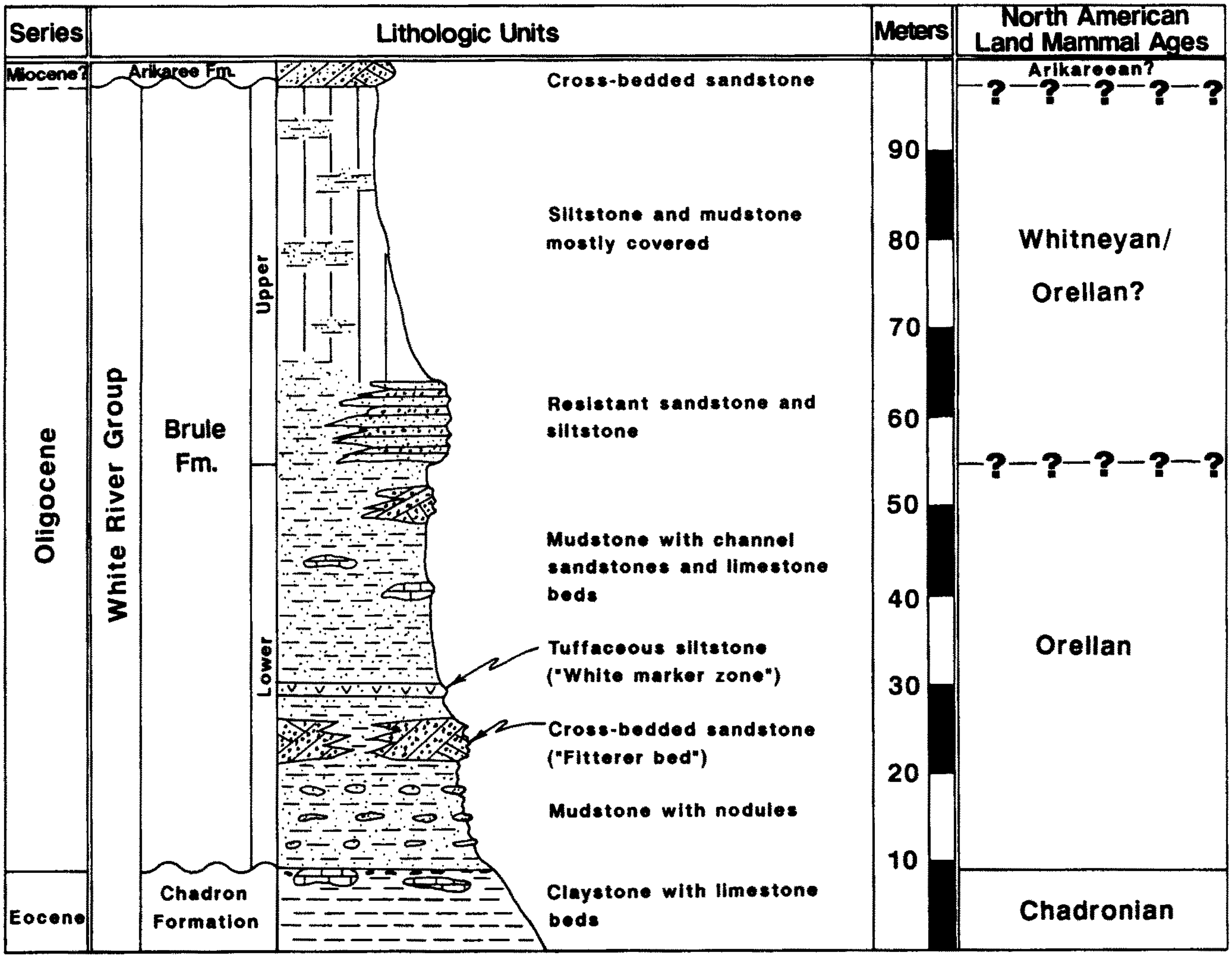

Figure 4-Generalized stratigraphic column of the Brule and adjacent formations based on measured sections from the Fitterer Ranch, Obritsch Ranch and Little Badlands proper localities.

Wood et al. (1941) based the Orellan and Whitneyan North American Provincial Ages on the Orella and Whitney Members of the Brule Formation, and the mammalian faunas that are contained in those members, as defined in northwestern Nebraska, southwestern South Dakota and eastern Wyoming. These ages were, therefore, based on lithostratigraphic units. This procedure was found to be objectionable by Emry et al. (1987) who advocated that the ages should be based on biostratigraphic criteria. Emry et al. (1987) cautioned that the characterization of these ages by Wood et al. (1941), especially the Orellan, is largely obsolete.

Emry et al. (1987) listed the following taxa as characteristic of, but not restricted to, the Orellan: *Archaeotherium*, *Hyracodon*, *Leptomeryx*, *Palaeolagus*, *Megalagus*, *Subhyracodon*, *Stylemys*, *Merycoidodon*, *Leptictis* (=*Ictops*), *Hyaenodon horridus*, *Hyaenodon crucians*, *Ischyromys*, *Eumys*, *Paradjidaumo trilophus*, *Adjidaumo minutus*, *Hesperocyon*, *Daphoenus*, *Dinictis*, *Hoplophoneus*, *Mesohippus*, *Poebrotherium*, *Hypertragulus*, and *Oligoscalops galbreathi*. Taxa that they suggested may be restricted to the Orellan are: *Metamynodon planifrons*, *Subhyracodon occidentalis*, *Leptictis haydeni*, *Ischyromys typus*, *Eumys elegans*, *Mesohippus bairdi*, *Archaeotherium mortoni*, *Poebrotherium wilsoni*, *Hypertragulus calcaratus*, and *Leptomeryx evansi*. There is little doubt, after comparing Emry's et al. (1987) list of Orellan taxa with the list of taxa (Table 1) recovered from the lower Brule in North Dakota, that at least the lower Brule in North Dakota is Orellan in age. That is, early Oligocene (between 32 and 34 million years ago) according to the revised North American late Paleogene chronology (Swisher and Prothero, 1990). This is the furthest northeast occurrence of Orellan age faunas in North America (Fig. 1).

Table 1-Vertebrate taxa from the Brule Formation in North Dakota	
Taxa	**Source**
CLASS OSTEICHTHYES	
Order Siluriformes	
Family Ictaluridae	
Ictalurus (*Amiurus*) sp.	r,*
Osteichthyes indeterminate spp.	p,q,*
CLASS AMPHIBIA	
Order Anura	
Family Pelobatidae	
Scaphiopus skinneri Estes, 1970	k
CLASS REPTILIA	
Order Chelonia	
Family Testudinidae	
Gopherus sp.	q,*
Stylemys nebrascensis Leidy, 1851	*
Stylemys sp.	l,p,q,*
Testudo sp.	p,*
Family Trionychidae	
Trionyx sp.	r,*
Chelonia indeterminate sp.	c
Order Squamata	
Squamata indeterminate spp.	p,q,*
CLASS AVES	
Aves indeterminate spp.	p,q,*
CLASS MAMMALIA	
Order Apatotheria	
?Apatemyidae indeterminate sp.	q,*
Order Leptictida	
Family Leptictidae	
Leptictis (=*Ictops*) *dakotensis* (Leidy, 1868)	*
Leptictis sp.	c,p,q,*
Order Insectivora	
Family Geolabididae	
Centetodon marginalis (Cope, 1873)	o
Family Proscalopidae	
Arctoryctes galbreathi Reed, 1956	g
?Apternodontidae indeterminate sp.	q,*
Order Chiroptera	
?Chiroptera indeterminate sp.	p,q,*
Order Creodonta	
Family Hyaenodontidae	

Taxa	Source
CLASS MAMMALIA (Continued)	
Hyaenodon (*Protohyaenodon*) *crucians* Leidy, 1853	m,r,*
Hyaenodon (*Neohyaenodon*) *horridus* Leidy, 1853	e,r,*
Order Carnivora	
Family Felidae	
Dinictis sp.	p,q,*
?Eusmilus sp.	q,*
?Hoplophoneus sp.	q,*
Family Canidae	
Hesperocyon sp.	p,q,*
Perictine indeterminate sp.	r,*
Family Amphicyonidae	
Daphoenus sp.	p,*
Cynodictus gregarius (Cope, 1873)	e
Amphicyonidae indeterminate spp.	q,*
Order Perissodactyla	
Family Equidae	
Mesohippus bairdi (Leidy, 1850)	a,q,s,*
Mesohippus exoletus (Cope, 1874)	s
Mesohippus sp.	c,d,e,p,*
Miohippus brachstylus? (Osborn, 1904)	a,q
Miohippus obliquidens (Osborn, 1904)	s
Miohippus sp.	h
Family Hyracodontidae	
Hyracodon nebrascensis Leidy, 1850	*
Hyracodon sp.	c,d,e,h,p,q,*
Family Rhinocerotidae	
Subhyracodon occidentalis (Leidy, 1851)	e,*
Subhyracodon sp.	i,q,*
Caenopus sp.	p,q
Aceratherium tridactylum (Osborn, 1893)	b,c,q
Metamynodon sp.	*
Rhinoceros sp.	c,e
Order Artiodactyla	
Family Entelodontidae	
Archaeotherium mortoni Leidy, 185	*
Archaeotherium sp.	p,q,*
Entelodon sp.	q
Family Anthracotheriidae	
Bothriodon sp.	p,q,*
Family Merycoidontidae	
Merycoidodon culbertsoni Leidy, 1848	c,d,e,j,q,*

Taxa	Source
CLASS MAMMALIA (Continued)	
Merycoidodon sp.	p,*
Merycoidodon (*Anomerycoidodon*) *dani* Schultz & Falkenbach, 1968	j,q
Otionohyus wardi Schultz & Falkenbach, 1968	j,q
Otionohyus (*Otarohyus*) *bullatus* (Leidy, 1869)	j,q
?Eporeodon sp.	h
Genetochoerus (*Osbornohyus*) *norbeckensis* Schultz & Falkenbach, 1968	j,q
Genetochoerus (*Osbornohyus*) *dickinsonensis* (Douglass, 1907)	c,j,q
Leptauchenia sp.	h
Paramerycoidodon georgei Schultz & Falkenbach, 1968	j,q
Paramerycoidodon (*Barbourochoerus*) sp.	q
Miniochoerus starkensis Schultz & Falkenbach, 1956	f,q
Miniochoerus (*Paraminiochoerus*) *helprini* Schultz & Falkenbach, 1956	f,q
Platychoerus heartensis Schultz & Falkenbach, 1956	f,q
Family Camelidae	
Poebrotherium sp.	c,e,p,q,*
Family Protoceratidae	
?Protoceras sp.	h,q
Family Hypertragulidae	
?Hypertragulus sp.	c,q,*
Family Leptomerycidae	
Leptomeryx evansi Leidy, 1853	c,d,e,*
Leptomeryx sp.	c,e,h,p,q,*
Order Rodentia	
Family Ischyromyidae	
Ischyromys typus Leidy, 1856	*
Ischyromys sp.	c,p,q,*
Titanotheriomys sp.	q,*
Family Aplodontidae	
?Cedromus sp.	h,q
Prosciurus sp.	h,q,*
Family Sciuridae	
Protosciurus sp.	p,q,*
Family Castoridae	
Agnotocastor praetereadens Stirton, 1935	*
Agnotocastor sp.	q,*
Family Eomyidae	
Adjidaumo douglassi Burke, 1934	q,*
Adjidaumo sp.	c

Taxa	Source
CLASS MAMMALIA (Continued)	
Gymnoptychus sp.	p,*
Paradjidaumo sp.	h,p,q,*
Family Heteromyidae	
?Heliscomys sp.	p,*
Family Cricetidae	
Eumys elegans Leidy, 1856	t,*
Eumys ?obliquidens A. Wood, 1937	t
Eumys brachyodus A. Wood, 1937	t
Eumys sp.	c,d,h,p,q,*
Cricetidae indeterminate sp.	n
Order Lagomorpha	
Family Leporidae	
Palaeolagus haydeni Leidy, 1856	u,*
Palaeolagus sp.	c,d,h,p,q,*
Megalagus sp.	p,q,u,*

Sources: a) Douglass (1908a); b) Douglass (1908b); c) Douglass (1909); d) Leonard (1919); e) Leonard (1922); f) Schultz and Falkenbach (1956); g) Reed and Turnbull (1965); h) Denson and Gill (1965); i) Chinburg and Holland (1966); j) Schultz and Falkenbach (1968); k) Estes (1970); l) Stone (1973); m) Mellett (1977); n) Korth (1981); o) Lillegraven et al. (1981); p) Hoganson and Lammers (1985); q) Kihm and Lammers (1986); r) Lammers and Hoganson (1988); s) Prothero and Shubin (1989); t) Kihm (1990); u) Wretling (1991); * this study.

The sparsity of fossils in the upper Brule restricts age determinations to speculation. Skinner (1951) suggested, without providing any biochronologic evidence, that the upper Brule at the Fitterer Ranch locality may be Whitneyan in age. Stone (1973), although little fossil evidence was available, stated that the upper Brule was probably late Orellan through Whitneyan in age. He based this interpretation on the stratigraphic position of the upper Brule compared with the stratigraphic position of Whitneyan age units in Nebraska and South Dakota and on an oral communication with Morris Skinner who stated that some..."vertebrate remains indicate a Whitneyan age for the upper Brule beds at the Fitterer Ranch" (Stone, 1973, p. 79).

Wood et al. (1941) interpreted a "White Butte local fauna," from what they presumed to be the Brule at White Butte, Slope County, to be Whitneyan in age but it is likely that the fossils on which their interpretation was based were from the overlying Arikaree Formation. Hoganson (1986) commented that very meager fossil evidence indicates an Oligocene age for the upper Brule but that it is uncertain whether it is Orellan or Whitneyan. Kihm and Lammers (1986) cited Douglass' (1908a) report of *Miohippus brachystylus?* and Denson and Gill's (1965) report of *Leptauchenia* and ?*Protoceras* as possible indicators of a Whitneyan fauna but the stratigraphic occurrence of these fossils is unclear. Kihm (1990) cited the presence of the rodent *Eumys brachyodus* in the Brule Formation from one locality in the Little Badlands as evidence for a Whitneyan age for most of the Brule in North Dakota. An acceptable biochronologic age assignment for the upper Brule must, however, await additional fossil finds.

DEPOSITIONAL ENVIRONMENTS AND HABITAT PREFERENCES

Lithologies characterizing the Brule Formation in North Dakota represent deposition by a dynamic fluvial system in a savanna setting in which sluggish, loosely-sinuous, aggrading streams, flanked by low-relief levees, transected a broad floodplain containing small ponds and/or ephemeral, swampy areas. The climate was seasonal and warm temperate with an annual rainfall within the subhumid to semiarid range (Retallack, 1983, 1984). This environmental and depositional setting provided a mosaic of habitats.

For many years, Orellan faunas have been regarded as being savanna-adapted (Clark et al., 1967; Webb, 1977). Savanna-adapted animals became abundant and diverse at that time when forests gave way to woodland savannas. The Brule fauna of North Dakota is no exception if the term savanna is used in the broadest sense, as Webb (1977, p. 356) intended, to include all "open-country formations with at least a few trees; only open steppe and grasslands are excluded". The Orellan age savanna in North Dakota contained stream-marginal, gallery woodlands. The floristic composition of those woodlands is mostly unknown because of the sparsity of plant fossils. Endocarps of hackberry trees, *Celtis hatcheri*, are the only plant fossils found, at times in abundance, in the stream marginal deposits. It is presumed, however, that many other kinds of trees, shrubs and herbs also grew in the woodlands at this time.

The fauna of the open woodland areas is represented by fossils recovered from the channel sandstone facies and vertically and laterally adjacent floodplain mudstone facies. The animals that apparently preferred this habitat were generally the larger Brule mammals including the rhinoceroses, *Subhyracodon occidentalis* and *Metamynodon*; the pig-like entelodont, *Archaeotherium mortoni*; the anthracotheriid, *Bothriodon*; oreodons including *Merycoidodon culbertsoni*; and the horse, *Mesohippus bairdi*. Most of these large animals did roam the open savanna but apparently preferred the wooded stream margins. This stream marginal community also included the tortoise, *Stylemys nebrascensis*; the rabbit, *Palaeolagus haydeni*; the squirrel-like rodent, *Ischyromys typus*; and the beaver, *Agnotocastor praetereadens*. Trace fossils, pupal cells of burrowing beetles (*Pallichnus dakotensis*) and larval cells of sweat bees (*Celliforma ficoides*), found in paleosols formed in open woodlands during this time (Retallack, 1984), are also found in these stream marginal deposits. Land snails (pupillids and the helicid, *Pseudolisinoe leidy*) also inhabited the streamside woodlands.

Only remains of large mammals, *Subhyracodon occidentalis*, *Archaeotherium mortoni*, *Merycoidodon culbertsoni*, and *Mesohippus bairdi*, were found in the "bone bed", channel sandstone facies ("Fitterer bed"), during our excavation. We envision that occasionally the bloated carcasses of these animals would float down stream and become stranded on sand bars. These carcasses were perhaps dismembered by scavengers or the bones were disassociated by decomposition before burial by lateral stream migration. The lack of bones of smaller animals in the channel deposits is probably due to nonpreservation because of the high energy depositional environment.

Generally, it seems that smaller animals inhabited the interstream, open-savanna plain habitats, although this interpretation may be biased by taphonomic influences. The savanna fauna included rodents such as, *Eumys elegans*, *Adjidaumo douglassi*, and *Ischyromys typus*; the deer-like ruminant, *Leptomeryx evansi*; rabbits, *Palaeolagus haydeni* and *Megalagus*; and the camilid, *Poebrotherium*. The tortoise, *Stylemys nebrascensis* and land snail, *Pseudolisinoe leidy*, although more common in the woodlands, also lived in this habitat. The insectivorous, *Leptictis dakotensis* and carnivores, *Dinictis*, *Hesperocyon*, and *Daphoenus* appear to have preferred the open country habitats but their fossils are encountered so infrequently that this is only speculation at this time. Shallow ponds or ephemeral swamps containing fish, algae (mats and charophyte oogonia), ostracods and gastropods (lymnaeids, physids, and planorbids) developed, at times, on the floodplain. Frequently, floodwaters deposited fine-grained sediments over the alluvial plain burying recently dead and decaying carcasses and partially disintegrated bones. Interludes of non-deposition of unknown duration, sometimes long enough to allow soil formation, occurred between the flooding events.

CONCLUSIONS

1) Five classes of vertebrates, Osteichthyes, Amphibia, Reptilia, Aves, and Mammalia are represented by fossils in the North Dakota Brule Formation. Mammalia is represented by at least 60 taxa from 28 families in 10 orders. Remains of freshwater and land gastropods, ostracods, trace fossils, and sparse plants were also recovered.

2) Vertebrate fossils were widely distributed in the lower Brule and no significant stratigraphic change was detected in species composition throughout the lower Brule section. Few fossils were recovered from the upper Brule.

3) Collectively, the vertebrate taxa present indicate an Orellan age for the lower Brule Formation in North Dakota. The age of the upper Brule could not be determined because of the sparsity of diagnostic fossils.

4) Lithologies characterizing the Brule Formation in North Dakota represent deposition by a dynamic fluvial system where streams transected a broad floodplain.

5) The fauna that inhabited North Dakota during Orellan time was savanna-adapted. Some of the animals preferred living in the stream-marginal gallery woodlands while others preferred the open savanna. A shallow-pond community was also identified.

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THE JOHNS LAKE SITE: A LATE QUATERNARY FOSSIL BEETLE (COLEOPTERA) ASSEMBLAGE FROM THE MISSOURI COTEAU OF NORTH DAKOTA

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ABSTRACT

A 4.27 m thick section of lacustrine sediments in the Johns Lake basin, 13 km SSW of McClusky in Sheridan County, North Dakota, was exposed in 1973 during construction of the McClusky Canal. Remains of the disarticulated skeletons of beetles were recovered from several stratigraphic horizons near the base of the section but were especially abundant in a peat bed (Unit 3). Wood from the peat bed has a radiocarbon age of 10,820 ± 150 yr B.P. (I-9556). The fossil assemblage is comprised of 84 species of beetles, including the rare scarabaeid beetle *Micraegialia pusilla* Horn. The beetles represent aquatic, water-marginal and upland habitats. Scolytid (bark) beetles associated with conifers, particularly spruce, were especially well-represented by fossils. The Johns Lake assemblage is similar in species composition to late-glacial, spruce-forest beetle associations described from sites elsewhere within the midcontinent. Close faunal analogues to the Johns Lake assemblage occur today in the southern parts of the boreal forest region.

INTRODUCTION

The Missouri Coteau is a broad band of low hills and small, closed lake basins that extends across North Dakota from the northwestern to the south-central part of the state. Its hummocky topography represents dead-ice moraine formed from the stagnation of large masses of glacier ice during the final phases of the last glaciation (Clayton, 1967; Clayton and Moran, 1982). Superglacial drift insulated the ice, and in some areas dead ice persisted until as late as ca. 9000 yr B.P. (Cvancara et al., 1971). Locally, melting of the ice resulted in the formation of lakes that were either moraine- or ice-walled (Clayton, 1967).

Ice-walled lake deposits with an age of 9750 ± 140 yr B.P. (I-4537) from the Seibold site, 17 km southeast of Woodworth, Stutsman County, North Dakota, contained exceptionally well-preserved plant, invertebrate, and vertebrate fossils (Cvancara et al., 1971). This assemblage, including numerous complete skeletons of fish and frogs, was representative of a biota whose analogue today is at the southern margin of the boreal forest. The Seibold fossil beetle assemblage (Ashworth and Brophy, 1972) has, until now, been the only one previously described from the Missouri Coteau. The fossil beetle assemblage recovered from the sediments of Johns Lake, a small kettle depression on the Missouri Coteau, is the subject of the present paper.

LOCATION, STRATIGRAPHY, AND DEPOSITIONAL HISTORY

Johns Lake, a small (ca. 294 ha), shallow lake was drained in 1973 during construction of the McClusky Canal, as part of the U.S. Bureau of Reclamation's Garrison Diversion Project. Fossiliferous, lacustrine sediments were exposed in a section along the west wall of the canal located 13 km SSW of McClusky, Sheridan County, North Dakota (NE 1/4, NW 1/4, SE 1/4, Sec. 16, T. 145 N., R. 77 W.; McClusky, N.D., 7.5' quadrangle) (Fig. 1).

The section selected for paleontological study is near the center of the lake basin about 320 m from the western shoreline. Lacustrine sediments, thickest near the center of the basin, were underlain by gravel. The stratigraphy of the sampled section (Fig. 1) is described in Table 1. Spruce wood from Unit 3 has a radiocarbon age of 10,820 ± 150 yr B.P. (I-9556).

Proceedings of the F. D. Holland, Jr., geological symposium, 1992, J. M. Erickson and J. W. Hoganson, eds., North Dakota Geological Survey Miscellaneous Series No. 76.

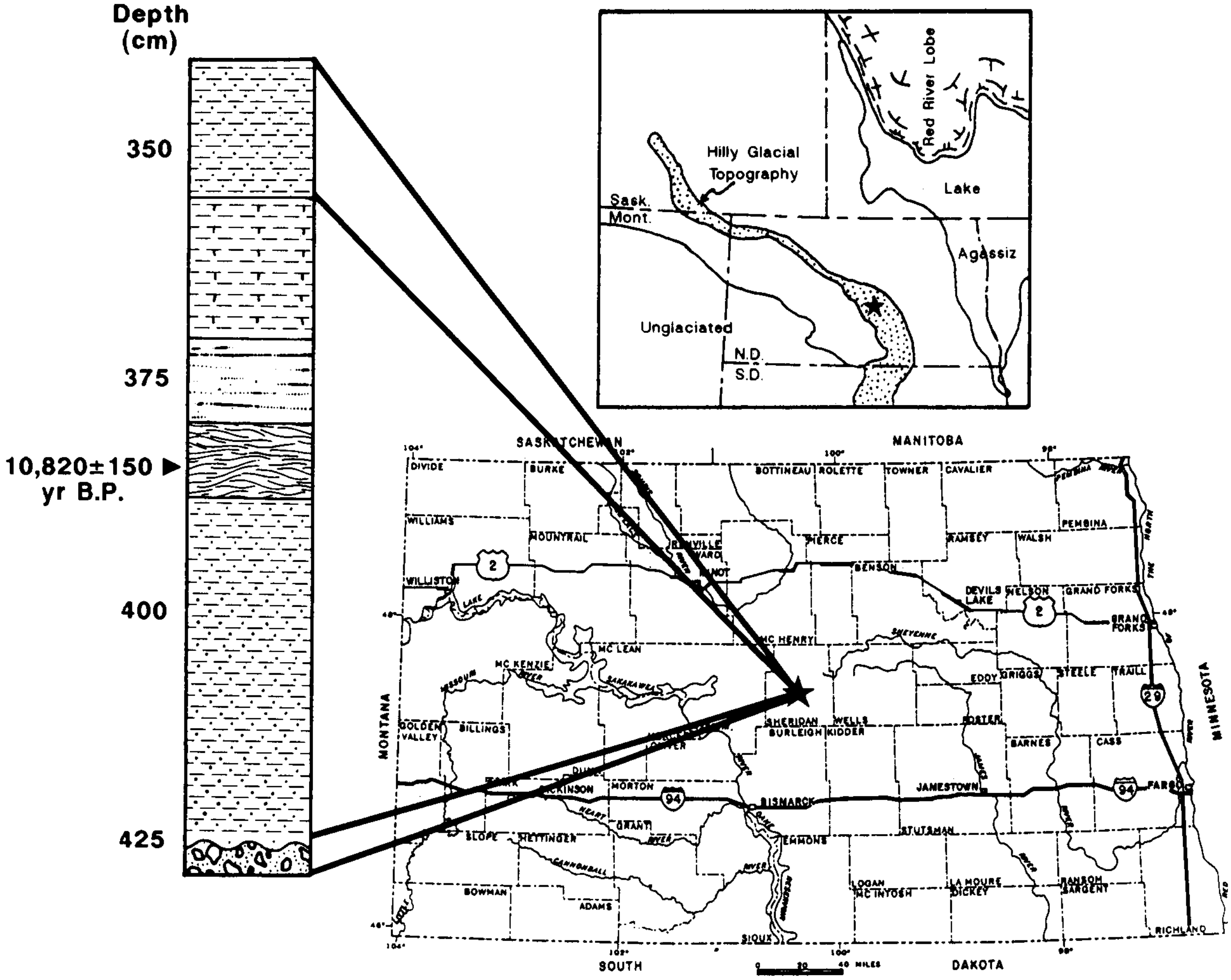

Figure 1-Location and stratigraphy of the Johns Lake site. Inset map shows major glacial features at ca. 11,000 yr B. P. (after Bluemle, 1988).

The early depositional history of the lake implied by lithological changes is one of changing water levels, presumably caused by episodic melting of buried ice. Sheet flows and mud flows, transporting occasional boulders from sparsely vegetated moraines, were probably the source of the initial sediments of the basin (Unit 2). As the lake shallowed, a bog developed (Unit 3). More melting of ice caused renewed basin subsidence, and the bog was slowly drowned by rising water level (Unit 4) until a marl lake developed (Units 5 and 6). Final melting of buried ice and the stabilization of the lake basin are indicated by the deposition of the grey silty clay (Unit 7) that overlies the marls. The silty clay is typical of the Holocene colluvium of prairie lake basins.

Differences in the species-richness and individual abundance of molluscs support an interpretation that there were major changes occurring in the lake basin between the deposition of Unit 5 and Unit 7. Sixteen species of molluscs, including the gastropods *Amnicola limosa* (Say), *Gyraulus parvus* (Say), *Helisoma anceps* (Menke), *H. campanulatum* (Say), *H. trivolvis* (Say), *Promenetus exacuous* (Say), *Physa gyrina* Say, *Valvata sincera* Say, *V. tricarinata* (Say), and the bivalves, *Pisidium* sp. and *Sphaerium simile* (Say) were identified from the lower marl (Unit 5), whereas only one species of gastropod, *H. anceps*, was identified from the upper part of the grey silty clay (Unit 7) (R. Carlson, written communication, 1976).

PALEOENTOMOLOGICAL STUDY

Sample preparation.--A stratigraphic series of samples, each weighing 2 kg, was collected at 10-cm intervals from the basal lacustrine sediments. In addition, bulk samples of 10 kg, were collected from each of Units 2-7. Chitinous insect remains were separated from the sediments by wet sieving and kerosene flotation (Ashworth, 1979). The disarticulated pieces of exoskeletons, mostly heads, pronota, and

Table 1. The stratigraphic section at Johns Lake, Sheridan County, North Dakota.

Unit No.	Thickness (cm)	Depth from surface (cm)	Lithology
Unit 7	15	340-355	Grey silty-clay, with occasional molluscs.
Unit 6	3	355-358	Light brown marl with molluscs.
Unit 5	12	358-370	Dark grey marl with abundant molluscs.
Unit 4	9	370-379	Brown peat comprised of the moss species *Calliergon richardsoni* (Mitt.) Kindb., *Drepanocladus aduncus* (Hedw.) Warnst., and *Scorpidium scorpioides* (Hedw.) Limpr.
Unit 3	8	379-387	Black peat with spruce wood and cones. Wood has an age of 10,820 ± 150 (I-9556).
Unit 2	37	387-427	Grey silty-clay with occasional plant fragments and molluscs. Boulders at the top.
Unit 1	149	427-576	Gravel. Base not seen.

elytra of beetles, were mounted on micropaleontological slides and are reposited in the collections of the Quaternary Entomology Laboratory at North Dakota State University.

Description of the fauna.--A rich assemblage of well-preserved beetle fossils was recovered from the lower stratigraphic units of Johns Lake, especially the peat bed (Unit 3). The disarticulated, exoskeletal body parts of at least 84 species representing 21 families of Coleoptera were identified from Units 2-5 (Table 2). Collectively, the species are characteristic of aquatic, water-marginal, forest, and open-xeric habitats. The position that these species would occur on a landscape is illustrated in Figure 2.

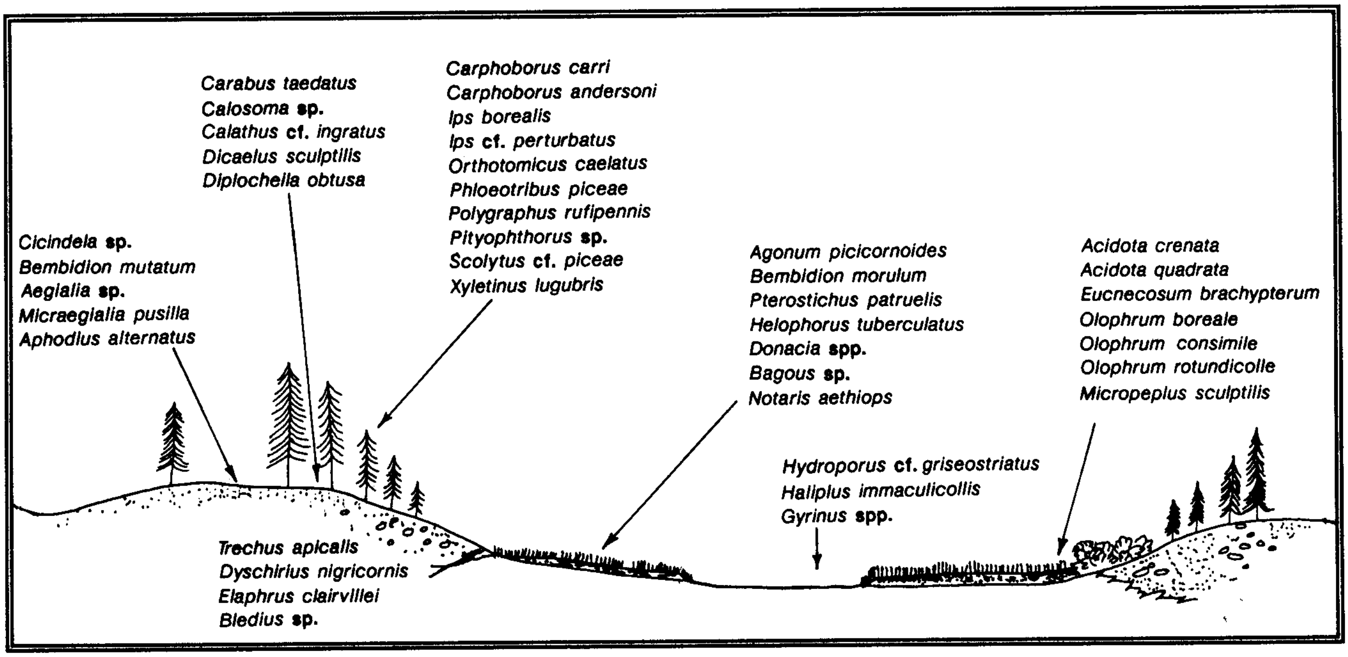

Figure 2-Reconstruction of the Johns Lake site based on the habitat requirements of the beetle species.

Table 2-Faunal list of Coleoptera represented as fossils in the Johns Lake site, Sheridan County, North Dakota[a].

Taxa	Skeletal Parts	Minimum number of individuals			
		Unit 2	Unit 3	Unit 4	Unit 5
CICINDELIDAE:					
Gen. indet.	mandible		1		
CARABIDAE:					
Carabus taedatus Fab.	L		1		
Calosoma sp.	R				1
Elaphrus clairvillei Kby.	P		2		
Dyschirius nigricornis Motsch.	P L R		4		
Dyschirius spp. (2)	L R		1		1
Patrobus stygicus Chaud.	H P		1		
P. foveocollis (Esch.)	H P		1		
Trechus apicalis Motsch.	P L R		4		
Bembidion mutatum G. & H.	P		1		
B. morulum LeC.	P L R		9		
B. cf. *concretum* Csy.	P		1		
Bembidion spp. (6)	H P L R	1	6		
Pterostichus patruelis (Dej.)	P L R		3		
Calathus cf. *ingratus* Dej.	P		1		
Agonum picicornoides Lth.	P L R		1		
Agonum spp.	L R		2		
Amara sp.	P		1		
Diplocheila obtusa (LeC.)	P		1		
Dicaelus sculptilis Say	L R		1		
cf. *Microlestes* sp.	P				1
HALIPLIDAE:					
Haliplus immaculicollis Har.	R	1			
DYTISCIDAE:					
Hydroporus cf. *griseostriatus* (DeG.)	L		1		
Agabini gen. indet.	P L R		2		
cf. *Graphoderus* sp.	L		1		
GYRINIDAE:					
Gyrinus minutus (Fab.)	R		1		
Gyrinus spp. (2)	R		2		
HYDROPHILIDAE:					
Helophorus tuberculatus Gyll.	H P R		1		
Helophorus sp.	H P		2		
Hydrobius fuscipes (L.)	H		1		
Cercyon sp.	H L		1		
LIMNEBIIDAE:					
Ochthebius sp.	L R		1		
MICROPEPLIDAE:					
Micropeplus sculptus LeC.	P L R		1		

Taxa	Skeletal Parts	Minimum number of individuals			
		Unit 2	Unit 3	Unit 4	Unit 5
STAPHYLINIDAE:					
Bledius sp.	P L R		1		
Eucnecosum brachypterum (Grav.)	P	1			
E. tenue (LeC.) or *brunnescens* (J. Sahlb.)	P L R	1	11		
Olophrum boreale (Payk.)	P		1		
O. consimile (Gyll.)	P L R		1		
O. rotundicolle (C. R. Sahlb.)	P L R		1		
Acidota quadrata (Zett.)	P	1			
A. crenata (Fab.)	P	1			
Geodromicus sp.	P	1	1		
Stenus spp. (3)	P L R	3	1		
Tachinus cf. *elongatus* Gyll.	sternite	1			
PSELAPHIDAE:					
Gen. indet.	H P		1		
LEIODIDAE:					
Catopinae gen. indet.	L R		3		
SCAPHIDIIDAE:					
Gen. indet.	L R		1		
HISTERIDAE:					
Hister sp.	H			1	
SCARABAEIDAE:					
Micraegialia pusilla Horn	L				1
Aegialia sp.	P L R		1		
Aphodius alternatus Horn	H		1		
Aphodius omissus omissus LeC.	H				1
Aphodius hamatus grp.	P L R		1		
HELODIDAE:					
cf. *Cyphon* sp.	L R		1		
BYRRHIDAE:					
Cytilus sp.	H P L R		1		
Simplocaria sp.	R		1		
Gen. indet.	L R		3		
ELATERIDAE:					
Negastrius sp.	P		1		
ANOBIIDAE:					
Xyletinus lugubris LeC.	L R			1	
Gen. indet.	P R		1		
CHRYSOMELIDAE:					
Donacia spp. (2)	P L R		2		
Plateumaris sp.	L		1		
Graphops sp.	H P R		1		

Taxa	Skeletal Parts	Minimum number of individuals			
		Unit 2	Unit 3	Unit 4	Unit 5
CURCULIONIDAE:					
Apion sp.	L R				1
Listronotus sp.	L R		1		
Notaris aethiops Fab.	H P L R		2		
Tanysphyrus sp.	L R		2		
Bagous sp.	H P L R		3		1
Rhinoncus sp.	R		1		
cf. *Cossonus* sp.	L			1	
SCOLYTIDAE:					
Scolytus cf. *piceae* (Sw.)	R		3		
Phloeotribus piceae Sw.	L R		3		
Carphoborus andersoni Sw.	R		2		
Carphoborus carri Sw.	L R	1	6		
Polygraphus rufipennis (Kby.)	L R		4		
Orthotomicus caelatus (Eich.)	L R		2		
Ips borealis Sw.	R		2		
Ips cf. *perturbatus* (Eich.)	R		1		
Pityophthorus sp.	H P L R			1	

[a] Numbers in parentheses refer to the number of indeterminate species within a taxon. Skeletal parts are abbreviated: H = head, P = prothorax, L = left elytron, R = right elytron. Minimum number of individuals listed are based on the most abundant skeletal part. Lithologies of samples are presented in Table 1 and Figure 1.

Aquatic and water-marginal beetles are abundant in Units 2 and 3 indicating that the basal sediments accumulated in a shallow body of water. A diverse assemblage of omaliine rove beetles (Staphylinidae), all associated with moist, organic debris or with emergent, subaquatic vegetation, dominates this component; included are *Olophrum consimile* (Fig. 3c), *O. rotundicolle*, and *O. boreale*, omaliine species today generally distributed throughout the boreal forest (Campbell, 1983). Also associated with moist organic debris and sedges (Smetana, 1985) is the hydrophilid *Helophorus tuberculatus*, a species that likewise has a boreal forest distribution (Fig. 3a). The presence of open water is indicated by the occurrences of the whirlygig beetles *Gyrinus* spp., the dytiscid *Hydroporus* cf. *griseostriatus*, and the haliplid *Haliplus immaculicollis*.

Terrestrial species are also well-represented in the Johns Lake fossil assemblages. One of the most diverse assemblages of bark beetles (Scolytidae) yet described from the late-glacial of North America occurs in Unit 3. All of the species are associated with conifers, with several, including *Carphoborus andersoni*, *C. carri*, and *Ips borealis*, restricted to spruce (*Picea*) (Wood, 1982). Most of the Johns Lake scolytids are distributed throughout the boreal forest (e.g., *I. borealis*, Fig. 3b). With a geographic range apparently restricted to Alaska, Yukon, and the Northwest Territories (Wood, 1982), *C. andersoni* is an exception; this species, however, is commonly encountered as a fossil in late-glacial sites from midcontinental North America.

Species of ground beetles (Carabidae) of Unit 3, e.g. *Carabus taedatus* and *Dicaelus sculptilis*, indicate that, at least locally, the forest floor was dry. Further evidence that sandy openings were present in the forest is provided by the occurrence of fossils of a tiger beetle, *Cicindela* sp., and of the byrrhids *Cytilus* sp. and *Simplocaria* sp. Open, sandy patches may also have been the habitat of *Micraegialia pusilla* (Table 2, Unit 5), a tiny, rare, aegialiine scarabaeid also known as a fossil from the late-glacial Norwood site in southern Minnesota (Ashworth et al., 1981). *M. pusilla* is presently known from only four localities (Fig. 3d) (Gordon and Cartwright, 1988), and its habitat requirements are unknown. From its fossil occurrences at Johns Lake and at Norwood, and from its present day occurrence, near Aweme, southern Manitoba, we infer that the habitat of this species is open sandy patches in spruce woodland.

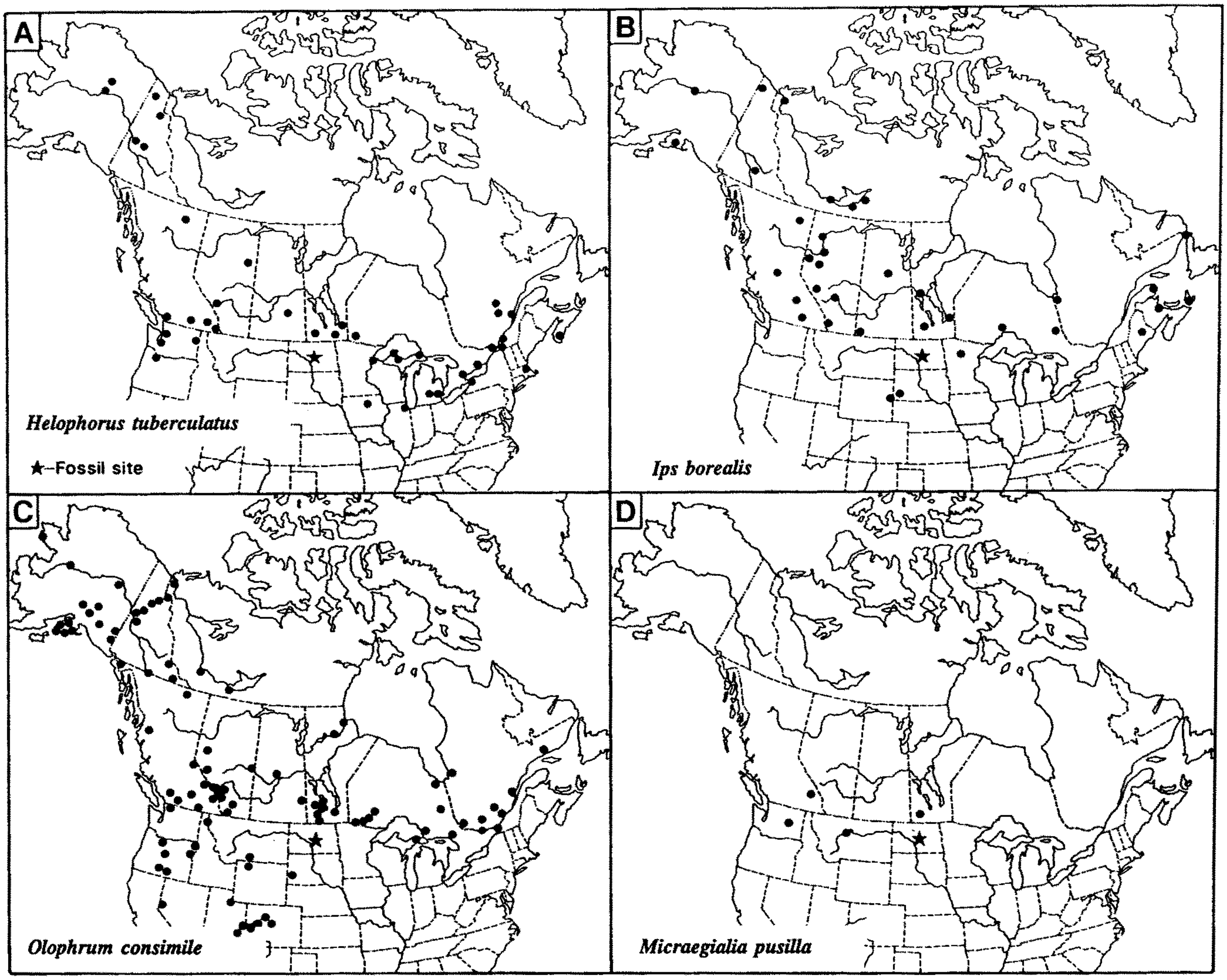

Figure 3-Modern distributions (black dots) of selected beetle species represented as fossils at the Johns Lake site (star).

DISCUSSION

The spruce forest environment inferred from the Johns Lake fossil beetle assemblage is in marked contrast to the treeless, prairie landscapes of the Missouri Coteau today. In the midcontinent, the existing ranges of the micropeplid *Micropeplus sculptilis*, the hydrophilid *Helophorus tuberculatus* (Fig. 3a), the scarabaeid *Micraegialia pusilla* (Fig. 3d), and the carabids *Dicaelus sculptilis*, *Agonum picicornoides*, and *Diplocheila obtusa* extend northward just into the southern portion of the boreal forest (Lindroth, 1966, 1968, 1969; Campbell, 1968; Smetana, 1985; Gordon and Cartwright, 1988). Consequently, despite the presence as fossils of the northern carabid *Bembidion morulum* and the northwestern scolytid *Carphoborus andersoni*, faunal analogues to the Johns Lake assemblage are best represented today within the southern boreal forest. In faunal composition, the Johns Lake assemblage has affinities to other late-glacial insect assemblages from the midcontinent (e.g., Morgan and Morgan, 1979; Garry et al., 1990). With its rich component of omaliine staphylinids and spruce- associated scolytids, the Johns Lake assemblage is similar to the insect assemblage from the "peat" at the Norwood site (Ashworth et al., 1981). The transition at Norwood from an open-ground fauna to a forest fauna is also represented at Johns Lake, although the absence of terrestrial species of open habitats in the basal silt at Johns Lake makes the evidence less compelling. The increase in numbers of species of bark beetles at Johns Lake, however, from one in the silt to eight in the peat, suggests that trees were not as abundant initially as they were later. As at Norwood, the fossil evidence could be interpreted to represent a local succession.

There are few paleoecological studies from North Dakota with which to compare the Johns Lake results. Pollen, plant macrofossils, and fossil beetles from the Seibold site indicate that a spruce-aspen forest persisted until at least 9750 yr B.P. (Cvancara et al., 1971; Ashworth and Brophy, 1972). The beetle faunas of both Johns Lake and Seibold indicate a vegetation that was an open rather than a closed forest.

An undated pollen profile from Woodworth Pond in Stutsman County (McAndrews et al., 1967) shows that spruce colonized the deglaciated landscape, and was then replaced by a short-lived deciduous forest, and finally prairie. The demise of the forested habitats was caused by the climatic warming and droughts associated with the Prairie Period. The onset of the Prairie Period in North Dakota, based on diatom evidence from Devils Lake, was a sudden event measured in tens of years rather than centuries (Fritz et al., 1991). Diatoms indicative of lake water with high salinity values rapidly replaced those of fresh water about 8500 yr B.P.

Regionally, pollen studies demonstrate that spruce forest colonized the retreating margin of the Laurentide ice sheet. By 11,000 yr B.P. in northeastern South Dakota, spruce forest became mixed with deciduous hardwoods, and by 10,000 yr B.P. was replaced by prairie (Barnosky et al., 1987). Further north, in Manitoba and Saskatchewan, spruce forest persisted from about 12,000 to 10,000 yr B.P. (Ritchie, 1987). One of the questions concerning the late-glacial spruce forest is whether it was a closed forest, an open forest, or a prairie-forest mosaic. Information on the composition of plant communities needed to answer this question cannot be inferred from palynological studies. No exclusively prairie species are represented in the Johns Lake beetle fauna but the occurrence of several species of open habitats suggests that the forest was not a closed forest like that of the boreal forest today.

ACKNOWLEDGMENTS

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TUFFS IN NORTH DAKOTA

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ABSTRACT

North Dakota tuffs have important relevance to geology in several ways: 1) The identification of well-preserved ancient tuffs in North Dakota refutes widely held notions that volcanic glass cannot be geologically old; 2) Bentonite and zeolite deposits in North Dakota are found in many cases still associated with unaltered portions of their progenitor ashes, providing perhaps unparalleled opportunities for study of glass-clay or glass-zeolite transitions; and 3) Absolute age information and petrologic signatures may be obtained from North Dakota tuffs. Provided is a listing and discussion of the Cretaceous Linton tuff, Cretaceous Marmarth tuff, Paleocene Sentinel Butte Formation tuff, Oligocene Brule Formation tuffs, Miocene(?) Arikaree Formation tuffs, and a potential correlative of the Linton tuff.

INTRODUCTION

Tuff is compacted volcanic airfall material. Although tuffs may contain up to 50% non-pyroclastic components, the dominant constituent of most tuffs is glass that results as molten material becomes quenched upon reaching Earth's surface. It has long been held that volcanic ash is necessarily young geologically because of the thermodynamic metastability of glass. Many geologists have been taught that natural glasses occur only in units that are of Miocene age or younger (<25 ma). It was thought that volcanic glasses are easily devitrified in the presence of water even at low temperatures. Marshall (1961) presented good arguments that devitrification of volcanic glasses <u>can</u> be a very slow process, but he also concluded that "the ubiquity of water on Earth severely limits the existence of volcanic glasses and accounts for the absence of glass in old formations."

The recognition of old tuff units in North Dakota has done much to change the eroneous notion that glass cannot be old. The widespread occurrence of these tuffs does not support the simple view that ashes must necessarily alter as a result of either aging or of the near ubiquity of water on this planet. Of additional significance is the fact that bentonites and some zeolitic deposits in North Dakota are found still associated with unaltered portions of their progenitor ash units. Perhaps this provides unparalled opportunities to gain field information about the process of alteration and preservation of tuffs.

Tuffs are very useful as marker units because they are isochronographic. That is, they commonly are deposited over broad regions during an instant of geologic time. They also are useful for assessing the age of enclosing sedimentary rocks because the primary constituents of tuffs had their radiometric and fission-track clocks set at the time of eruption. Therefore, study of tuffs in North Dakota is of use toward determining the age of sedimentary intervals, and toward establishing regional correlations.

This report is primarily a listing and general description of tuffs in North Dakota. Additional details about some of these tuffs can be found in Forsman (1984, 1985, 1986). Efforts are currently underway to obtain absolute ages of all tuffs in North Dakota and to investigate possible correlations with other midcontinent tuffs. Many opportunities exist for continued study.

The Linton Tuff

The oldest documented tuff in North Dakota is the Linton tuff of Cretaceous age. It is exposed locally on

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hillslopes near the town of Linton in Emmons County, North Dakota (Fig. 1). This light gray silt-size material has accumulated to a thickness of at least 8 m, in what Erickson (this volume) has interpreted to be a broad erosional trough within the basal portion of the Fox Hills Formation. The Linton tuff is therefore potentially younger than its proximity to the underlying Pierre Shale would suggest. A radiometric age determination of this tuff has not been reported. Although some exposures of the Linton tuff appear "fresh" or only slightly-weathered, preliminary petrographic examinations have been conducted only on material from a relatively highly weathered exposure. The material examined consists of 67% volcanic glass shards, 9% phenocrysts and/or admixed detrital grains, and 24% secondary clay. Except where coated by the clay mineral montmorillonite, glass grains appear unaltered and reveal no birefringence. The glass is of rhyolitic composition, determined by microprobe analysis. Additional detailed characterization of materials in the Linton tuff is necessary in order to fully evaluate its scientific value.

The Marmarth Tuff

Another Cretaceous tuff occurs near the town of Marmarth in Slope County, North Dakota. The Marmarth tuff occurs a few meters below the top of the Hell Creek Formation and is overlain and underlain by bentonite. The term "bentonite" is used in a scientific rather than industrial sense, referring to a clay unit that originated through the alteration of a glassy igneous material. The lower bentonite caps very broad benches underlain by steep Hell Creek sandstone scarps. The tuff is normally 60 to 90 cm thick, but is 4.6 m thick in an isolated outlier. Examined samples of the Marmarth tuff consist of 86% glass grains (Fig. 2), ~8% phenocrysts and admixed detrital grains, and ~6% secondary montmorillonite. The glass is rhyolitic in composition and ranges in size from medium silt to fine sand. Glass grains appear perfectly preserved except where thinly coated by authigenic montmorillonite. Ripple-bedding within the gray-white tuff is evidence that it was at least locally deposited by water. In the vertical sequence of bentonite-tuff-bentonite, there occurs a nonvolcanic sandy parting at the base of the tuff. This is evidence that either (1) reworking of a broader ash mantle toward low-lying areas was discontinuous and interrupted by accumulation of other sediments, or that (2) more than one eruption event contributed material to this sequence.

Biotite from the Marmarth tuff has been dated at 68 ±3.2 ma by the K-Ar method (Frye, 1967). Addi-

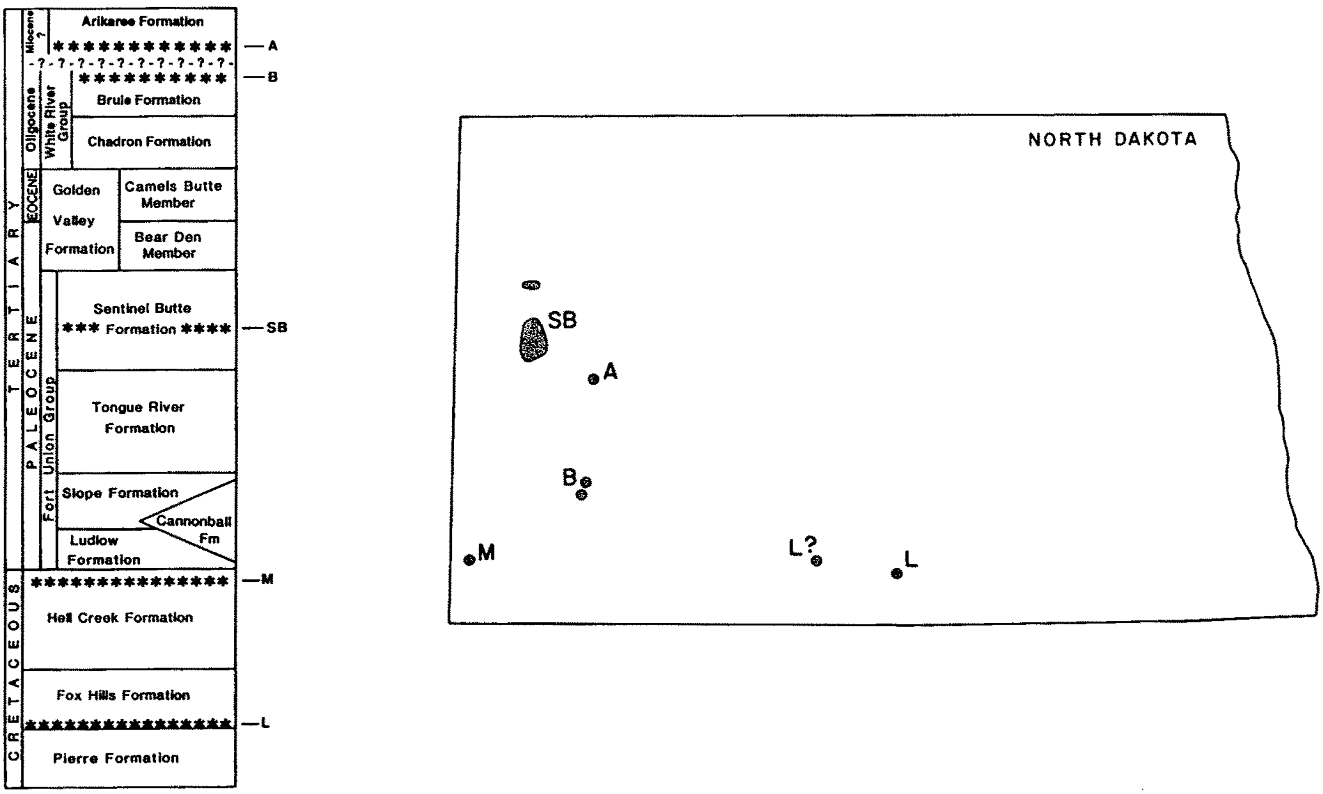

Figure 1-Stratigraphic column showing positions of North Dakota tuffs and map showing geographic location of the tuffs.

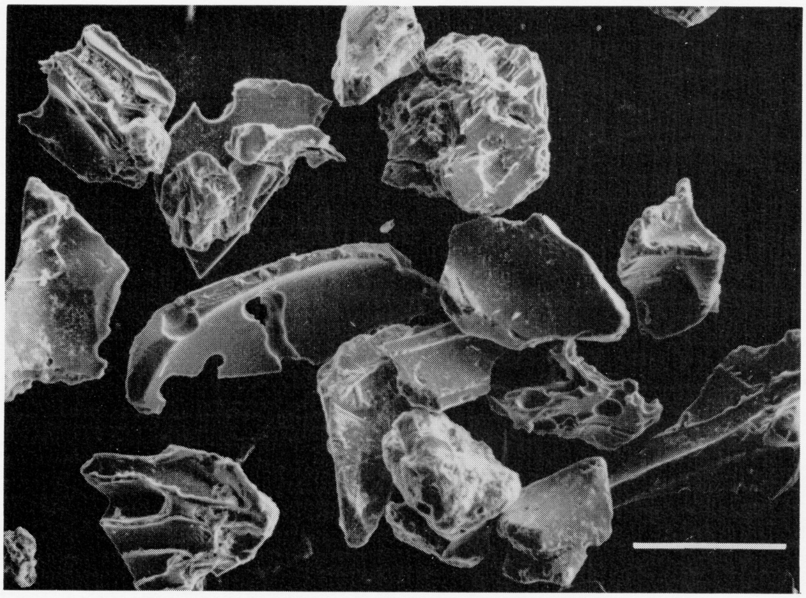

Figure 2-Scanning electron photomicrographs of glass grains from the Marmarth tuff. Bar = 100 microns.

tional study of this deposit is needed to determine if there were separate eruption events and to test for equivalence with other tuff exposures in North Dakota and neighboring regions.

The Sentinel Butte Formation Tuff

A tuff unit of Paleocene age occurs over a broad region within and near the North Unit of Theodore Roosevelt National Park in McKenzie County, North Dakota. The tuff occurs within the Sentinel Butte Formation and can be traced visually as a nearly continuous deposit over many kilometers through badlands terrain. It can be mapped over an area of nearly 1500 square kilometers (Fig. 3). The tuff is everywhere overlain and underlain by bentonite. With the resulting tri-partite unit ranging up to 7.5 meters thick (Fig. 4). The lower bentonite forms broad resistant benches because of the cohesive character of constituent clays. These prominent benches of up to 3.7 meter-thick bentonite are overlain by gray-white tuff ranging from 0.6 to 2.4 meters in thickness.

The tuff, is in turn, overlain by 0.6 to 1.5 m of bentonite. The tuff consists of approximately 67% glass shards, 23% phenocrysts plus admixed detrital grains, and 9% authigenic montmorillonite. Most of the glass shards are of very fine silt. The glass grains are isotropic except for a thin, discontinuous birefringent rim seen on relatively few grains. This birefringence is the result of partial alteration of glass grains to montmorillonite.

All three layers of this tuff-bentonite sequence contain glass grains, with 11%, 75%, and 4.5% glass grains occurring in the silt fractions of the lower bentonite, tuff, and upper bentonite, respectively. Microprobe analyses indicate no difference in major element composition of glass grains between the three layers. Non-clay minerals present within each of the three layers include biotite, muscovite, dolomite, quartz, chlorite, plagioclase, calcite, apatite, cordierite, sphene, and zircon. It has not yet proven possible to confidently distinguish between phenocrysts and admixed detrital components in this unit.

The contacts between the tuff and the overlying and underlying bentonites at first appear abrupt, but are actually gradational over a few centimeters, with clay content increasing toward the bentonites (Fig. 4). No non-volcanic partings have been detected between the tuff and bentonites. The upper and lower bentonites appear to have formed through progressive alteration of an originally thicker single ash accumulation. It is hypothesized that this alteration progressed inward from the upper and lower contacts with enclosing strata as metal ions necessary for the development of montmorillonite were delivered from those strata by groundwater. The reason for the preservation of the enclosed tuff remains uncertain. This tri-partite Paleocene unit offers an unusual opportunity for comparison of progenitor glass materials with secondary alteration products.

The widespread lateral continuity of this unit,

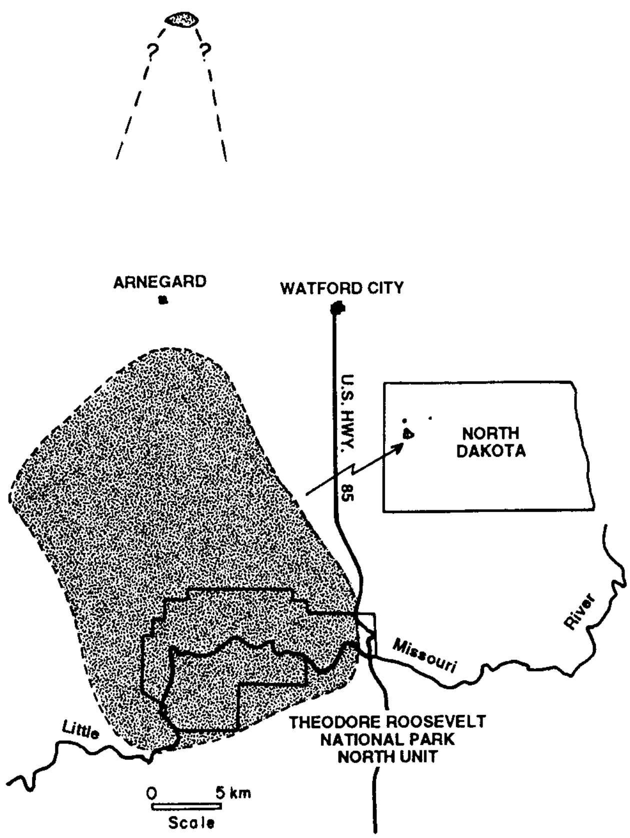

Figure 3-Areal extent of Sentinel Butte tuff exposures.

together with the presence of water-formed ripples at the base of the lower bentonite at several localities (Forsman, 1985; Larsen, 1988), is evidence of a lacustrine environment of deposition. In that the nearest possible Paleocene volcanic centers were over 400 km distant, the ash presumably was deposited over a broad region as a thinner mantle, later to become concentrated on the floor of a large lake or lakes through normal drainage processes.

Brule Formation Tuffs

Two tuffs within the Oligocene Brule Formation occur locally in the "Little Badlands" region south of Dickinson, in Stark County, North Dakota. These tuffs are separated by only a few miles. One is located on the Obritsch ranch, at SE¼ NW¼ SE¼, Sec. 29, T. 138 N., R. 97 W. It consists almost solely of glass shards; feldspar phenocrysts are rare and epiclastic grains are apparently absent. After laboratory treatment to remove authigenic montmorillonite, this would seem to be an ideal tuff from which to obtain a chemical signature to compare with tuffs from other regions.

The second tuff unit occurs on the Fitterer ranch, at NW¼ NW¼ SE¼, Sec. 7, T. 137 N., R. 97 W. of Stark County. This tuff consists of over 90% glass grains but also contains a higher proportion of mineral grains than the tuff from the Obritsch ranch. The authigenic species montmorillonite, erionite, and calcite are also present in the Fitterer ranch tuff. The mineralogic differences between tuff samples from these two localities are perhaps due only to differences in epiclastic input and diagenesis. Perhaps the two tuffs are actually from the same eruption event. There is an apparent slight difference in the refractive index of glass grains from the two sites ($n=1.498$ vs $n=1.497$), but these values are too close to claim significance. Samples from the two sites are currently being compared by trace element analysis to determine whether they are portions of a single correlative unit or represent two distinct eruption events. One, or both, of these tuffs may be of value for regional correlations with White River Group units in South Dakota and Nebraska. Of course, the identification of many tuff units representing distinct eruption events increases the chances of correlating North Dakota tuffs with those from other regions.

Arikaree Formation Tuffs

Glass-rich sedimentary rocks and tuffs are also present in Arikaree Formation strata exposed in the Killdeer Mountains in Dunn County, North Dakota. Some equivocal paleontologic information is suggestive of a Miocene age for these strata, but substantiating absolute age evidence is needed.

Two Arikaree units may be recognized as tuffs even though they contain some quantity of epiclastic material. One of these tuff units occurs as a 60 to 90 cm thick, partially lithified to friable, light gray unit immediately below a cliff-rimming ledge near the top of North Mountain. This unit contains 77% glass grains. Additional tuff occurs within a conspicuous, widespread eight-foot thick ledge that flanks portions of South Mountain. The ledge has a comb-like appearance, formed by the erosion of friable layers repeated between multiple indurated layers. This ledge forming unit is informally referred to as the burrowed marker unit because of the abundant presence of prominently exposed trace fossil burrows. Glass grains comprise up to 61% of each of the layers of this unit.

The Arikaree Formation tuff samples examined have each gone through a similar sequence of diagenetic changes. In fact, diagenesis has caused glass grains in these Miocene(?) tuffs to be in many cases less well preserved than the older glass grains discussed above. Even though many unaltered glass grains remain in these Arikaree tuffs, other glass grains have undergone

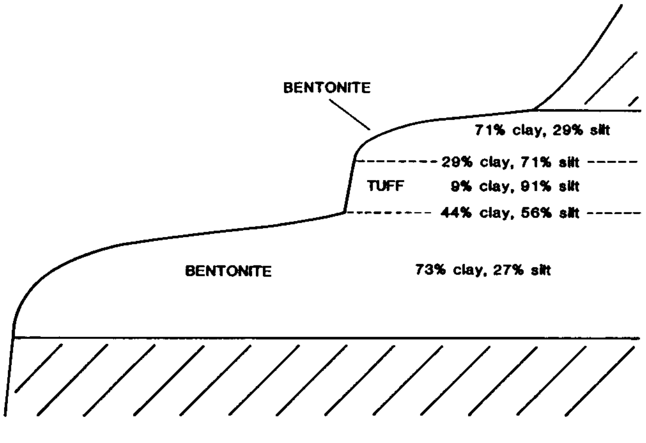

Figure 4-Field expression and grain size characteristics of the Sentinel Butte tuff.

pronounced surface dissolution. All grains were eventually coated with authigenic montmorillonite, with even later erionite crystals growing outward from the montmorillonite substrates. Glass grains in the indurated portions of the burrowed marker unit have been largely replaced by calcite, leaving glass ghosts visible in thin sections.

Further details concerning the character of tuffs in the Killdeer Mountains are found in Forsman (1986). Samples from the burrowed marker unit are currently being evaluated in an effort to determine how many distinct eruptive episodes are recorded within that unit. An overall petrographic characterization including trace element analysis is being conducted to determine the age of the Killdeer Mountain strata through comparisons of these tuffs with tuffs from other regions where time-stratigraphic assignments are well established.

Additional Tuffs

An additional tuff unit was reported by Frye (1967) to occur in the Fox Hills Formation in the Center, Sec. 31, T. 134 N., R. 82 W., Sioux County, North Dakota. He suggested that this tuff may be correlative with the Linton Tuff of this report. He reported a rhyolitic composition based on an index of refraction of $n=1.50$ to $n=1.51$. He also reported that silt-size glass shards comprise 98% of this deposit, and that intact vesicles are seldom seen, suggesting breaking of grains due to wave action on a beach.

This deposit forms a prominent scarp bordering the eastern floodplain of the Cannonball river within the Standing Rock Indian Reservation. It has not been studied since 1967. Advancements in petrologic fingerprinting of volcanic glasses can now be applied to the question of possible correlation of this deposit with the Linton Tuff. Demonstrating equivalence of these two deposits would be of great benefit to paleogeographic reconstructions in the region.

Since 1986 four tuffs in North Dakota have been discovered, and the prominent Sentinel Butte Formation tuff was not recognized as such until 1980. Other tuff units may remain unrecognized in North Dakota and neighboring regions.

SUMMARY

Glass-rich tuffs occur in North Dakota in rocks of Miocene(?), Oligocene, Paleocene, and Cretaceous age. The state of preservation of these units negates the view that glass is so unstable as to necessarily alter to crystalline forms within ≈25 million years. The presence of bentonites in association with some tuffs, and the presence of authigenic mineral phases within other tuffs provides opportunities for study of the alteration process(es) of ashes. North Dakota tuffs are also potentially useful for absolute age assessments and for petrologic fingerprinting that may allow correlations with tuffs from other regions.

Important scientific information is contained in the surface strata of western North Dakota. These rocks contain a record of the waxing and waning of a great sea, of the extinction and consequent emergence of species, of the rate of uplift and erosion of ancestral mountains, of changes in climate, and of past geographic patterns. Tuffs are of great value in the deciphering of Earth history because they mark an instant of geologic time and that time can be determined by absolute dating methods. The tuff units in North Dakota are of use to paleontologists, stratigraphers, and sedimentologists as they continue studies aimed at furthering our understanding of the geologic history of the midcontinent.

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ZONED CRYSTALS

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ABSTRACT

Crystals that are coated or rimmed by different colored minerals are classed as zoned crystals. Molten material in the earth's crust called magma is host to the various stages of crystallization. The sequence of crystallization in a magma is called Bowen's Reaction Series. One series is discontinuous in descending order of temperature and pressure from olivine to pyroxene to amphibole, then mica and quartz, as indicated by the reaction rims or coronas. The other series or sequence is continuous from high temperature calcic plagioclase to albite at the sodium end. One mineral grows around another mineral as its nucleus. Feldspar crystals with calcic cores and sodic shells are normal constituent minerals in most lava dikes and flows.

Garnets are especially susceptible to zonal intergrowths with other minerals. Several occurrences of zoned garnets, feldspar crystals, mica and related minerals are given.

INTRODUCTION

Many of us are fascinated by crystals that are coated or rimmed by different colored material. These are zoned crystals and they occur most generally in the granite family of rocks. The zoned crystals represent changes in the sequence of crystallization from the early molten rock material due to changes in temperature and pressure and consequent changes in composition. Some of the first materials to crystallize in the igneous magma are the high-temperature heavier iron and magnesium minerals like olivine and pyroxene (augite). Next in the sequence or order of crystallization are the amphiboles (hornblende), followed by biotite.

Magma, molten material in the earth's crust, is host to the various stages of crystallization related to changing orogenic and convective processes. Some of the early crystals like olivine and anorthite commonly disappear, their components going to form crystals lower in the reaction series.

The sequence of crystallization in a magma is called Bowen's Reaction Series after N. L. Bowen (1928) an American scientist who studied the order of crystallization in rocks and reported two reaction series. One series is discontinuous in descending order from olivine, a solid solution of fosterite and fayalite, then magnesium pyroxene, magnesium-calcium pyroxene, amphibole, biotite, potash feldspar, muscovite, and quartz. Each mineral may be derived from the one above by reaction in the melt.

The other sequence of crystallization is continuous from high temperature calcic plagioclase anorthite, to bytownite, to labradorite to the more alkaline andesine to oligoclase, then albite at the sodium-rich end of the reaction. These plagioclase minerals are listed in the order of descending temperature. Because the sequence is continuous, zoning is quite common in plagioclase feldspar crystals. The bytownite center may be surrounded by layers of each descending concentration of plagioclase crystal to equal calcium-sodium aluminum silicate, andesine, to the alkali sodium albite outer shell or zone.

A graph of these "frozen" mineral zones of changed composition symbolizes the phase rule and phase diagram of the anorthite-albite system. See the diagram below after Professor Howell Williams, 1954.

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Discontinuous Series	Continuous Series
Olivine	Anorthite
Pyroxene	Bytownite
(Fe/Mg increasing)	
	Labradorite
Pyroxene	Andesine
Hornblende	Oligoclase
Biotite	Albite
Quartz	
	Potash feldspar
Zeolite	
Water-rich solutions	

Information from artificial melts and from the study of thin sections of natural rocks indicates three reaction series. The alkali feldspars form another continuous reaction series from potassium sanidine, to sanidine, to sodium sanidine, to anorthoclase to albite and some to zeolites. The zoned sequence can be constructed singly or as pairs rhythmically reversed when the anorthite content is diminished in the melt. Remember that the magma, the molten mass, is the product of the great pressures and heat of moving crustal plates and associated hot spots or plumes. Quantities of the melt are squeezed and filtered from masses of growing crystals. Crystals also settle in the melt and the mother liquid is subject to change and convection currents.

These growths are not limited to deep-seated magma chambers. Zoned feldspar crystals with calcic core and sodic shells are normal constituent minerals in most dikes and lava flows. Twinning is associated with zonal structured crystals and with mosaics of crystals, and as crystals with disordered or disturbed crystal zones and graphic intergrowths.

The composition of the twinned feldspar crystal zones is clearly determined from thin sections with the petrographic microscope. The parallel twin intergrowths of alternating bands extinguish (turn black) under polarized light. The crystals with broad bands are calcium-rich or basic plagioclase as labradorite, and the thin multiple intergrowths characterize the andesine-albite sodium-rich end of the continuous reaction series. The hand lens also can help distinguish the zones from calcium-rich core to the outer rim of albite.

Perthite, is the eutectic intergrowth of orthoclase and albite with their combined composition. The mineral in excess of the eutectic proportion is usually the larger one. The eutectic (interpenetrating and intimately mixed crystals) simultaneous crystallization from a mutual solution or melt of the constituents produce graphic intergrowths and zoned crystals.

Without using the phase rule and equilibrium diagrams the following descriptions should illustrate the formation and existence of zoned crystals.

Brookite is formed at places with different disordered zones resulting from different growth rates due to different adsorption reactions.

Another type of reaction zone may be seen in some biotite hypersthene diorite where the discontinuous reaction series is stopped or frozen and crystals of augite are mantled with hornblende and biotite. These reactions occur by adjustment of the mineral assemblage to reduced pressure and temperature.

Considering Bowen's discontinuous reaction series it is logical to expect and find a wide range of minerals fringed and mantled with their alteration products lower in the series.
Some examples are:

1. Resorbed olivine rimmed with augite.
2. Augite rimmed with hornblende, homoaxially grown from the augite. In some cases augite with enstatite then hornblende zones.
3. Dark greenish brown hornblende and kataphorite with a rim of grass-green aegirine.
4. Mica, phlogopite crystals from a minette (dark mica-syenite) dike in Wyoming have tan magnesium rich centers rimmed with brown iron-rich biotite. Thus, the magnesium mica crystallized before the iron-rich biotite.

Some biotite may appear to be zoned with green chlorite where the potassium and aluminum are leached during metasomatism or weathering. This is an alteration product and not a zoned crystal from a dry magmatic melt.

Similarly, zircon, an early crystallizing accessory mineral may occur as inclusions in mica crystals. Radioactive elements in the zircon form pleochroic halos of radiated biotite about the zircon inclusions. These are bleached reaction rims and not zones of primary crystallization. The wider halos may indicate older crystals and an older igneous host rock.

Blue-green chlorite may line vesicles in lava where the center of the cavity is filled with calcite. These are amygdules. In basic lava, they may be filled with prehnite associated with zeolites. Others may be lined with amethyst crystals, etc.

Augite may be rimmed with uralite, a secondary hornblende. Hypersthene in high temperature metamorphic granulite may crystallize as radiating green crystals about red garnets. Hornblende caught in intense heat of volcanic action may, through fusing, develop internal and external zones of magnetite crystals. Both magnetite and pyroxene may appear. Hornblende may also become pleochroic by oxidation and loss of hydrogen to form brown basaltic hornblende. Serpentinization during intrusion of dunite may produce pseudomorphs of brown iddingsite along the cracks and rims of olivine.

Some of the more complex zoning is attributed to borders of granite plutons that were part of mass movements in the earth. This is seen in the Colville batholith of Washington state. At the Skaergaard intrusion in Greenland about two-fifths of the granodiorite consists of zoned plagioclase. These crystals grade into cloudy potassic feldspar intergrowths with quartz as micropegmatite in the margins of the intrusion. Large pink phenocrysts of orthoclase are mantled with oligoclase feldspar in the Shap Granite of England. This is called rapakivi texture where the potassic core is surrounded by basic plagioclase, a reverse in the continuous reaction series. Some of the coatings may radiate between layers to produce orbicular texture.

Phenocrysts, two inches long, of white orthoclase coated with quartz and biotite occur in the granite east of Salt Lake City, Utah. These weather out and collect at the base of some outcrops.

Kelyphitic rims and concentric shells easily result in ultrabasic magma where crystals of green spinel are enclosed in red garnet. Also, crystals of spinel may be enclosed by a rim of anthophyllite, and pale brown phlogopite, surrounded by radiating fibers of tremolite and actinolite all enclosed in a field of labradorite crystals.

Olivine crystals in gabbro may be enclosed in a shell of hypersthene and an outer shell of actinolite and green spinel all in a groundmass of large broadly twinned labradorite crystals.

Kelyphitic borders or rims are established terms but many in the science prefer "coronas" for rims produced by primary magmatic reaction and kelyphitic when produced by secondary deuteric reactions (paulopost), a little bit later.

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OIL DEVELOPMENT IN NORTH DAKOTA: A HISTORICAL AND STRATIGRAPHIC REVIEW

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ABSTRACT

Petroleum development in North Dakota may conveniently be divided into two cycles. The first cycle began with discovery in an unexplored basin in April, 1951, and ended with the Arab Oil Embargo in 1973. During the first cycle, drilling activity peaked with 454 completions in 1958; and oil production peaked at 27.1 million barrels in 1966. Activity levels reflected restricted markets and relatively low prices. About 5,000 wells were drilled during the cycle.

The second cycle has been marked by an explosive rise and then a collapse of oil prices. Drilling activity peaked with 834 completions in 1981, and an additional 6,500 wells having been drilled. Oil production peaked at 50.7 million barrels of oil in 1984.

The main emphasis of exploration during the first cycle was the Madison (Mississippian) reservoirs which accounted for about 80 percent of the production. The Duperow (Devonian) reservoirs accounted for 7 percent of the production, primarily from the Beaver Lodge initial discovery pool. Average depths of wells was about 6,700 feet.

The second cycle was marked by exploration of the deeper horizons. This was fueled by the economics of $28-to $35-a-barrel oil, improved seismic techniques, and the multiple pays in the central basin area. This combination led to a wildcat success ratio of 21 to 30 percent and an average depth of wells of about 9,000 feet for the period from 1978 through 1983.

The American Association of Petroleum Geologists classifies oil fields on the basis of ultimate recovery. Class A fields are defined as greater than 50 million barrels, Class B - 25 to 50 million, Class C - 10 to 25 million, Class D - 1 to 10 million, Class E - less than 1 million and Class F - abandoned within one year of discovery. Using this classification, 5 Class A, 4 Class B, 22 Class C, and 106 Class D pools have been found in North Dakota. Three of the Class A and 4 of the Class B pools were found in the initial 1951 to 1958 surge of exploration. The other 2 Class A pools were found in the second cycle. Stratigraphically, Madison reservoirs account for 4 Class A and 2 Class B pools while one Class B pool is defined as a Spearfish-Madison pool. The other Class A pool is from the Duperow Formation, and the other Class B pool is from the Tyler Formation (Pennsylvanian).

HISTORICAL REVIEW

Oil development in North Dakota may be divided into two major cycles of activity (Fig. 1) with each cycle influenced by external forces superimposed on exploration success within the state. The first cycle began with discovery of the Beaver Lodge Field by the Amerada Petroleum Corporation - Clarence Iverson No. 1 well in April 1951. Prices received during the first cycle were generally in the $2 to $3 per barrel range in North Dakota and reached $3.50 per barrel near the end of the first cycle. This cycle ended in late

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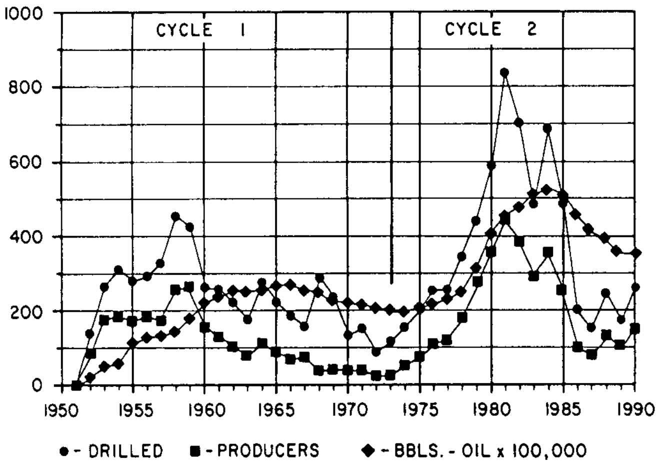

Figure 1-Total wells drilled, producers completed and yearly oil production for North Dakota.

1973 with the Arab oil embargo and its accompanying abrupt upward price changes. The second cycle began with "old" oil at $5.25 per barrel and "new" oil at $12 per barrel. Oil pricing went to a multi-tiered system in the late 70's with "new" oil at $28 per barrel. Since 1981 prices have been decontrolled and have followed worldwide price. In North Dakota this meant $38 per barrel briefly in 1981 followed by a slide to $28 and then to $25 per barrel by 1985. The price plunged to $10 per barrel in 1986.

Activity during the first cycle peaked at 454 completions in 1958, 266 producers were completed in 1959 and production reached about 27.1 million barrels of oil in 1966. There were several pulses of exploration activity (Fig. 2) during this cycle. The initial surge saw

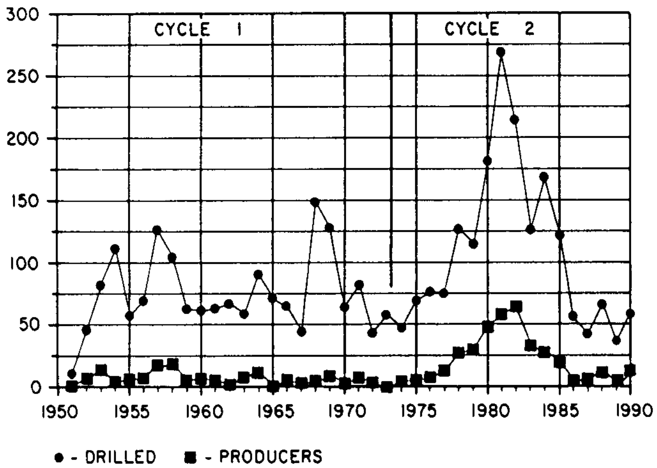

Figure 2-Total wildcats drilled and wildcats completed as producers in North Dakota.

increased activity through 1954 with increased success through 1953. This reflected steady success along the Nesson Anticline and initial discoveries in Bottineau County in 1953. Widespread exploration without success in eastern North Dakota and a refocusing of exploration activity occurred in 1954. The 1957 and 1958 increase of activity and success reflects development in the Burke and Bottineau County area. Producers completed from 1953 through 1957 resulted from steady development of Madison reservoirs along the Nesson Anticline. The 1959 peak for producers completed reflects full development of Madison reservoirs along the Nesson Anticline. After early development, productive capacity along the Nesson exceeded the capacity of the Mandan Refinery until November of 1965. As a result, production in that area was restricted and the production peak was delayed until 1966. The surge in wildcats in 1968 and 1969 marks a widespread search for Cretaceous Newcastle "Muddy" sandstone reservoirs based on discovery of the giant Bell Creek Field in southeastern Montana. Success ratios declined for exploration during the first cycle from 15.3 per cent for the first three years to 5.4 per cent for the last eight years with an overall success ratio of 8.8 per cent (Fig. 3). Exploration was concen-

	W-D	W-P	%	%
1951 - 53	138	21	15.2	
1954 - 58	467	52	11.1	
1959 - 64	404	40	9.9	
1965 - 73	702	38	5.4	
CYCLE 1	1711	151	8.8	
1974 - 75	117	10	8.5	
1976 - 77	161	20	12.4	
1978	126	27-6	21.4	4.8
1979	115	29-7	25.2	6.1
1980	182	48-7	26.3	3.8
1981	267	58-12	21.7	4.5
1982	214	64-13	29.9	6.1
1983 - 85	414	78-17	18.8	4.1
1986	56	5	8.9	
1987 - 88	119	19	16.0	
CYCLE 2	1761	358	20.3	

Figure 3-Summary of per cent of wildcats completed as producers in North Dakota. The second number for wildcat producers for 1978 through 1985 indicates number of Class A to D discoveries.

trated during the first part of the first cycle, on Mississippian Madison or shallower reservoirs with the average depth of wells decreasing from 8,000 feet in 1952 to less than 6,000 feet by 1965. Exploration and development of Ordovician Red River and Pennsylvanian Tyler reservoirs in southwestern North Dakota during the latter stages of this cycle resulted in increasing depths except for the Cretaceous play in 1968 and 1969 (Fig. 4).

During the second cycle drilling peaked at 834 completions and 453 producers in 1981 and production reached about 52.6 million barrels of oil in 1984. Wildcat activity peaked at 267 in 1981 and there were 64 discoveries in 1982. The higher success ratios in this cycle resulted from a number of factors including improved seismic techniques, Red River exploration which provided multiple uphole possibilities and higher prices which allowed smaller reserves to be economic. The average depth increased through 1982 reflecting this Red River emphasis, but as prices decreased deeper exploration slowed.

Comparison of exploration success during the two cycles shows nominal success ratios of 20.3 per cent during the second cycle compared to the 8.8 per cent during the first cycle. However, if the quality of the discoveries based on estimated ultimate recoveries is considered, and the classification of the American Association of Petroleum Geologists is used (Carsey and Roberts, 1963), then it is not so favorable (Fig. 5, Table 1). Eighty-one of the 151 wildcat producers during the first cycle and 84 of the 358 wildcat producers during the second cycle found at least 1 million barrels of oil. Three of the 5 Class A pools, 4 of the 5 Class B and 21 of the 34 Class C pools were found in the first cycle and much of that success was during the first decade of exploration.

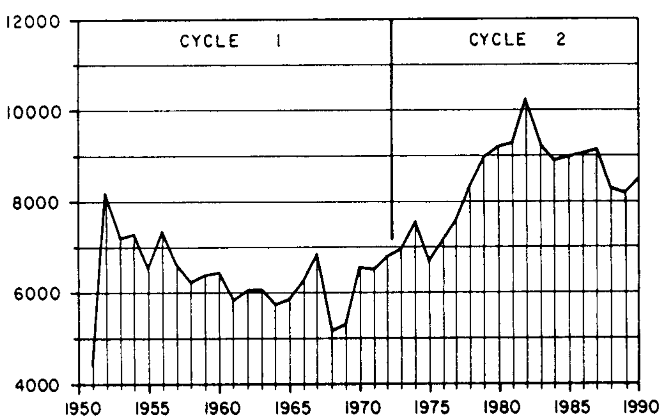

Figure 4-Average depth of all wells drilled in North Dakota each year.

	A	B	C	D	
1951 - 59	3	4	15	28	50
1960 - 73			6	25	31
CYCLE 1	3	4	21	53	81
	A	B	C	D	
1974 - 79	2	1	6	22	31
1980 - 82			5	29	34
1983 - 85			2	15	17
1986 - 88				2	2
CYCLE 2	2	1	13	68	84

Figure 5-Wildcat discoveries grouped by size of expected ultimate recoveries. Class A - greater than 50; Class B - 25 to 50; Class C - 10 to 25; Class D - 1 to 10 million barrels.

STRATIGRAPHIC AND GEOGRAPHIC REVIEW

Stratigraphically, most of the Paleozoic carbonate and sandstone units have produced oil in North Dakota (Fig. 6), but 99 per cent has been produced from 9 horizons (Fig. 7). The Mississippian Madison reservoirs have been primary targets through both cycles and account for nearly 2/3 of the cumulative production. Most of the Madison production has been from the Frobisher-Alida Interval. A stratigraphic comparison of the two cycles (Figs. 8 and 9) shows the increased emphasis on older Paleozoic strata during the second cycle although most of these successes have been smaller accumulations.

Geographically, six of the ten largest pools are located along the Nesson Anticline (Fig. 10). Five of these were found in the first cycle of exploration. Eight of the ten largest pools have used water injection to enhance cumulative production (Table 1).

Production from the Spearfish Formation has been limited to an area in central Bottineau County (Fig. 11). In that area, there is sandstone present at the base of the Spearfish redbeds and in some areas this sandstone lies unconformably on the Madison Formation at depths of around 3,000 feet. Since many of the wells are perforated in both the Spearfish and Madison Formations, some of these pools, and both of the largest pools, are listed as Spearfish-Madison pools (Fig. 7). The Newburg pool was developed between

TABLE 1-List of pools ranked by current and expected ultimate recovery, *indicates unitized for secondary recovery operations. Updated from the time of the Holland symposium to reflect subsequent data.

Pool	Discovery	1-1-92 Cum. Prod.	1991 Production
Class A			
Tioga-Madison	1952	57.439*	.244
Little Knife-Madison	1977	57.181	1.982
Beaver Lodge-Devonian	1951	53.567*	1.224
Beaver Lodge-Madison	1952	51.155*	.105
Big Stick-Madison	1979	42.021*	.886
Class B			
Blue Buttes-Madison	1955	31.997*	.380
Newburg-Spearfish-Madison	1955	28.209*	.499
Charlson-Madison	1952	24.661*	.307
Dickinson-Tyler	1958	24.527*	.374
Charlson-Interlake	1977	14.842	.460
Class C			
Glenburn-Madison	1958	19.649	.357
Sherwood-Madison	1958	17.237	.397
Fryburg-Tyler	1954	16.534*	.671
North Tioga-Madison	1957	16.284*	.143
Antelope-Madison	1956	15.966*	.099
Cedar Creek-Red River	1960	15.531*	.304
Rival-Madison	1957	14.412*	.087
Hawkeye-Madison	1955	13.527*	.062
Rough Rider-Madison	1959	13.345	.472
Mondak-Madison	1976	13.343	.218
Redwing Creek-Madison	1972	12.205*	.437
Wiley-Madison	1958	12.047	.222
Capa-Madison	1953	11.730*	.044
Fryburg-Madison	1953	11.665	.281
Antelope-Bakken	1953	11.547	.107
S. Westhope-Spearfish-Mad.	1956	11.382	.194
Fryburg-Madison	1953	11.665*	.281
Tree Top-Madison	1979	9.930	.276
North Elkhorn Ranch-Madison	1981	9.277*	.456
Clear Creek-Madison	1958	8.932*	.069
Elkhorn Ranch-Madison	1974	8.697	.348
Beaver Lodge-Silurian	1951	8.426	.061
Blue Buttes-Interlake	1980	8.004	.424
TR-Madison	1978	7.438	.347
Medicine Pole Hills-RR	1967	6.855*	.364
Indian Hills-Madison	1982	6.845	.392
Zenith-Tyler	1968	5.784*	.219
Charlson-Duperow	1960	5.524	.107
Lone Butte-Madison	1981	5.413	.325
Whiskey Joe-Madison	1979	4.943	.337
Elkhorn Ranch-Bakken	1961	4.515	.682
Knutson-Madison	1983	3.969	.279
Glass Bluff-Madison	1982	3.776	.217
East Fork-Madison	1984	3.142	.267

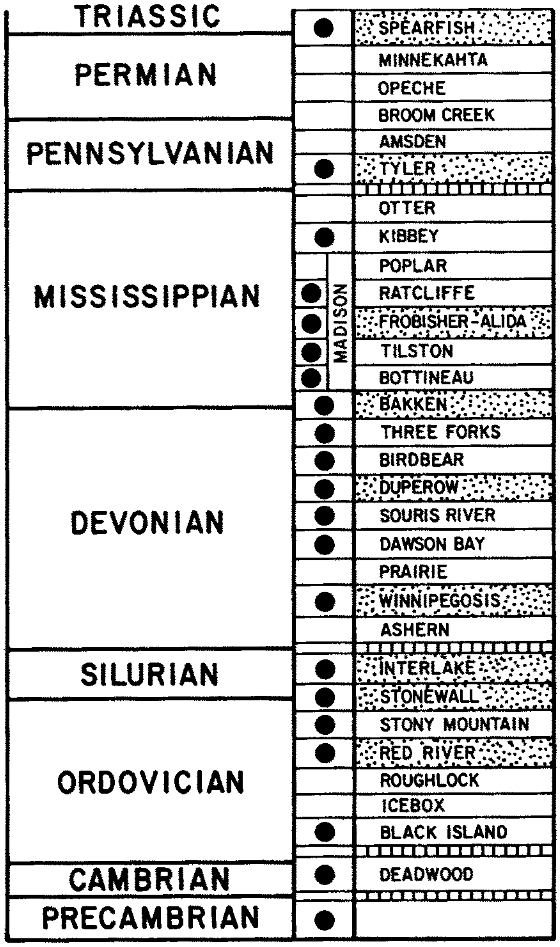

Figure 6-A portion of the North Dakota stratigraphic column. Dots indicate units which have produced oil from at least one well.

FM.	MBO	%
SP/ MAD.	42.8	4.0
TYLER	63.7	5.9
MADISON	680.6	63.4
BAKKEN	28.2	2.6
DUPEROW	105.8	9.8
WINNIPEGOSIS	5.1	.5
INTERLAKE	46.4	4.3
STONEWALL	5.9	.6
RED RIVER	88.8	8.2

Figure 7-North Dakota cumulative oil production through 1988 by producing horizon in millions of barrels.

1957 and 1959, was unitized in 1967 and has been a very successful secondary recovery unit (Appendix) accounting for about 2/3 of the production credited to these reservoirs.

The Pennsylvanian Tyler Formation is present throughout most of southwestern North Dakota. Production has been from channel sandstones at the Rocky Ridge Field and from offshore bar sandstones from the Medora to Dickinson area (Fig. 12). These reservoirs are present at depths of around 7500 to 7800 feet. The largest of these pools, the Dickinson pool, was fully developed by 1970, was unitized in 1973 and has also been a very successful secondary recovery unit (Appendix).

The Bakken Formation is present in a large portion of western North Dakota (Fig. 13). It consists of three members, an upper black shale, a middle calcareous siltstone and silty carbonate, and a lower black shale. The initial production and the largest pool has been referred to as the Antelope-Sanish pool because in the Antelope area there is a sandstone below the lower black shale which has been referred to as the "Sanish Sand". Subsequent development of that pool found perforations in the underlying Three Forks Formation as well as each of the members of the Bakken Formation. The Antelope Field was discovered in 1953 and is the only significant pool along the Nesson Anticline from these strata.

In the late 1970's, exploration began near the southwest limit of the Bakken Formation (Fig. 15). These reservoirs were marked by high pressures, little or no water and very gradual decline rates. This area has become the focus for evaluation of horizontal drilling techniques since the 1987 completion of a horizontal wellbore in the Elkhorn Ranch Field. That well was completed in September of 1987 and through 1988 produced 109,680 barrels of oil and 258 barrels of water. The upper shale has been the major

CYCLE 1

FM.	A	B	C	D	T
SP/MAD.		1	1		2
TYLER		1	2	3	6
MADISON	2	2	12	36	52
BAKKEN			2		2
DUPEROW	1		1	6	8
DAWSON BAY					
WINNIPEGOSIS					
INTERLAKE			1	2	3
STONEWALL					
RED RIVER			2	6	8
TOTAL	3	4	21	53	81

Figure 8-Cycle 1, Class A to D discoveries arranged stratigraphically.

CYCLE 2

FM.	A	B	C	D	T
SP/MAD.					
TYLER				2	2
MADISON	2		12	23	37
BAKKEN				6	6
DUPEROW				15	15
DAWSON BAY				1	1
WINNIPEGOSIS				1	1
INTERLAKE		1	1	3	5
STONEWALL				2	2
RED RIVER				15	15
TOTAL	2	1	13	68	84

Figure 9-Cycle 2, Class A to D discoveries arranged stratigraphically.

target. It is about 10 feet thick at the limit of the lower black shale (Fig. 13) and thins to a depositional limit.

Minor quantities of oil have been recovered from sandstones of the Black Island and Deadwood Formations. As a result, clastics account for 8 to 12 per cent of the production depending upon how much of the Spearfish-Madison production is assigned to sandstone of the Spearfish Formation.

Development of Madison reservoirs began along the Nesson Anticline where these reservoirs are at depths ranging from about 7800 feet at the north end to 9500 feet at the south end (Fig. 14). Initial development in Bottineau County was from stratigraphic traps at the unconformity with overlying Mesozoic strata. Subsequent exploration has been largely combination structural-stratigraphic accumulations where facies changes from porous carbonates to updip evaporites or dense carbonates are associated with slight flexures in the area from Bottineau to Burke County. These reservoirs are at depths of 3,000 feet in Bottineau County and progressively deeper westward to 6,000 to 7,000 feet in Burke County. The major Madison development in the south--western area was during the second cycle high lighted by discovery of the Class A Little Knife and Big Stick Fields (Fig. 10). Reservoirs in this area are at depths of around 9,000 feet at Little Knife. These also appear to be combination structural-stratigraphic accumulations.

Secondary recovery operations in Madison reservoirs have produced mixed results. Generally units in Burke County and the northern portion of the Nesson Anticline did not perform as projected and secondary recovery operations were discontinued. Units in the southern portion of the Nesson Anticline and other areas have shown varying degrees of success. A combination of water and nitrogen injection was used in the Clear Creek Unit to exceed preliminary projections.

Duperow development is marked by numerous small accumulations in the central basin area which were found primarily during the second cycle (Fig. 15). These reservoirs are present at depths ranging from around 8,500 feet in Divide County to 11,500 feet in Dunn County. Rapid porosity changes indicate that these are usually combination structural-stratigraphic traps.

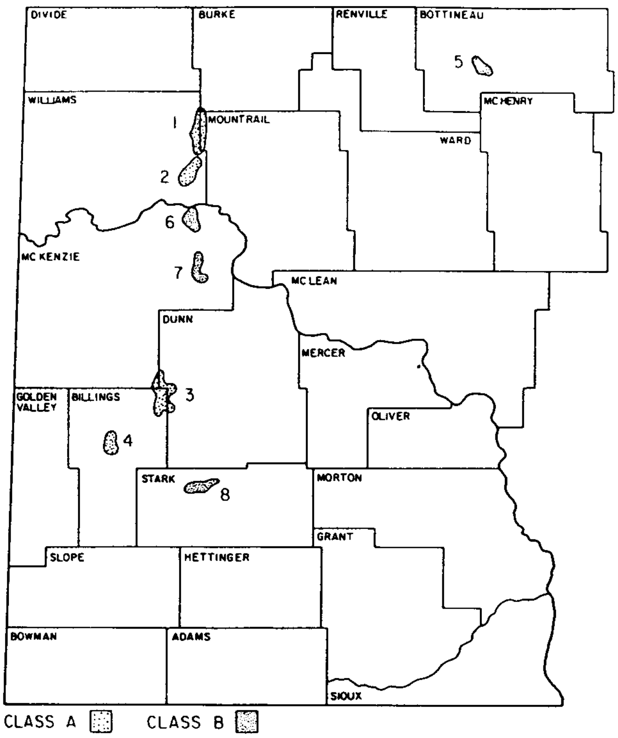

Figure 10-Class A pools are: 1) Tioga-Madison; 2) Beaver Lodge-Madison and Duperow; 3) Little Knife-Madison and 4) Big Stick-Madison. Class B pools are: 5) Newburg-Spearfish, Madison; 6) Charlson-Madison and Dickinson-Tyler.

The Beaver Lodge Field accounts for more than half of the Duperow production. This field was developed on a 320 acre spacing pattern from 1957 through 1959. It was unitized in 1962 and in 1973 an infill drilling program which added injectors in the central portion of the field began. A primary recovery of about 24.1 million barrels was estimated. Current production (December 1988) of about 3,400 barrels per day with cumulative recovery of nearly 50 million barrels makes it likely that the projected 61.5 million barrels for ultimate recovery will be attained (Appendix).

Production credited to the Interlake Formation is primarily from the upper portion of the upper member in reservoirs present at depths of 11,000 to 11,500 feet along the Nesson Anticline. Early development was in the northern part of the anticline while the southern part has seen most of its development in the second cycle. Magathan (1987) asserted that these are fresh water carbonates and suggested that Interlake strata contain sufficient organic matter to serve as source beds for

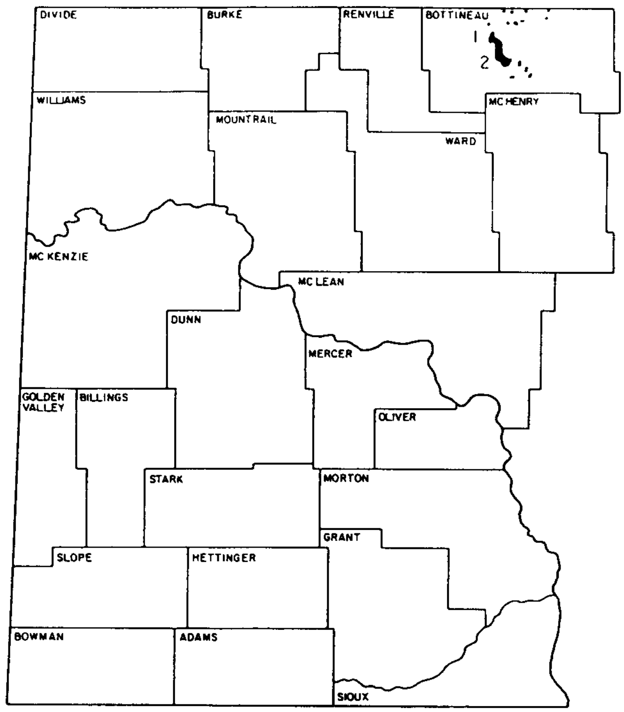

Figure 11-Locations of Spearfish Formation production. Major pools are: 1) South Westhope and 2) Newburg.

these reservoirs. She referred to argillaceous strata which have generally been placed at the base of the upper member of the Interlake Formation as the Grondale Formation. She placed the Grondale Formation in her Middle Interlake Subgroup while noting that the top of the Cedar Lake Formation marks the end of the normal marine deposition of Silurian strata. These argillaceous strata are therefore retained in the upper Interlake isopach and the area where they exceed 20 feet in thickness is shown (Fig. 16).

There is Red River production throughout the western tier of counties (Fig. 17). The first significant production and the largest Red River field, the Cedar Creek Field, extended production from these strata in Montana into North Dakota in 1960. Most of the smaller fields on the east flank of the Cedar Creek Anticline in Bowman County were found in the late 1960's and early 1970's. Reservoirs in this area are found at depths of around 8,000 feet. Most of the development west of the Nesson Anticline was during the second cycle and was concentrated during the time when oil prices exceeded $27 per barrel. Depths there range to as much as 14,000 feet.

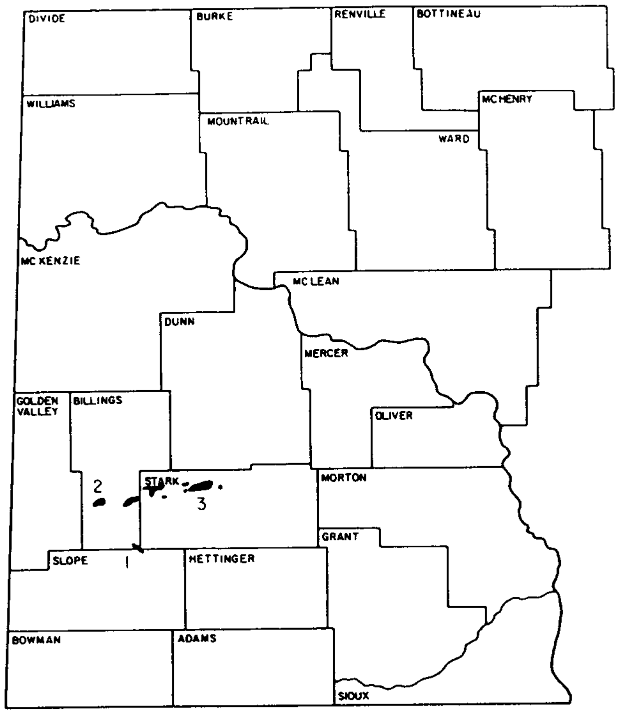

Figure 12-Locations of Tyler Formation production. Pools identified are: 1) Rocky Ridge, 2) Medora and 3) Dickinson.

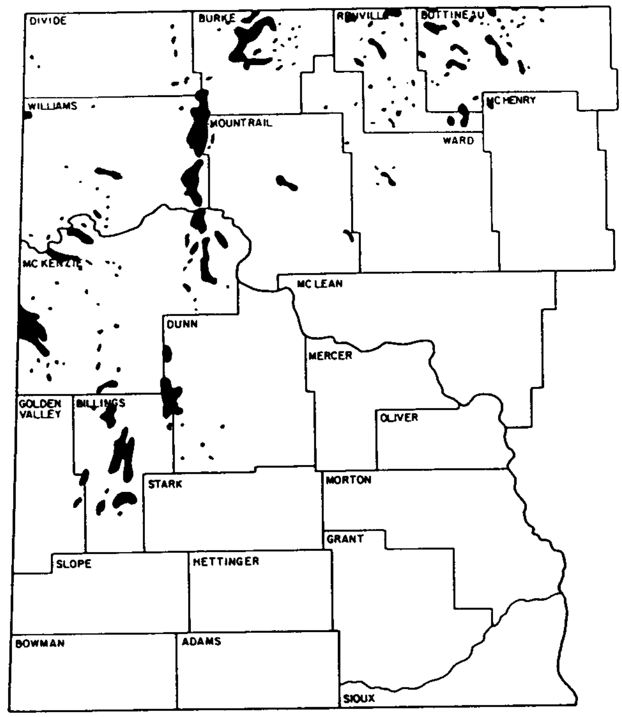

Figure 14-Locations of Madison production.

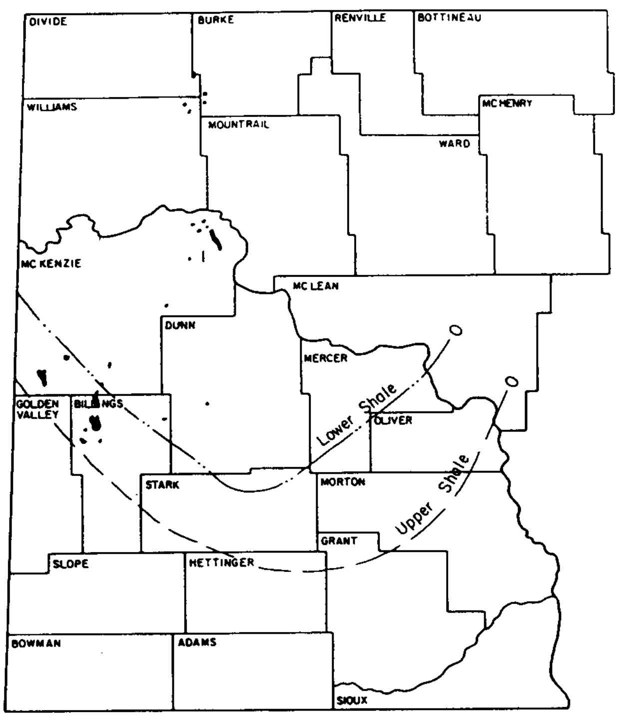

Figure 13-Locations of Bakken production and depositional limits of the upper and lower black shale members, 1) Antelope Field.

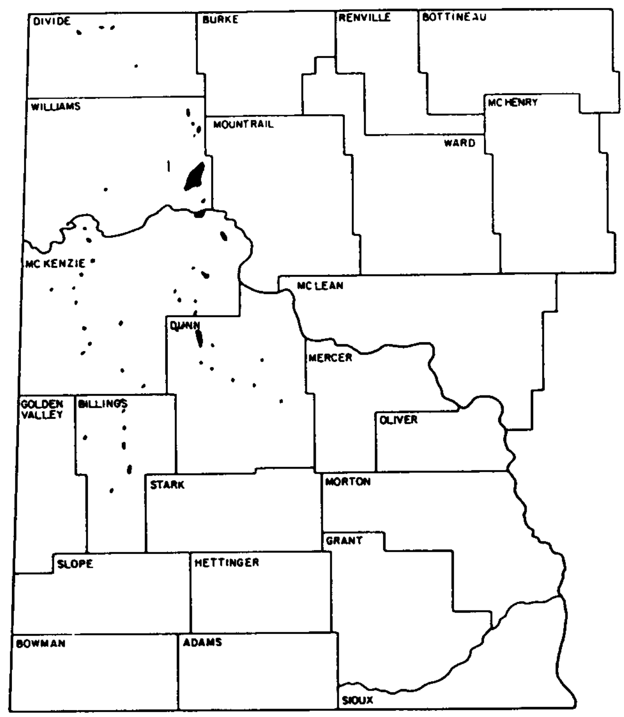

Figure 15-Locations of Duperow production, 1) Beaver Lodge Field.

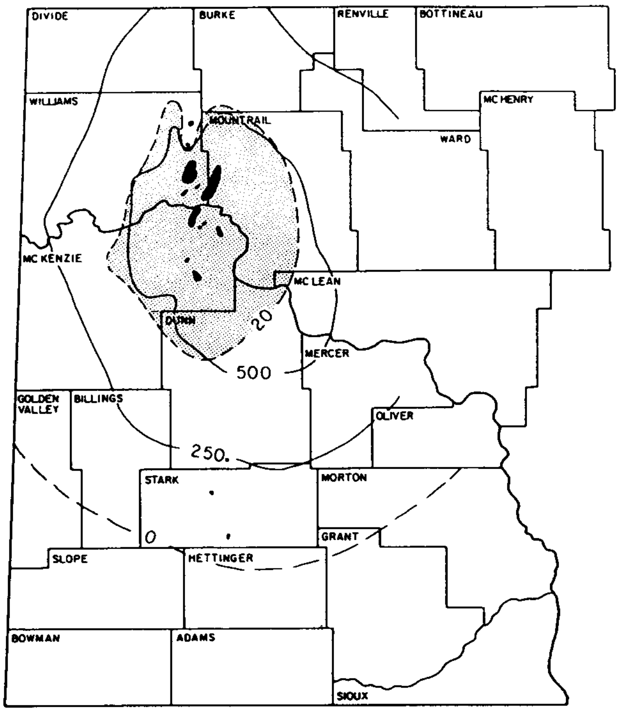

Figure 16-Locations of Interlake production. Isopach of upper member of the Interlake Formation and area where argillaceous "Grondale" beds exceed 20 feet.

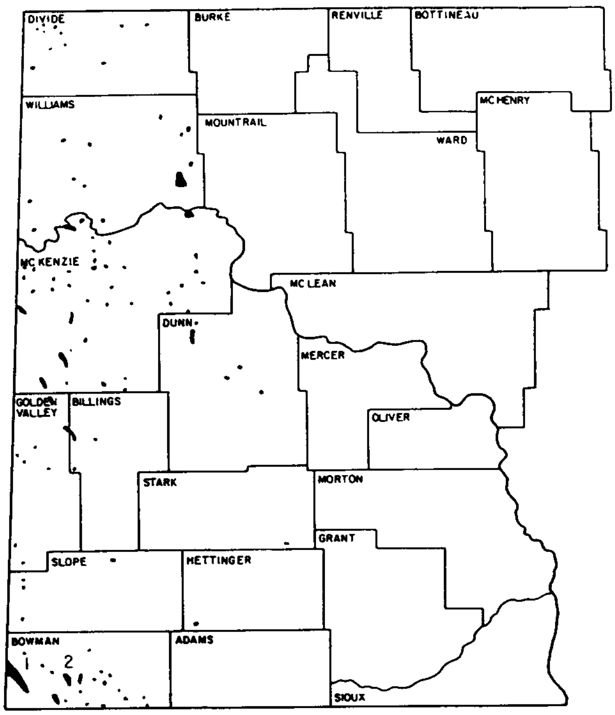

Figure 17-Locations of Red River production.

The Cedar Creek Field is the largest of the Red River pools and has been a relatively successful water injection secondary recovery unit. The Medicine Pole Hills Field was unitized in 1985 for a fireflood project. The price decline delayed injection until October 1987. A productive response began in August 1988, so it appears that this will be a successful project.

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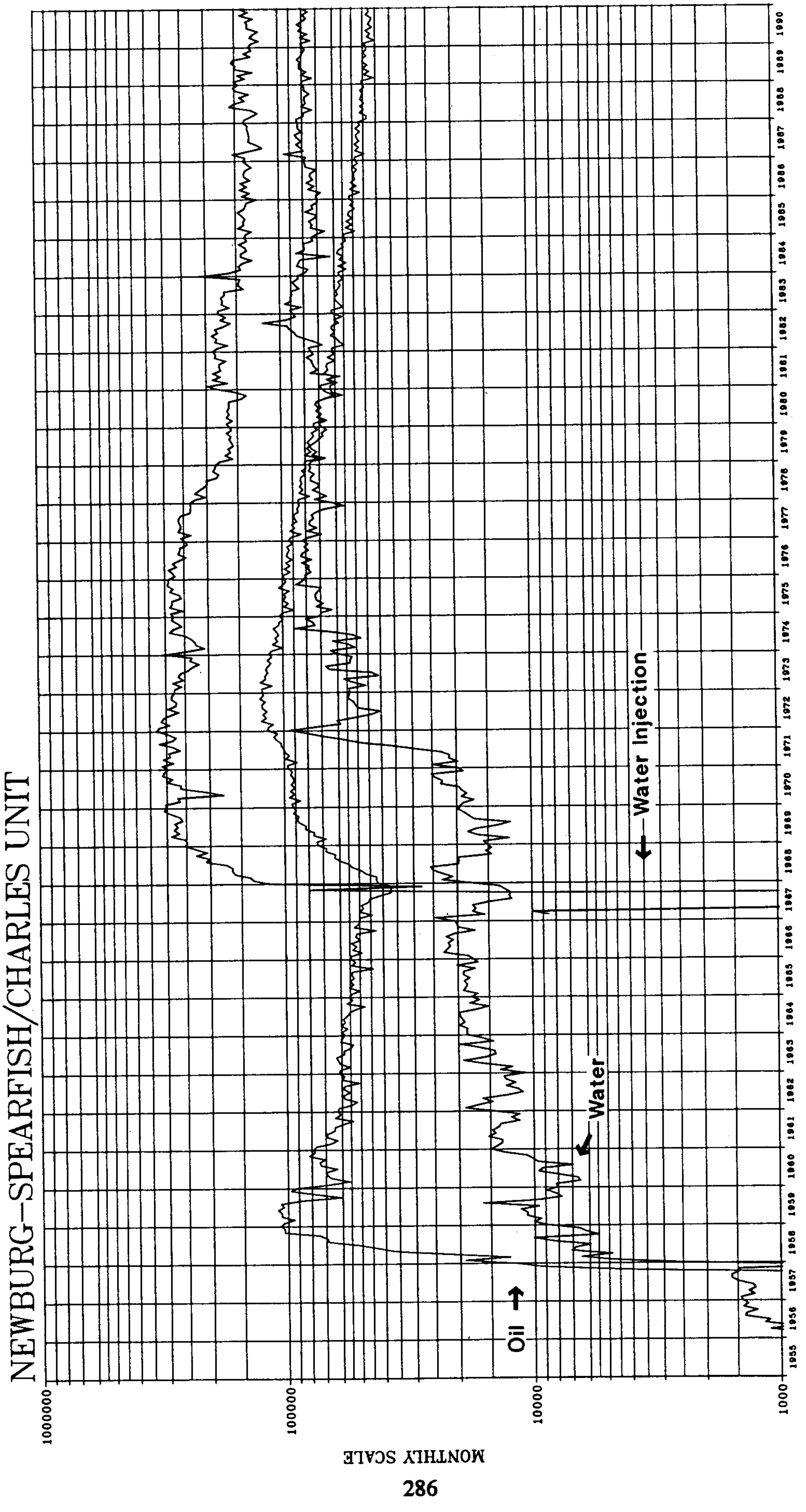
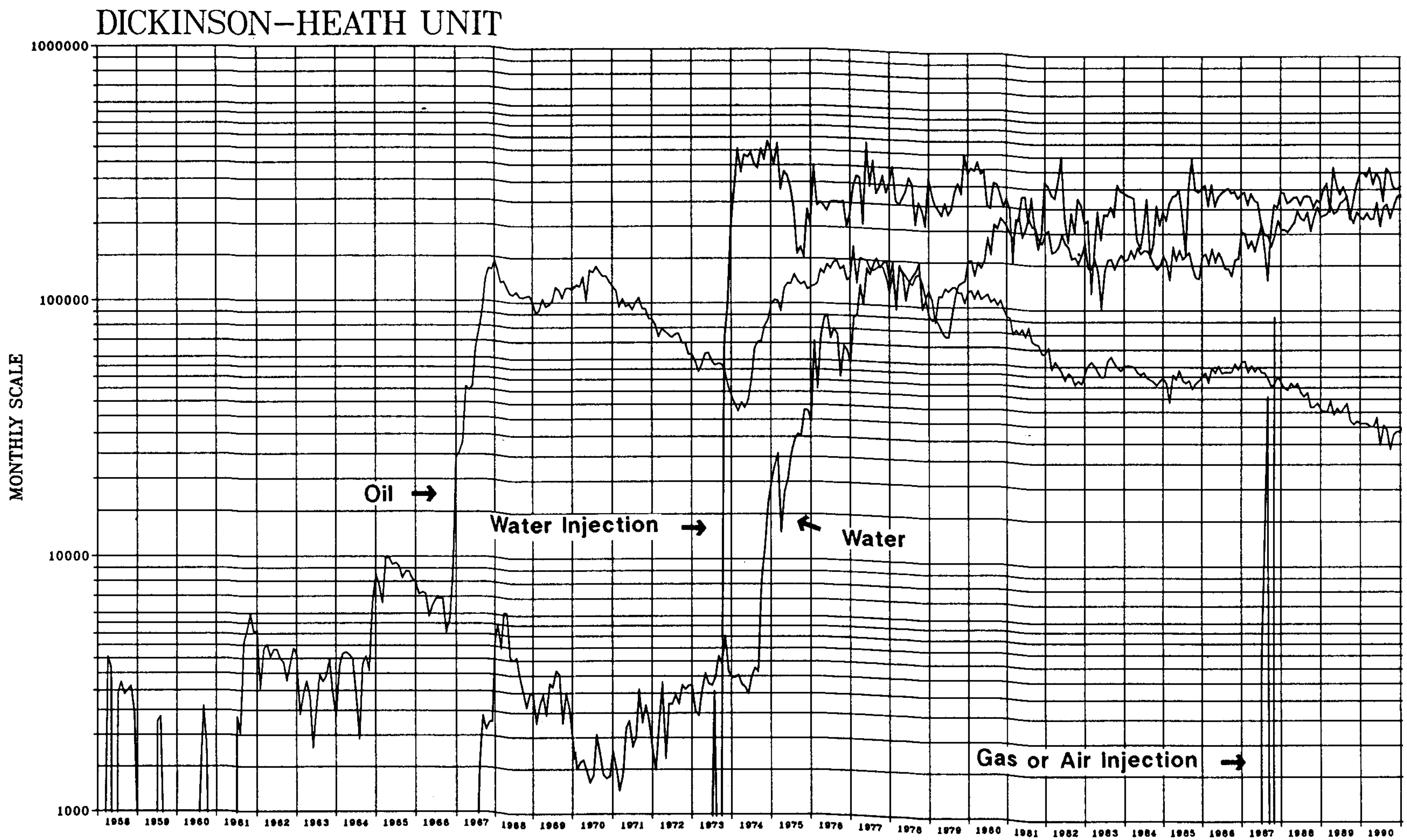
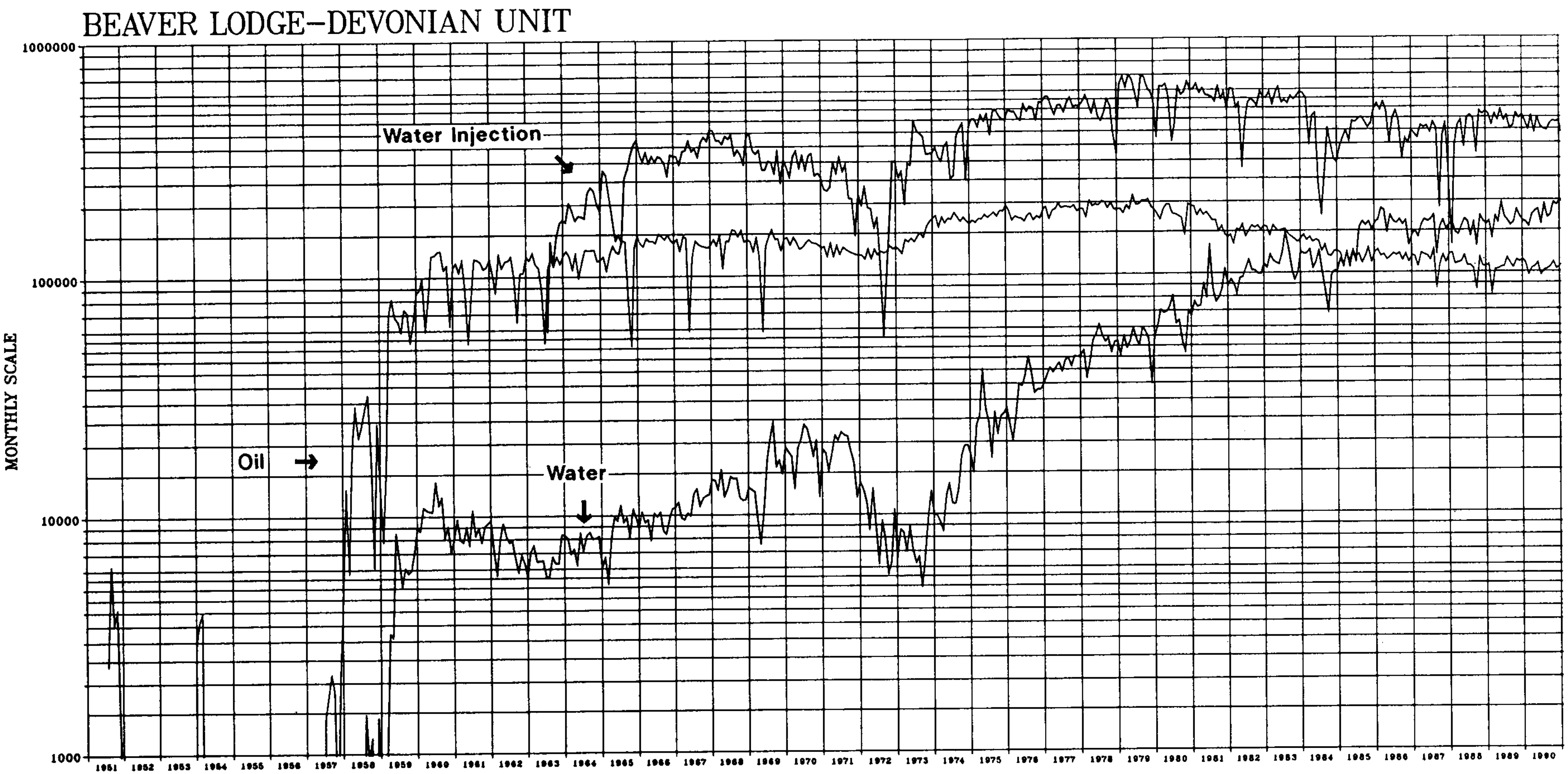


Decline curve for the Newburg-Spearfish, Charles unit.



Decline curve for the Dickinson-Heath (Tyler) unit. Originally these strata were thought to be Mississippian-Heath.



Decline curve for the Beaver Lodge - Devonian pool.

STRATIGRAPHIC CONTROLS ON GOLD MINERALIZATION CARLIN TREND, NEVADA

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ABSTRACT

The Carlin Trend is a 60 km long northwest alignment of epithermal, sediment-hosted, disseminated gold deposits. Since 1965, more than 250 tonnes (8 million troy ounces) of gold have been produced from this mineral district; current identified geologic resources in 20 deposits exceed 1,600 tonnes (52 million ounces).

Gold deposits occur within rocks ranging in age from Ordovician through Mississippian deposited across the Lower Paleozoic continental margin. Lithologically dissimilar units were juxtaposed along the regionally significant, Mississippian-age, Roberts Mountains Thrust Fault. These rocks constitute three distinct stratigraphic packages: autochthonous miogeoclinal carbonates, allochthonous eugeoclinal chert, shale, siltstone and sandstone, and an overlying coarse clastic overlap assemblage deposited on both upper and lower plate packages at the leading edge of the thrust. Gold deposits occur within all three rock packages.

Gold mineralization was both structurally and stratigraphically controlled, with economic concentrations localized at structural and stratigraphic settings similar to those which characterize petroleum traps; effective permeability was apparently of critical importance in channeling and focusing the flow of gold-mineralizing fluids. Along structural breaks, gold is selectively concentrated within favorable stratigraphic units. These include silty dolomite of the Silurian-Devonian Roberts Mountains Formation (Carlin deposit), limestone depositional breccia of the Devonian Popovich Formation (Post deposit) and siltstone of the Mississippian Webb Formation (Rain deposit).

Host stratigraphy controls the character of the ore, including average grade, grade variability, physical properties and metallurgical response. For example, the Gold Quarry deposit, with reserves exceeding 300 tonnes (10 million ounces), consists of two distinct zones. The Main zone, hosted within highly fractured siliciclastic rocks, is a low grade, highly variable, metallurgically amendable orebody. The Deep West zone, a stratabound concentration at the underlying limestone-clastic contact, has a relatively uniform grade approximately twice that of the Main ore zone but is metallurgically refractory.

Detailed stratigraphic mapping and logging plays a critical role in exploration and geologic mine planning for Carlin-type gold deposits.

INTRODUCTION

The Carlin Trend is a 60 km long northwest alignment of epithermal, sediment-hosted, disseminated gold deposits. Since 1965, more than 250 tonnes (8 million troy ounces) of gold have been produced. During 1988, more than 32 tonnes (1,050,000 ounces) were produced from six active mines; 1989 production is forecast to exceed 50 tonnes (1,630,000 ounces) (Spolede, 1989, and Anonymous, 1989). Current identified geologic resources in 20 deposits exceed 1,600 tonnes (52 million ounces). The Carlin Trend

Proceedings of the F.D. Holland, Jr., geological symposium, 1992, J.M. Erickson and J.W. Hoganson, eds., North Dakota Geological Survey Miscellaneous Series No. 76.

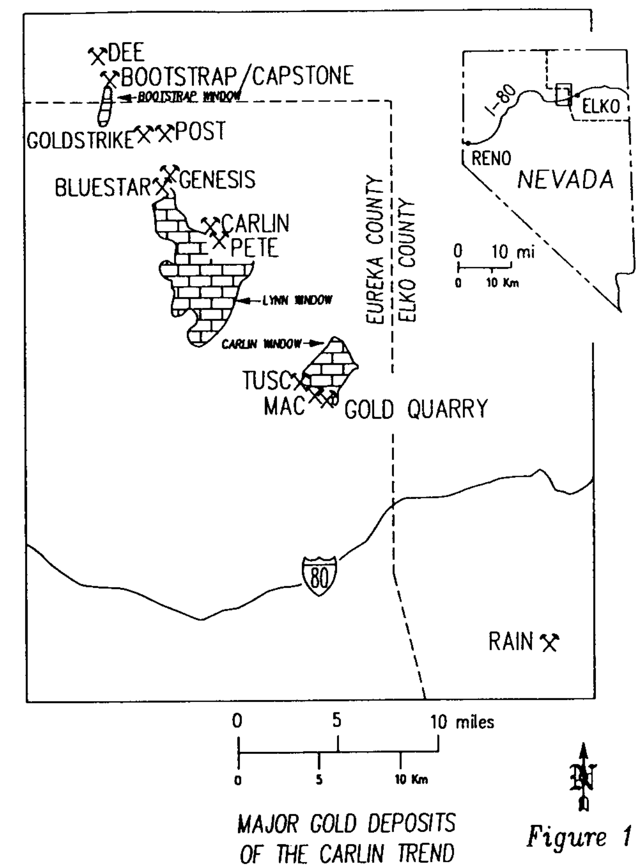

Figure 1-Major gold deposits of the Carlin Trend, Nevada. Patterned areas are windows exposing eastern assemblage Paleozoic carbonate rocks through overlying western assemblage Paleozoic siliceous rocks (after Rota and Hausen, 1989).

is the premier gold district in the United States and is currently the center of a major gold rush.

The Carlin deposit, located near the center of the Trend (Figure 1), has become the type deposit for the class of sediment-hosted, disseminated gold deposits. Discovered in 1960 by Newmont Mining Company geologists, it was the first significant gold deposit in the world to be exploited by bulk mining methods. Since that time, more than 30 separate centers of gold mineralization have been identified along the Carlin Trend. While all of these deposits possess similarities, there are significant differences between the individual deposits. Six subdistricts are distinguished, based upon geographic, structural, lithologic, alteration, geochemical, and mineralization characteristics (Christensen and others, 1987).

REGIONAL GEOLOGIC SETTING

The Carlin Trend is located centrally within the Great Basin geologic province of the western United States. Host rocks for the deposits include sedimentary units ranging in age from Ordovician through Mississippian, as well as a Jurassic-Cretaceous granodiorite stock.

During the Early Paleozoic, the area that is now eastern Nevada lay along the passive western margin of the North American continent. A westward thickening and deepening wedge of sedimentary units was deposited across the shelf and slope. Rock units deposited vary from eastern miogeoclinal continental shelf carbonates to western fine-grained clastic and cherty units (Stewart, 1980).

Tectonic activity associated with the Late Devonian to Early Mississippian Antler Orogeny resulted in the eugeoclinal western assemblage siliceous rocks being thrust eastward over time-equivalent transitional and miogeoclinal eastern assemblage carbonate units along the Roberts Mountains thrust fault system. The leading edge of the allochthonous Roberts Mountains thrust plate formed the emergent Antler highland, from which siliceous clastic sediment, eroded from the overriding plate, was shed eastward into the adjacent foreland basin. Local terminology refers to the three major units of the geologic architecture as the eastern assemblage, the western assemblage, and overlap assemblage for the autochthonous shelf carbonates, the allochthonous siliceous lithologies, and the coarser clastic flysch deposits, respectively.

In late Mesozoic time, plutonic activity was accompanied by doming and folding of the sedimentary units along the north-northwest trending axis of the Tuscarora Anticline. Several windows, eroded through the overthrust western assemblage units along the broken trend of the anticline, expose eastern assemblage rocks of the lower plate. A Jurassic-Cretaceous granodiorite stock is exposed in the vicinity of the Post Mine.

Tertiary stocks and dikes of intermediate composition are common, but generally poorly exposed throughout the district. Cenozoic extensional faulting began about 17 Ma, creating the present Basin and Range topography characteristic of the area.

The age of gold mineralization is poorly constrained. A maximum age of approximately 145 Ma is indicated by the mineralized granodiorite of the Goldstrike intrusive. A minimum age of approximately 5 Ma is indicated by the presence of gold mineralized clasts in Pliocene Carlin Formation alluvial conglomerates overlying the Gold Quarry deposit. A middle to late Tertiary age of gold mineralization is most likely.

CARLIN-TYPE GOLD DEPOSITS

Common features of sediment-hosted gold deposits have been summarized by Romberger (1986), and Cunningham (1988). Sediment-hosted gold deposits occur throughout the western United States but are most highly concentrated in the Basin and Range Province, many occurring along regional trends characterized by coincident alignments of igneous rocks and geophysical anomalies (Percival and others, 1988).

High- and low-angle faults are important features in all deposits. Fracturing and brecciation associated with structural intersections facilitated optimum hydrothermal fluid introduction into and interaction with receptive host rocks.

Hydrothermal alteration varies from negligible to intense between deposits. Typically this includes decalcification, silicification, argillization, and baritization. Gold mineralized and altered rocks are characteristically geochemically enriched with Ag, As, Sb, Hg, and Tl.

Sedimentary host rocks can be nearly any lithology if the permeability was favorable for the introduc-

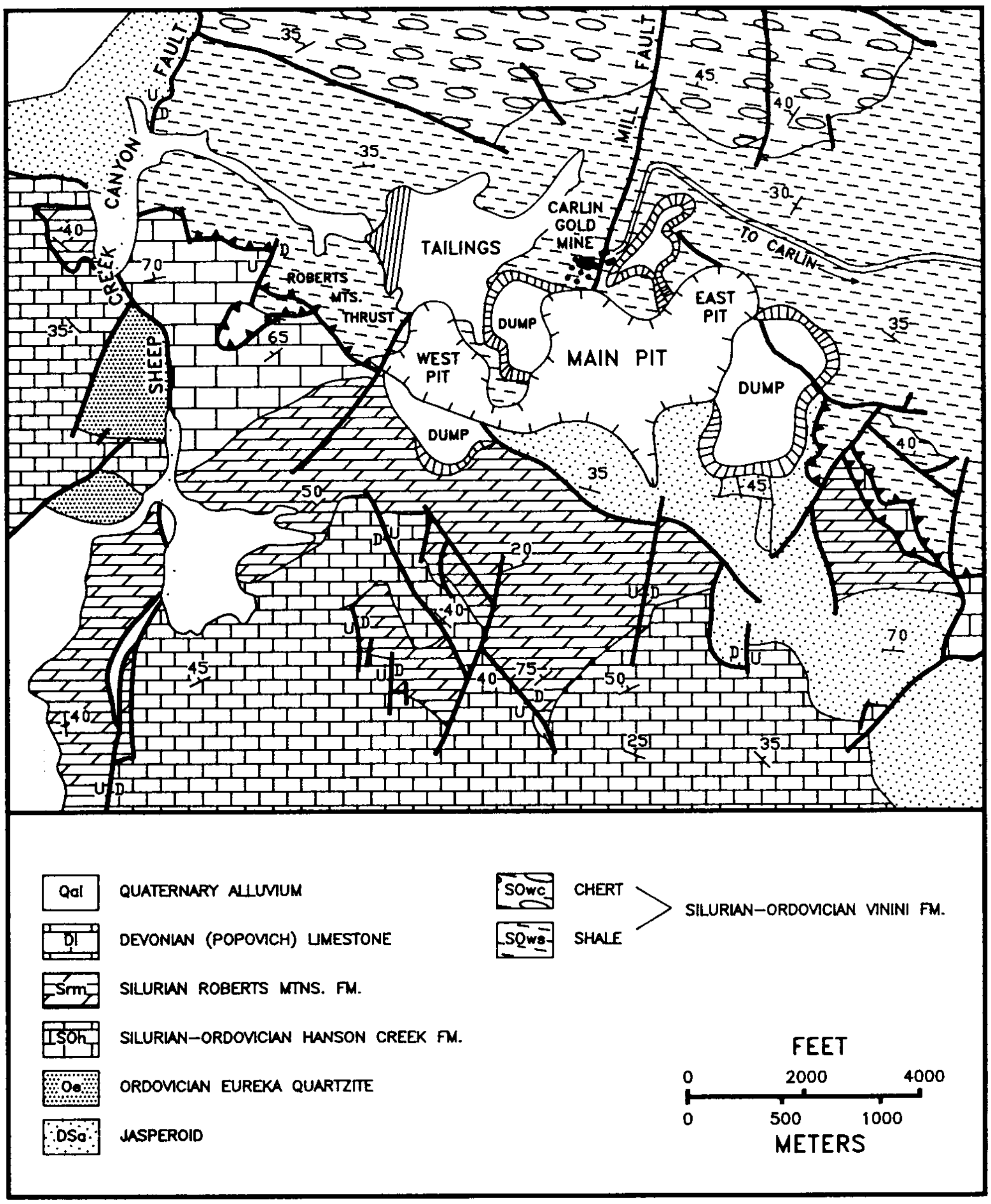

Figure 2-Geologic map of the Carlin gold deposits (after Radtke, 1985, and Rota and Adkins, 1984).

tion of hydrothermal fluids. Gold mineralization along the Carlin Trend is hosted within silty dolomite of the Roberts Mountains Formation (Carlin), massive fossiliferous limestone (Post and Bootstrap), interbedded chert and shale (Gold Quarry), and coarser clastic lithologies of the Mississippian Webb Formation (Rain).

Extensive exploration and mining experience has demonstrated that host stratigraphy, however variable, plays a critical role in gold ore localization and in the physical and chemical character of the ore. Three examples from the Carlin Trend provide useful examples.

CARLIN DEPOSIT

The Carlin deposit, centrally located along the Carlin Trend, lies near the northeastern margin of the Lynn Window, in which Silurian and Devonian carbonates of the lower plate are exposed through overlying upper plate Ordovician cherts and siliceous shales (Figures 1 & 2). Mining began at Carlin in 1965 and continued through 1987. The gold ore at Carlin occurred in three principal zones aligned some 2,100 m (7,000 feet) in an east-west direction, roughly parallel both with bedding and with the trend of the Roberts Mountains thrust. During mining, the structural control on gold mineralization was evident from thickened ore zones in the vicinity of north-trending cross structures. Although gold deposition was controlled by high-angle faults on a district scale, it was largely confined to replacement of favored permeable facies, resulting in conformable, tabular orebodies (Figure 3).

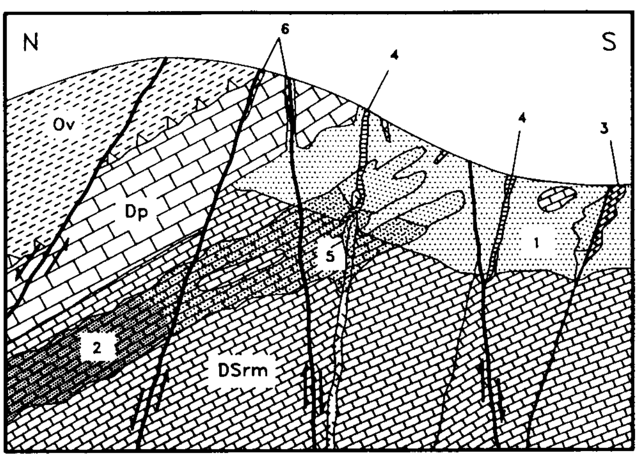

Figure 3-Generalized cross section of the Carlin gold deposit showing important geologic features. Lithologic units include Ordovician Vinini Formation (Ov), Silurian-Devonian Roberts Mountains Formation (DSrm), and the Devonian Popovich Limestone (Dp). 1, zone of leaching and alteration; 2, main ore zone including lower unoxidized ore and upper oxidized ore; 3, jasperoid bodies; 4, barite veins; 5, quartz veins; 6, calcite veins (after Radtke, 1985, and Rye, 1985).

Most of the gold ore occurs within the upper 250 m of the Middle Silurian to Late Devonian Roberts Mountains Formation, with only minor occurrences within structurally or stratigraphically adjacent units (Radtke, 1985). The Roberts Mountains Formation, originally a platy, silty dolomitic limestone, has been strongly altered in mineralized areas. Carbonate removal, along with local bleaching and iron staining, left a porous low-density rock that ranges in composition from an argillaceous to dolomitic siltstone.

The upper part of the ore zone has been oxidized; conformity of the bottom of the oxide zone with the present topographic surface suggests that the oxidation was at least in part a supergene feature. Oxide ores consist of fine-grained mixtures of quartz, illite, kaolinite and iron oxides.

Unoxidized deeper ores are characterized by abundant sulfide minerals, much carbonaceous material, and minor barite with residual calcite, dolomite, and illite. The carbonaceous material at Carlin has been characterized as pyrobitumen, the thermally altered residue of petroleum. Over 90% of the gold within the unoxidized ores is sub-microscopic (less than 0.2 microns in diameter) (Rota and Adkins, 1984).

The orebodies in the Carlin deposit were formed as multiple pulses of hydrothermal fluids which were focused upward along high-angle structures, penetrated the stucturally broken dolomitic beds of the Roberts Mountains Formation, altered the permeable lithology, and left behind a residue of gold. The ultimate geometry of the ore zones was significantly controlled by the stratigraphic distribution of permeable receptive lithologies within the Roberts Mountains Formation.

GOLD QUARRY

Gold Quarry is the largest sediment-hosted gold deposit discovered to date on the Carlin Trend. Proven reserves are estimated to be 223 million tonnes (246 million st) grading 1.5 g/t (.044 oz/ton) and containing 290 tonnes (9.3 million troy ounces) of gold (Newmont Gold Company, 1989). Mining and milling at Gold Quarry began in 1985; dump leaching began in 1986. The Gold Quarry ore body is to be developed by an open pit that will eventually be 1,830 m (6,000 ft) long, 1,220 m (4,000 ft) wide and 300 m (1,000 ft) deep (Rota and Hausen, 1989).

Gold Quarry is located along the southwestern margin of the Carlin Window, a carbonate fenster

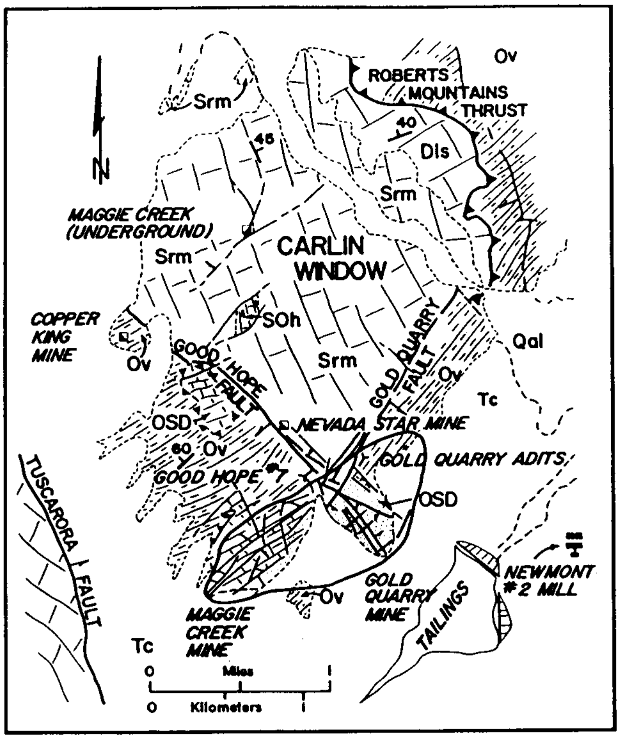

Figure 4-Geologic map of the Gold Quarry mine area. Qal = Quaternary alluvium, Tc = Tertiary Carlin Formation, Dls = Devonian limestone, OSD = Lower Paleozoic transitional limestone, Srm = Silurian Roberts Mountains Formation, SOh = Silurian Hanson Creek Formation, Ov = Ordovician Vinini Formation (after Rota and Ekburg, 1988).

roughly circular in outline and about 3 km (2 miles) in diameter (Figure 1). Steeply dipping normal faults and fractures associated with the window margins are the primary control on the distribution of mineralization. The two principal structures are the northeast-trending Gold Quarry Fault and the northwest-trending Good Hope Fault (Figure 4) (Rota, 1987).

Extensive exploration and ore-definition drilling has demonstrated that the Gold Quarry deposit consists of two distinct ore zones, termed the Main and Deep West zones. The Main zone, which is dominantly structurally-controlled, is located above the dominantly stratigraphically-controlled Deep West zone, with a gold-poor zone between (Figure 5) (Rota and Hausen, 1989).

The Main ore zone is hosted by a 450 m (1,500 ft) sequence of siltstone, shale, sandstone, silty limestone, and chert which is interpreted to be part of a transitional sequence of strata, deposited on the Paleozoic slope between the eastern and western assemblage rocks. The siliciclastic sediments are typically thin-bedded and noncompetent.

Gold mineralization in the Main ore zone is principally structurally controlled. Tabular to irregularly shaped high-grade ore shoots are directly related to northeast and northwest trending faults and fractures. The intersections of structures often host significant, though discontinuous, ore pods. The intervening rock, generally less fractured and altered, constitutes the majority of the low-grade ore in the Gold Quarry deposit.

The deposit can be best characterized as consisting of pods of high grade gold ore distributed irregularly throughout a much larger body of lower-grade material. The Main ore zone strikes generally north-south and dips 45-50 degrees to the east and is continuous over a strike length of 600 m (2,000 ft).

Alteration is so extreme in Gold Quarry that ore types are distinguished more by intensity of alteration than by primary lithology, which is often not recognizable. The distribution of alteration, like that of gold, is highly variable and complex, being related to high-angle faults and fractures. Silicification is the most pervasive style of alteration, with several episodes of silicification and brecciation evident. Silica flooding has produced rocks which range from relatively unaltered siltstone to a cherty, flint-like, rock that is more than 97% silica.

Argillization and alunitization followed the main silicification event; baritization is locally common in the Main zone, especially in the vicinity of larger faults. Supergene alteration followed the formation of the Gold Quarry orebody. Primary, unoxidized, carbonaceous ore is present at depths greater than 120 to 200 m (400-650 ft) beneath the original ground surface.

The Deep West zone is a highly silicified, stratabound, replacement ore zone that averages about 75 m (250 ft) in thickness. The zone strikes approximately N20E and dips 30-35 degrees to the southeast; the zone is recognized over a strike length of 770 m (2,500 ft). The average gold grade of this zone is approximately twice that of the Main zone. Deep ores are carbonaceous and pyritic.

The Deep West zone lies immediately above the lithologic contact between a lower limestone unit and the overlying transitional siliciclastic rocks. Both the upper and lower limits of the zone are marked by abrupt grade boundaries. Gold-barren, thin-bedded grey limestone lying beneath the Deep West has been interpreted to be Roberts Mountains Formation, although the intensity of alteration is sufficient enough to obscure the contact as sampled in drill holes.

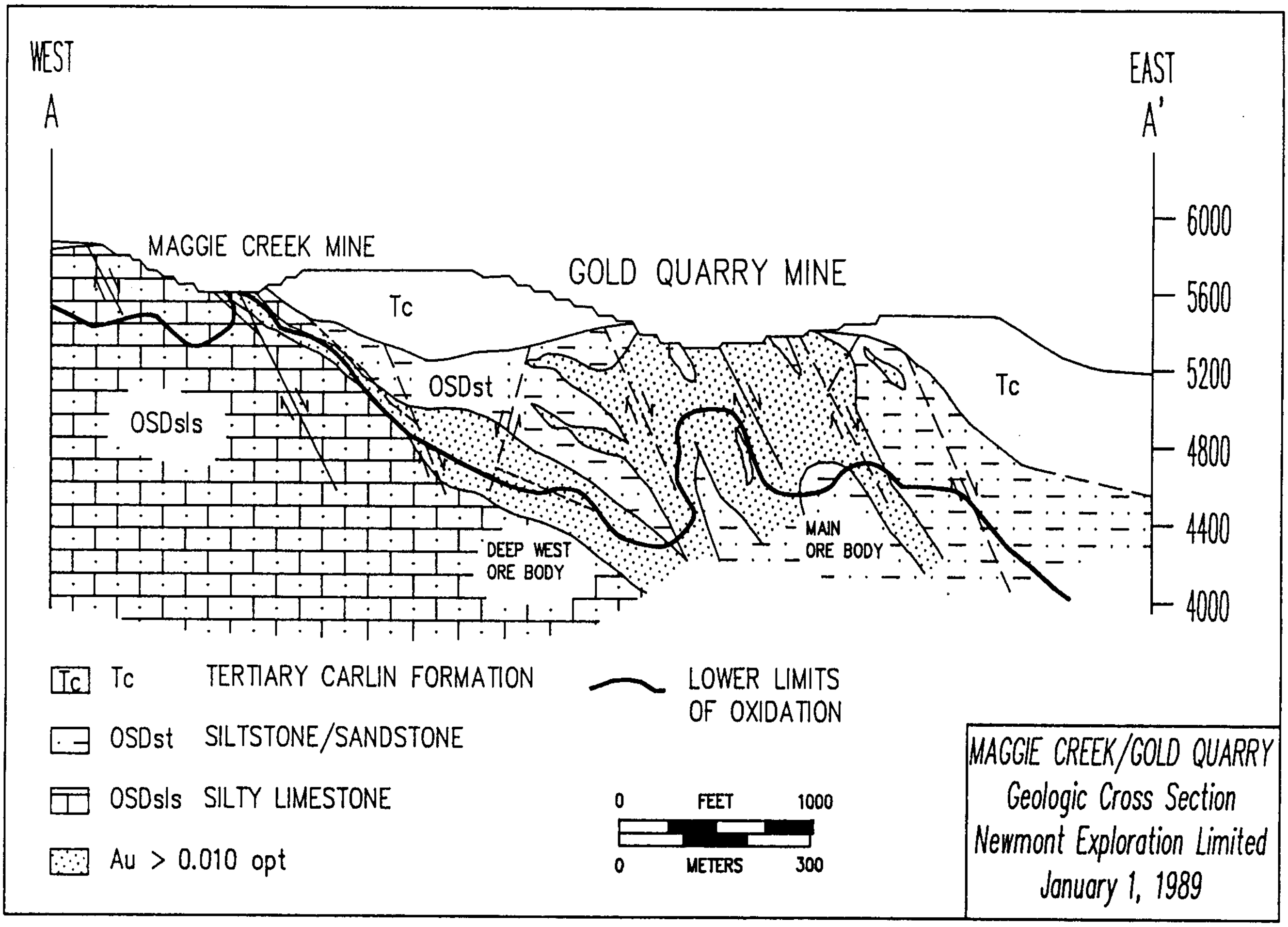

Figure 5-Generalized geologic cross section through the Maggie Creek and Gold Quarry orebodies (after Rota and Hausen, 1989).

The style of mineralization within the Deep West can be characterized as more passive, and more continuous, than the Main ore zone. In style, it is very similar to the Carlin deposit.

Mineralization at Gold Quarry is inferred to be of Tertiary age. The hydrothermal system responsible for gold mineralization was probably characterized by deeply convecting, probably meteoric, water driven by an underlying heat source. The system appears to have been aerially extensive, and long-lived. The primary down-dip structural conduit was an inferred range-front structure parallel to the Gold Quarry Fault. Fluid flow from the feeder structure was focused through the permeable lithologies at the carbonate-clastic contact, altering and mineralizing the host to form the Deep West zone. Rising along structures in the overlying siliceous rocks, the fluids reached a level where boiling resulted in the alteration, brecciation, and gold mineralization of the Main zone.

The differing geologic characteristics of the two zones result in markedly different physical and chemical properties, which significantly affect the exploitation of the deposit. Geologic information is utilized daily to segregate different metallurgical ore types, to distinguish hard and soft milling ores for blending, and for grade control.

RAIN DEPOSIT

The Rain deposit is the southernmost of the producing deposits along the Carlin Trend, located 14 km (8 miles) south of Carlin, Nevada, near the crest of the Carlin-Pinon Range (Figure 1). The deposit was discovered in 1979; production began in 1988 (Thoreson, 1987; and Knutsen and West, 1984).

The Rain orebody is located near the base of the Mississippian Webb Formation where it unconformably overlies the Devonian Devils Gate Limestone. The

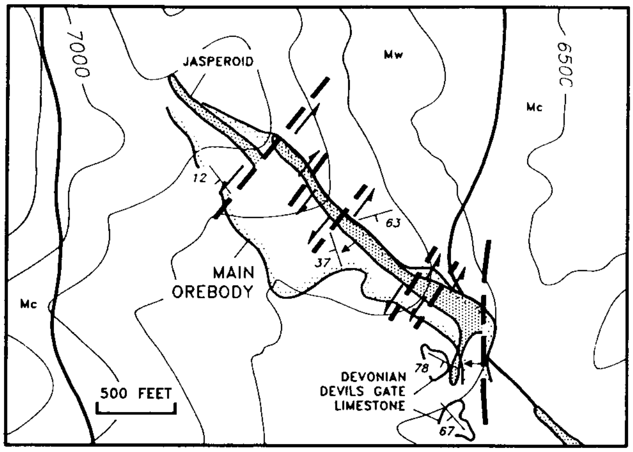

Figure 6-Geologic map of the Rain gold deposit, Mc = Mississippian Chainman Shale, Mw = Mississippian Webb Formation (after Knutsen and West, 1984).

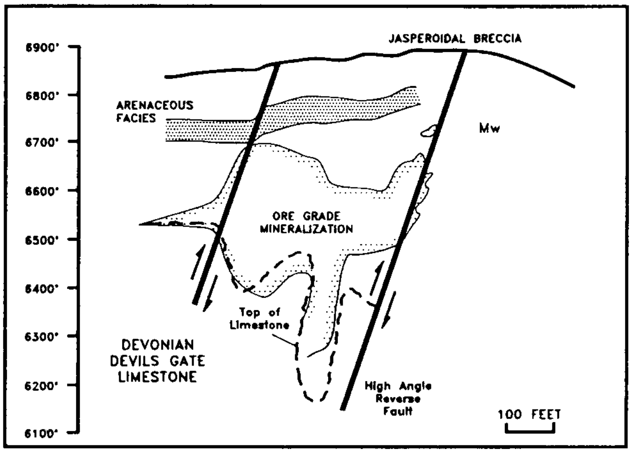

Figure 7-Generalized cross section through the Rain deposit (after Knutsen and West, 1984).

Webb Formation is part of the overlap assemblage, deposited within the Mississippian foreland basin near the then-emergent Antler highland. The Webb Formation at Rain consists of a sequence of siliceous mudstones, claystones, siltstones, and interbedded fine to medium-grained sandstones.

An apparent high-angle reverse fault, trending west-northwest and dipping southwestward, is the dominant ore-controlling structure (Figure 6). In general, the main orebody is an elongate manto within the coarser basal Webb Formation in the hanging wall of the high-angle fault (Figure 7).

Hydrothermal alteration processes included oxidation, argillization, silicification, and baritization. While much of the ore-bearing host rock is argillized and oxidized, silicification is restricted to the main hydrothermal conduit structure and to the ore zone. Hydrothermal barite occurs within the jasperoidal fault breccia as fragments, as replacements of other rock fragments, and as massive white interstitial barite.

Other smaller gold deposits in the vicinity of the Rain deposit are similarly and exclusively hosted at this Devonian-Mississippian unconformity, a surface of substantial solution porosity, and within permeable coarser basal lithologies. Again, effective permeability played an important role in focusing the ore-forming hydrothermal fluids, and the combination of stratigraphy and structure controlled the location and geometry of the resulting deposit.

SUMMARY

Disseminated sediment-hosted gold deposits of the Carlin Trend represent the greatest currently-identified gold resources in the United States. Twenty explored deposits contain a gold resource exceeding 1,600 tonnes (52 million troy ounces).

While each deposit is unique in its particular combination of lithologies, structural elements, alteration, mineralization style, and geometry, all possess common elements. Principal among these are the strong control exhibited by both structures and host-rock stratigraphy upon the flow course and chemical interaction of hydrothermal fluids during deposit formation.

Mineralization styles vary from the passive stratabound replacement within relatively permeable and porous silty limestone at the Carlin deposit, to the highly variable, structurally-controlled, Main ore zone at Gold Quarry. Economic concentrations of gold are localized at structural and stratigraphic settings similar to those which characterize petroleum traps.

Where permeability of the host rocks was relatively uniform, the resulting gold deposits are of relatively uniform grade and physical character; where the host rock was marked by physical inhomogeneity, as in the case of fracture permeability in siliceous rocks, the resultant ores are similarly highly variable. Recognition of the importance of stratigraphic and structural control upon the distribution of ore and upon the physical, chemical, and metallurgical properties of the ores is critical to the efficient exploration for and exploitation of these deposits.

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CHARACTERIZATION OF LIQUID-WATER PERCOLATION IN TUFFS IN THE UNSATURATED ZONE, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

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ABSTRACT

A surface-based borehole investigation currently (1989) is being done to characterize liquid-water percolation in tuffs of Miocene age in the unsaturated zone beneath Yucca Mountain, Nye County, Nevada. Active in-situ testing and passive in-situ monitoring will be used in this investigation to estimate the present-day liquid-water percolation (flux).

The unsaturated zone consists of a gently dipping sequence of fine-grained, densely fractured, and mostly welded ash-flow tuffs that are interbedded with fine-grained, slightly fractured, non-welded ash-flow and ash-fall tuffs that are partly vitric and zeolitized near the water table. Primary study objectives are to define the water potential field within the unsaturated zone and to determine the in-situ bulk permeability and bulk hydrologic properties of the unsaturated tuffs. Borehole testing will be done to determine the magnitude and spatial distribution of physical and hydrologic properties of the geohydrologic units, and of their associated water potential fields.

The study area of this investigation is restricted to that part of Yucca Mountain that immediately overlies and is within the boundaries of the perimeter drift of a U.S. Department of Energy proposed mined, geologic, high-level radioactive-waste repository. Vertically, the study area extends from near the surface of Yucca Mountain to the underlying water table, about 500 to 750 meters below the ground surface. The average distance between the proposed repository and the underlying water table is about 205 meters.

The investigation involves dry drilling and coring of 19 vertical boreholes 60 to 760 meters in depth and 1 horizontal borehole about 300 meters in length, for a total of about 6,850 meters. It also involves in-situ pneumatic borehole studies and vertical seismic profiling (VSP). Other investigations related to and supported by this drilling program include testing of matrix-hydrologic properties, testing of physical rock properties, age dating of contained pore water, geologic and lithologic logging, neutron-moisture logging and monitoring, geophysical logging, fracture mapping, and gas-flow evaluation. A final unsaturated-zone model for the Yucca Mountain site will be based on data collected from system-analysis and integration studies of the unsaturated zone, and on data collected during other investigations for characterization of the geohydrologic system of Yucca Mountain.

INTRODUCTION

Yucca Mountain is located west of the Nevada Test Site in Nye County, southern Nevada; the mountain is about 140 kilometers northwest of Las Vegas (Fig. 1). The unsaturated zone at Yucca Mountain consists of gently dipping sequence of tuffs that were deposited during Miocene volcanism (Waddell, et al., 1984). These tuffs consist of: (1) The Paintbrush Tuff having the Tiva Canyon, the Yucca Mountain, the Pah Canyon, and the Topopah Spring Members; (2) the tuffaceous beds of Calico Hills; and (3) the Crater Flat Tuff that

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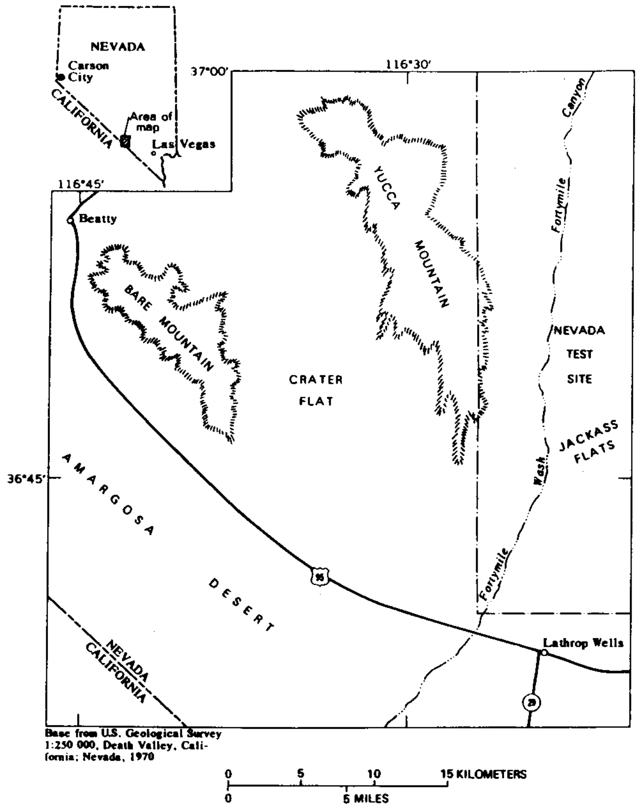

Figure 1-Map showing location of Yucca Mountain study area.

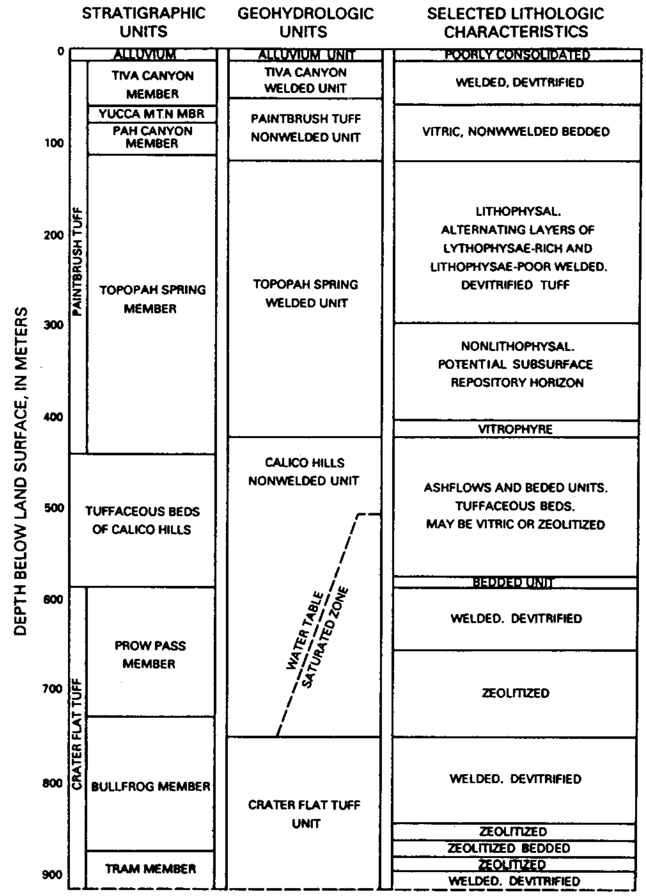

Figure 2-Diagram showing relationship between stratigraphic units and selected lithologic characteristics.

includes the Prow Pass Member, the Bullfrog Member, and the Tram Member (Fig. 2). Most of these rocks are ash-flow tuffs that are: (1) fine-grained and poorly consolidated; (2) generally densely to moderately fractured; (3) generally densely to moderately welded, with some slightly welded to nonwelded; and (4) vitric, devitrified, or vitrophyre. Interbedded with these are ash-flow and ash-fall tuffs that are: (1) mostly fine-grained, poorly consolidated or bedded, and, in part reworked; (2) slightly fractured to nonfractured; (3) slightly welded to nonwelded; (4) partly vitric and zeolitized near the water table. The water table is about 500 to 750 meters below the ground surface.

A surface-based borehole investigation currently (1989) is being done to characterize the liquid-water percolation in tuffs in the unsaturated zone at Yucca Mountain, Nevada. This investigation supports, through active in-situ testing and passive in-situ monitoring, a determination of the liquid-water percolation (flux). Two objectives of this investigation are to define the water potential field within the unsaturated zone and to determine the in-situ bulk permeability and bulk hydrologic properties of the unsaturated tuffs. The purpose of this article is to describe the current investigation to characterize liquid-water percolation in tuffs in the unsaturated zone.

The definition and spatial distribution of the physical and geohydrologic properties of the different hydrologic flow media and their associated water potential fields are the subject of much of the testing in this investigation. Some initial work has been done by Kume and Hammermeister (1987) who have studied geologic factors that affect physical and hydrologic properties of volcanic tuffs in the unsaturated zone. System-analysis and integration studies of the unsaturated zone needed to develop a comprehensive conceptual model of the unsaturated zone will depend on these data as well as data collected during other investigations to characterize liquid-water percolation. A conceptual model is needed to guide the final evaluation of the unsaturated zone for the storage of high-level nuclear waste. Montazer and Wilson (1984) proposed a preliminary conceptual model that has helped guide the early planning stages of this investigation.

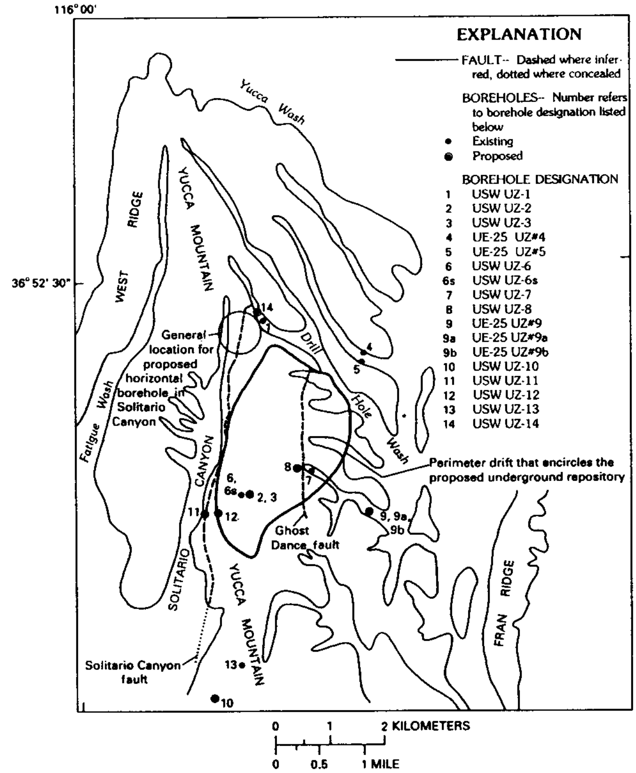

Figure 3-Map showing existing and proposed borehole location for the surface-based, unsaturated-zone percolation study.

The study area is restricted to that part of Yucca Mountain immediately overlying and within the bound aries of the perimeter drift of the U.S. Department of Energy (1986) proposed mined, geologic, high-level radioactive-waste repository (Fig. 3). Vertically, the rocks being studied in this investigation extend from the near surface of Yucca Mountain to the underlying water table up to 750 meters below.

The concept of storing high-level radioactive-waste and spent, nuclear-reactor-fuel in a well-drained, thick (500 to 750 m) unsaturated-zone environment in an arid region is of great interest because percolating water may not have ready access to the waste-package environment after repository closure. This environment is expected to serve as the primary barrier to the transport of radionuclides. One of the early workers, Roseboom (1983), suggested that locating a repository in the unsaturated zone of an arid region would eliminate or simplify many of the technological problems involved in designing a repository for operation below the water table and in determining its performance. He also stated that such a location offered possible accessibility and ease of monitoring throughout the operational period, and possible retrieval of the waste packages long after emplacement.

The principal advantage of this proposed site is that the thick welded and nonwelded tuffs comprising and immediately surrounding the proposed geologic repository are unsaturated. The average distance between the proposed repository and the underlying water table is about 205 meters.

DRILLING AND CORING

Dry drilling and coring for this investigation includes 19 vertical boreholes (7 already drilled and 12 proposed) ranging in depth from 60 to 760 meters for a total of about 6,850 meters. The investigation also includes drilling and coring of one horizontal borehole about 300 meters in length. The location of these boreholes (Fig. 3) is within or near the boundary of the proposed repository.

The rationale used in siting of the individual boreholes was based on the need to provide areal coverage of Yucca Mountain for sufficient detail to determine the local effects of faulting, topographic relief, and surface drainage on geohydrologic conditions at depth, and to minimize the disturbance of the main body of the proposed repository. The multiple-borehole sites are for cross-hole pneumatic testing, gas-tracer tests, and vertical seismic-profiling investigations.

Drilling of the boreholes into the unsaturated zone makes it possible to: (1) define structure and stratigraphy; (2) characterize the spatial variability of the hydrologic and geologic properties associated with each geohydrologic unit; (3) recover cores and drill-bit cuttings for laboratory measurement of matrix-hydrologic and physical-rock properties; (4) determine saturation of each geohydrologic unit as a function of depth; (5) perform in-situ pneumatic and hydraulic tests to evaluate bulk-permeability characteristics of the combined matrix and fracture systems; (6) recover matrix-pore water and in-situ gases for age dating and hydrochemical analysis; (7) measure and monitor, in-situ, the water potential field within which unsaturated flow occurs; (8) make vertical seismic profiles that will be used to extend the evaluation of fracture permeability, bulk permeability, and porosity to zones away from a near-borehole environment; (9) visually observe and record the density and orientation of fractures with depth; (10) evaluate gas tracer travel times by using gas-tracer tests; and (11) do borehole geophysical logging.

TESTING AND MONITORING

Testing and monitoring for this investigation consists of: (1) in-situ pneumatic testing of 19 vertical and 1 horizontal boreholes; (2) gas-tracer diffusion studies at two sites with multiple vertical boreholes; (3) vertical seismic profiling (VSP) across the middle section of Yucca Mountain; and (4) downhole instrumentation and monitoring of ambient water potentials for 3 to 5 years.

In-situ pneumatic testing (nitrogen gas injection and packer tests) will be used to calculate bulk pneumatic permeability and porosity of each geohydrologic unit and across geohydrologic-unit contacts. Large structural features, such as faults and shear zones, also will be tested when present. This method of in-situ testing is designed to measure the combined permeability of the rock matrix and associated features.

Gas-tracer (inorganic gas) diffusion studies in vertical boreholes (UE-25 UZ#9, UE-25 UZ#9a, UE-25 UZ#9b, USW UZ-2, USW UZ-3, and USW UZ-6) are designed to: (1) measure in-situ gaseous travel time through an unsaturated fracture-rock system; (2) measure contaminant transport and pneumatic properties of the rock; and (3) establish whether diffusion or convection is the dominant gaseous-transport mechanism.

VSP will be done in two vertical boreholes (UE-25 UZ#9 and USW UZ-6) at Yucca Mountain. Acoustic properties of the rocks can be measured at the boreholes as well as in the intervening area. Hydrologic properties, including bulk permeability and porosity, and fracture and fault permeability, will be tied to, or correlated to, accoustic velocity and reflectivity.

Downhole instrumentation and testing will be done to determine the magnitude and spatial distribution of physical and hydrologic properties of the geohydrology units and their associated water potential fields. Downhole sensors that consist of pressure transducers, thermocouple psychrometers, and thermal sensors (thermistors) will be installed in each of the vertical and horizontal boreholes.

Downhole testing will be done to determine the flux, which needs to be evaluated within a time-dependent, three-dimensional, anisotropic, and heterogeneous setting. An evaluation will be made of the in-situ distribution of potential energy and the properties of the conducting rock. The vertical and horizontal downhole testing will be used to define the in-situ water potential distribution and in-situ conductive properties of the unsaturated zone at Yucca Mountain. This information will be used to calculate flux within geohydrologic units.

The rock volume to be studied is bounded by an infiltration system near the surface and a recharge system at the water table. The distribution of flow between these boundaries is impossible to measure directly at either boundary. Usually, flow across these boundaries is as a residual quantity that is estimated from mass-balance calculations. Definition of the in-situ water potential flux distribution and in-situ conductive properties of the unsaturated zone, as determined by this surface-based borehole investigation, will enable a more direct and independent approach to flow determination. Results of this testing will be used in two-dimensional and three-dimensional computer simulations of the natural geohydrologic system.

Downhole monitoring will be done using an automated, Martin Marietta Corporation integrated data-acquisition system (IDAS). The IDAS system is designed to scan, record, transmit, and achieve downhole sensor readings. It fulfills the following technical, management, and quality-assurance requirements: (1) minimum measurement error; (2) protection of data; (3) minimum cost in collection and storage of data; (4) facilitation of data management; (5) flexibility, not only for future technological improvements, but also for multiple modes of downhole sensor operation to enhance borehole usefulness; and (6) timely warning of IDAS system failure to ensure against unacceptable loss of data.

RELATIONSHIP TO OTHER INVESTIGATIONS

The surface-based borehole investigation for characterization of liquid-water percolation in the unsaturated zone is only one of several investigations currently (1989) being conducted to provide an understanding of the geohydrology beneath Yucca Mountain. Data generated in this investigation will directly support several other investigations concerning the unsaturated-zone hydrologic system.

Results from the onsite tracer testing, air-permeability testing, and testing of matrix hydrologic properties will contribute to dispersive/diffusive/advective transport studies in the unsaturated zone. Several elements outlined in the testing will sustain, either directly or indirectly, work in the stratigraphy and structure necessary to locate the proposed underground facility and the development of a computer-based, three-dimensional model of rock properties at the proposed repository site.

The drilling and coring are related to and will sustain, either directly or indirectly, a number of other investigations. For example, the drilling samples (cores and drill-bit cuttings) can be used for: (1) testing of matrix-hydrologic properties and testing; (2) physical-rock-property testing; (3) geologic and lithologic logging; and (4) age dating of the sample-contained pore water. Also, included in these investigations is the characterization of vertical and lateral distribution of geohydrologic units within the proposed site area.

Data from laboratory testing will support several other investigations and will include: (1) measurements of gravimetric and volumetric moisture content; (2) matric- and osmotic-potentials; (3) intrinsic and relative permeability; (4) standard rock analysis grain-size distribution; (5) bulk and grain densities; and (6) clay contents. The boreholes will enable access to the unsaturated zone for: (1) borehole geophysical logging; (2) neutron-moisture logging and monitoring; (3) fracture mapping; and (4) evaluation of barometric and topographic effects on gas flow in the unsaturated zone.

The downhole instrumentation and monitoring of ambient potentials for 3 to 5 years will provide facilities for recovery of in-situ pore gases and water vapor for gas chemistry analysis and for tritium and isotope-ratio measurements and will provide instruments for measuring in-situ pneumatic pressures as part of the gaseous-phase movement study. After this monitoring, downhole hydraulic (water injection) testing will be done in each borehole.

REFERENCES CITED

Kume, Jack, and Hammermeister, D.P., 1987, Geologic factors that affect physical and hydrologic properties of volcanic tuffs in the unsaturated zone, Yucca Mountain, Nevada (abs.): Geological Society of America Abstracts with Programs, v. 20, p. 735.

Montazer, Parviz, and Wilson, W. E., 1984, Conceptual hydrologic model of flow in the unsaturated zone, Yucca Mountain, Nevada: U.S. Geological Survey Water-Resources Investigations Report 84-4345, 55 p.

Roseboom, E. H., Jr., 1983, Disposal of high-level nuclear waste above the water table in arid regions: U.S. Geological Survey Circular 903, 21 p.

U.S. Department of Energy, 1986, Final Environmental Assessment, Yucca Mountain Site, Nevada Research and Development Area, Nevada: Department of Energy/RW-0073, Washington, D.C., 3 volumes.

Waddell, R. K., Robisson, J. H., and Blankennagel, R. K., 1984, Hydrology of Yucca Mountain and vicinity, Nevada-California--Investigative results through mid-1983: U.S. Geological Survey Water-Resources Investigations Report 84-4267, 72 p.

THE IMPACT OF F. D. HOLLAND, JR. ON GEOLOGICAL LITERATURE

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ABSTRACT

The impact of F. D. Holland, Jr. on geological literature is evidenced by his 62 publications spanning 39 years, by more than 140 publications of his 29 graduate students and by the range of journals in which they have appeared. The expanded impact can be estimated from the range of references where these papers have been cited. The publications of over 150 other graduate students on whose committees Holland has participated plus scores of undergraduate majors who came in contact with Dr. Holland are an additional contribution not included in this impact study.

Of importance to the science, and to geological education, is the reverence for the scholarly literature of geological science, a hallmark of Holland's professionalism that has often been conveyed to students and colleagues. It is recognized by dedication of the F. D. Holland, Jr. Geological Library in Leonard Hall at the University of North Dakota.

INTRODUCTION

This contribution to the Holland Symposium is made to document F. D. Holland, Jr.'s impact on geological literature. We found that this can be measured at various levels. The first or primary impact, of course, is made by the papers he authored or co-authored. (A bibliography of his papers is included elsewhere in this volume.)

The distribution of Holland's publications within the broad field of geosciences is interesting to note. He has published not only in the field of paleontology but also in the areas of history of geology, linquistics, regional geology, guidebooks, education, and biography. These papers have been published in a wide variety of journals. The largest percentage of articles appear in North Dakota publications. The North Dakota Geological Survey publications and North Dakota Academy of Science Proceedings are at the top of the list (Table 1). Papers and abstracts published by two of the major geoscience societies, the American Association of Petroleum Geologists and the Geological Society of America, are next.

The importance that F. D. Holland has placed on education and involvement with students is reflected by the two volumes of student papers he edited for Beta Zeta Chapter of Sigma Gamma Epsilon as well as by his own six papers in The Compass of Sigma Gamma Epsilon. Table 1 is a listing of places in which his publications have appeared and the number of articles published in each source. The list also reveals some of the diversity of his publications and interests. For example, articles were published in Stone Magazine, a magazine for building contractors, the Proceedings of

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TABLE 1

List of F. D. Holland, Jr.'s Publication Sources

Publication Title	Number of Articles
North Dakota Geological Survey	8
North Dakota Academy of Science Proceedings	7
American Association of Petroleum Geologists	5
Geological Society of America Meetings Abstracts	5
The Compass of Sigma Gamma Epsilon	6
Geotimes	4
Journal of Paleontology	4
Radiocarbon	2
University of North Dakota Geology Dept. Guidebooks	2
Bulletins of American Paleontology	1
Council on Education in the Geological Sciences Newsletter	1
Earth Science Curriculum Program Newsletter	1
Journal of Geological Education	1
Journal of College Science Teaching	1
North Dakota Outdoors	1
Stone Magazine	1
Prairie Naturalist	1
Society of Paleontologists and Mineralogists Annual Midyear Meeting	1
16th International Congress of Zoology Proceedings	1
Linguistic Circle of Manitoba and North Dakota	1
University of North Dakota Anthropological Papers	1
North Dakota Regional Environmental Assessment Program	1
Saskatchewan Geological Society Special Publication 9	1
Annals of the Carnegie Museum	1
Canadian Paleontology and Biostratigraphy Seminar	1

the Linguistics Circle of Manitoba and North Dakota, and in North Dakota Outdoors. The list also reveals an international impact of his publications. Four of his papers were published in international or foreign publications.

The second level of F. D. Holland Jr's impact on geological literature is measured by citations to the first level publications. Table 2 is a listing of six papers that have been cited by others and where these articles were cited. The 1952 paper in the American Association of Petroleum Geologists Bulletin is the most often cited having been referenced seven times, first in 1955 and most recently in 1978, 26 years after it was published. One of his abstracts on conodonts, published in 1955 in the Geological Society of American Bulletin was cited in 1982, 27 years after publication. This appears to be the longest impact span to date. His doctoral dissertation has the next longest impact span--21 years--having been last cited in 1979. From these data we can only make general statements of his total impact on geological literature because Science Citation Index only collects citations from the "core journals" in science. A detailed citation analysis that included University of North Dakota theses and dissertations and North Dakota Geological Survey Publications would expand the results of this part of the study.

The third level of F. D. Holland's impact on geological literature is through his graduate students and their graduate theses and related publications. Appendix A is a list of graduate theses and dissertations and related articles of Holland's graduate students. Papers jointly authored with his students are listed in his bibliography. F. D. Holland, Jr. was graduate committee chairman for twenty master's theses and nine doctoral dissertations.

Other papers selected for Appendix A are publications related to his graduate student's research. Listed are 96 papers that have appeared in 34 journals or other publication sources. Table 3 lists in order of number of papers published, the publication sources of Holland's students. The distribution pattern of these papers is similar to Holland's own, in that his students have published most often in the North Dakota Geolo-

TABLE 2

Citations to F. D. Holland Jr.'s Papers from Science Citation Index, 1955-1985

Cited Paper	Citing Reference
1952 American Association of Petroleum Geologists Bulletin 36(9), p. 1697	1955 Geol. Soc. Am. Bull., 66, p. 1385 1959 Jour. Paleo., 33, p. 977 1959 Geol. Soc. Am. Bull., 70, p. 207 1961 Jour. Paleo., 35, p. 1193 1962 Jour. Paleo., 36, p. 1291 1977 Jour. Paleo., 51, p. 1133 1978 Jour. Paleo., 52, p. 1346
1955 Geological Society of America Bulletin 66(12), p. 1574	1959 Jour. Paleo., 33, p. 211 1982 Jour. Paleo., 56, p. 1029
1957 North Dakota Geological Survey Miscellaneous Series 5	1963 Geol. Soc. Am. Bull., 74, p. 673
1958 Journal of Paleontology 32(3), p. 495	1959 Jour. Paleo., 33, p. 194 1971 Jour. Paleo., 45, p. 838 1976 Jour. Paleo., 50, p. 985
1958 Ph.D. Dissertation, Univ. Cincinnati	1979 Ohio Jour. Science, 79, p. 233
1975 Bulletins of American Paleontology, 67, p. 235	1988 Jour. Sed. Petrology, 58, p. 706

gical Survey publications and North Dakota Academy of Science Proceedings. The Compass of Sigma Gamma Epsilon also ranks high on this list along with the American Association of Petroleum Geologists Bulletin and Geological Society of America Meeting Abstracts. This reflects Holland's well-known encouragement of student involvement in organizations as well as his encouragement of students to take part in professional meetings. Table 3 does not include papers co-authored by F. D. Holland and a student or students; those were included in Table 1. There are 32 papers with F. D. Holland as co-author. An argument might be made that Holland's influence on research style and writing style extends beyond these selected papers because of his editing, his refereeing of papers, and because one of his students has been editor of two national journals, but we chose to limit this study to what we considered to be the most direct influences.

Table 4 is an attempt to carry Holland's impact on geological literature to a fourth level by investigating where his students' papers have been cited. This

TABLE 3

List of F. D. Holland, Jr.'s Student's Publication Sources

Publication Title	Number of Articles
North Dakota Academy of Science Proceedings	11
North Dakota Geological Survey Publications	11
The Compass of Sigma Gamma Epsilon	10
Geological Society of American Meeting Abstracts	10
American Association of Petroleum Geologists Bulletin	9
5th International Williston Basin Symposium	5
Williston Basin: Anatomy of a Cratonic Oil Province	4
Journal of Paleontology	4
Journal of Sedimentary Petrology	3
North Dakota Quarterly	3
Geological Association of Canada Special Paper 13	2
Nautilus	2
Society of Economic Paleontologists and Mineralogists Midyear Meeting Abstracts	2
Sterkiana	2
3rd International Williston Basin Symposium	2
4th International Williston Basin Symposium	2
2nd International Williston Basin Symposium	1
American Midland Naturalist	1
Palaeontology	1
Malacologia	1
Mountain Geologist	1
Sedimentary Geology	1
Canadian Society of Petroleum Geologists Memoir 9	1
University of Michigan Museum Paleontology Contributions	1
Hydrocarbon Source Rocks of Greater Rocky Mountain Region	1
Montana Geological Society 24th Annual Conference	1
Saskatchewan Geological Society Special Publication 7	1
Canadian Paleontology and Biostratigraphy Seminar Program Abstracts	1
Society of Economic Paleontologists and Mineralogists Core Workshop 7	1
7th Biennial Conference American Quaternary Association	1
3rd North American Paleontological Convention	1
International Association for Quaternary Research Abstracts	1
Late Cainozoic Palaeoclimates of the Southern Hemisphere	1
Annals Entomological Society of America	1

TABLE 4

Citations to Papers Written by F. D. Holland, Jr.'s Students from Science Citation Index, 1955-1985

Student	Cited Paper	Citing Reference
Caramanica, F. P.		
	1975 Jour. Paleo., 49, p. 1126	
		1978 Jour. Paleo., 52, p. 121
		1978 Palaeont., 21, p. 307
Carlson, C. G.		
	1960 N. D. Geol. Survey Bull. 35	
		1962 Jour. Paleo., 36, p. 1214
		1967 Am. Jour. Sci., 265, p. 232
		1970 Jour. Paleo., 44, p. 743
		1970 GSA Bull., 81, p. 3197
		1978 Jour. Paleo., 52, p. 444
		1982 AAPG Bull., 66, p. 989
		1984 CIM Bull., 77, p. 39
		1985 Geology, 13, p. 620
Cvancara, A. M.		
	1966 Univ. Mich. Mus., Paleo Contr. 20, p. 777	
		1971 Jour. Paleo., 45, p. 838
		1981 Malacologia, 21, p. 111
		1984 Geology, 12, p. 205
Erickson, J. M.		
	1969 Compass, 47, p. 5	
		1971 GSA Bull., 82, p. 3475
	1971 J. Sed. Pet., 41, p. 589	
		1977 J. Sed. Pet., 47, p. 1342
	1974 Bull. Am. Paleont., 66, p. 131	
		1976 Jour. Paleo., 50, p. 481
		1980 Palaeont., 23, p. 391 (as "Erikson")
		1986 Bull. Mar. Sci., 39, p. 565
	1978 N. D. Acad. Sci. Proc., 32, p. 79	
		1986 Nature, 324, p. 148
		1987 Palaeogeo. P., 61, p. 33
Feldmann, R. M.		
	1972 N. D. Geol. Survey Bull. 61	
		1979 Wat. Reso. Res., 15, p. 1479
	1973 Geol. Assoc. Can. Sp. Paper 13	
		1981 Jour. Paleo., 55, p. 401
		1987 Palaeogeo. P., 61, p. 1
		1987 Palaeogeo. P., 60, p. 189
	1976 Jour. Paleo., 50, p. 985	
		1980 Jour. Paleo., 54, p. 862
		1983 Jour. Paleo., 57, p. 900
		1985 Jour. Paleo., 59, p. 605

TABLE 4 (Continued)

Student	Cited Paper	Citing Reference
Grenda, J. C.		
	1978 Economic Geology of Williston Basin	
		1982 AAPG Bull., 66, p. 984
Hoganson, J. W.		
	1982 3rd. N. Am. Paleo. Conv. Proc., 1, p. 251	
		1987 Nature, 328, p. 609
Kume, Jack		
	1963 N. D. Geol. Survey Bull. 39	
		1967 Am. Jour. Sci., 265, p. 332
		1983 AAPG Bull., 67, p. 2165
		1986 J. Petr. Geol., 9, p. 125
Morgan, D. H.		
	1964 Compass, 41, p. 156	
		1984 R. Palaeob. Pal., 43, p. 89
Royse, C. F.		
	1967 Ph.D. Dissertation	
		1970 Sed. Geol., 4 p. 19
		1976 J. Sed. Pet., 46, p. 97
	1968 J. Sed. Pet., 38, p. 1177	
		1970 J. Sed. Pet., 40, p. 1007
		1970 Sed. Geol., 4, p. 19
		1975 J. R. Soc. N. Z., 5, p. 421
		1978 Can. J. Ear. Sci., 15, p. 190
		1974 J. Sed. Pet., 44, p. 985
		1976 J. Sed. Pet., 46, p. 97
		1982 Hydrobiol., 91, p. 341
		1984 Sed. Geol., 38, p. 421
		1985 Ear. Sur. Proc., 10, p. 281
		1986 Sci. Tot. Env., 50, p. 103
	1967 N. D. Geol. Survey R. I. 45	
		1968 J. Sed. Pet., 38, p. 1171
		1973 AAPG Bull., 57, p. 1038
		1970 Sed. Geol., 4, p. 19
	1970 Sed. Geol., 4, p. 19	
		1979 AAPG Bull., 63, p. 194
		1976 Sci. Geol. Sinica, p. 33
		1973 AAPG Bull., 57, p. 1038
		1974 Science, 183, p. 1077
		1986 Sci. Tot. Env., 50, p. 103
		1986 Geoderma, 37, p. 295
		1986 Soil Sci. Soc., 50, p. 490
	1972 N. D. Geol. Survey Misc. Ser. 50	
		1986 Geoch. Cos. Acta, 50, p. 2033

TABLE 4 (Continued)

Student	Cited Paper	Citing Reference
Tuthill, S. J.		
	1961 N. D. Acad. Sci. Proc., 15, p. 19	
		1971 Science, 171, p. 172
		1970 GSA Bull., 81, p. 3593
		1976 Can. J. Zool., 54, p. 1688
		1979 Quatern. Res., 11, p. 93
	1962 Sterkiana, 8 and 10	
		1976 Can. J. Zool, 54, p. 1688
	1963 M. A. Thesis	
		1971 Science, 171, p. 172
		1976 Can. J. Zool., 54, p. 1688
	1963 Nautilus, 77, p. 81	
		1976 Can. J. Zool., 54, p. 1688
	1964 Am. Midland Naturalist, 71, p. 344	
		1968 GSA Bull., 79, p. 855
		1976 Can. J. Zool., 54, p. 1688
		1985 P. Acac. Nat. Sci., 135, p. 85
		1985 Arctic Alpine R., 17, p. 49
	1966 Geol. Soc. Am. Spec. Pap. 101, p. 223	
		1968 GSA Bull., 79, p. 855
	1969 Ph.D. Dissertation	
		1971 Science, 171, p. 172
		1976 Can. J. Zool., 54, p. 1688
	1967 N. D. Geol. Survey Misc. Ser. 30	
		1976 Can. J. Zool., 54, p. 1688
		1979 Quaternary R., 11, p. 93
Webster, R. L.		
	1982 M. S. Thesis	
		1985 AAPG Bull., 69, p. 567
		1986 J. Petr. Geol., 9, p. 125
		1986 J. Petr. Geol., 9, p. 313
		1987 AAPG Bull., 71, p. 95
	1984 Hydrocarbon Source Rocks	
		1986 J. Petr. Geol., 9, p. 125
		1986 Organic Geoch., 10, p. 915
		1987 AAPG Bull., 71, p. 368
Ziebarth, H. C.		
	1964 3rd Internat. Williston Basin Sym.	
		1982 AAPG Bull., 66, p. 989
		1984 AAPG Bull., 68, p. 178

list is long and varied. It reflects some impact outside the standard geological journals, for example, The Canadian Journal of Zoology and Science of the Total Environment. Widespread international impact is indicated by citations in the Journal of the Royal Society of New Zealand, Scienta Geologica Sinica from the People's Republic of China and Palaeontology. There are ten citations to his student's theses or dissertations. It is interesting to note that some papers tend to be cited shortly after publication and others may not be cited for many years. Another observation is that some papers such as C. G. Carlson's North Dakota Geological Survey Bulletin 35 published in 1960 may be considered classics. That paper was first cited in 1962, has been referenced eight times and was most recently cited in 1985. Another article with continuing influence is the 1968 paper by C. F. Royse in the Journal of Sedimentary Petrology. It was cited ten times between 1970 and 1986. A total of 30 of the more than 140 of Holland's student's publications have been cited at least once in major journals. The initial impact of F. D. Holland's 60 papers, of which six were cited 15 times, has been expanded by inclusion of his student's articles (including those represented herein) to a total of 200 papers, 36 of which have been cited 96 times in major journals. We could carry this a step further if we included all the other graduate students whose committees Holland served on and also undergraduate majors who were his advisees. For this study we decided not to attempt that expansion.

There are other ways to assess Bud Holland's influence on the geological literature. A review of the literature on the paleontology of North Dakota published between 1954 and 1988 reveals that 98 (43%) of the 228 articles, were written by F. D. Holland and/or his graduate students. An impact on paleontological nomenclature has been the description of new fossil taxa in honor of F. D. Holland, Jr. by four of his former students. These are:

Hercorhyncus hollandi named by J. Mark Erickson, 1974 in "Revision of the Gastropoda of the Fox Hills Formation, Upper Cretaceous (Maestrichtian) of North Dakota": Bulletins of American Paleontology, 66 (284), 122 p.

Crassatellina hollandi named by Rodney M. Feldmann and T. W. Kammer, 1976 in "*Crassatellina hollandi*, n. sp. (Bivalvia: Astartidae) from the Fox Hills Formation (Maestrichtian: Cretaceous) of North Dakota and South Dakota:" Journal of Paleontology, 50, p. 481-487.

Cyathophylloides hollandi described by Frank P. Caramanica, 1991, in "Ordovician Corals of the Red River-Stony Mountain Province." (this volume).

Tylericaris hollandi described by James C. Grenda, 1991, in "*Tylericaris hollandi* n. gen., n. sp. (Malacostraca: Tealliocarididae) from the Tyler Formation (Pennsylvanian) of North Dakota:" (this volume).

Bud Holland's concern for the organization and preservation of geological literature, is the last impact that will be discussed. His 1961 paper, "The Status of Paleontology in North Dakota," provided the historical background for the first bibliography of North Dakota geology (Scott, 1972). His personal library provided Many of the older reports for annotation to be inlcuded in that volume. Holland also encouraged the two writers of this paper to pursue careers in the field of geolibrarianship thereby perpetuating a lasting impact on geological libraries and librarians in the United States since we have both served as president of the Geoscience Information Society.

At the University of North Dakota, F. D. Holland, Jr. has worked diligently to develop the Geology Library. In the late 1940's and the 1950's, the Geology Library was located with the North Dakota Geological Survey in a government surplus building near the site where Witmer Hall stands today on the University of North Dakota campus. Some of the geology laboratories were located on the other side of campus in the basement of Merrifield Hall. During that time the Geology Library was open only a few hours a week. Holland saw to it that a file of article reprints was maintained in one of the laboratory classrooms to make geological literature more readily accessible to students.

Later, as chairman of the building committee for Leonard Hall, he helped to design a Geology Library that was convenient for students, faculty, and survey personnel. He planned the building with growth of the library in mind by increasing the strength of the floor and increasing the height of the building to allow for a later addition of a second level to the library. He worked to see that the library is staffed by qualified librarians and that the hours that it is open are adequate for student research. He has worked untiringly on the University and departmental Library Committees to assure an appropriate level of support for acquisitions for all campus libraries. It is fitting that the new double-decked library in Leonard Hall has been named the F. D. Holland, Jr. Geological Library by the North Daktoa State Board of Higher Education and University of North Dakota President T. J. Clifford in honor of all of F. D. Holland's diverse contributions to scholarly research and education through the printed word.

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APPENDIX A

THESES AND SELECTED RELATED PUBLICATIONS OF F. D. HOLLAND, JR'S GRADUATE STUDENTS

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