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Prepared by: J. R. Ehrets
M. L. Hendricks
D. L. Kissling
E. R. Megathan
N. E. Voldseth

Edited by: D. W. Fischer

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Sidney B. Anderson,
Acting State Geologist

This volume is intended to be not only a guide to the proceedings of the core workshop, but also a formal discussion and documentation of the interpretations and theories presented.

Appreciation is expressed to the authors of the four papers. Each paper represents a significant contribution of not only geological insight, but also time.

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WINNIPEGOSIS PLATFORM MARGIN AND PINNACLE REEF RESERVOIRS, NORTHWESTERN NORTH DAKOTA

by
James R. Ehrets and Don L. Kissling
Jackalope Geological Ltd.
1327 Spruce Street, Suite 3
Boulder, CO 80302

ABSTRACT

Differentiation of the Elk Point shelf into distinct platform and basin regimes during deposition of the Middle Devonian Winnipegosis Formation stimulated the development of a reef and slope complex along the platform margin and allowed for sustained growth of pinnacle reefs in a subsiding basin. The platform margin is subdivided into slope, reef, and peritidal facies which prograded as sedimentary wedges into the basin. Platform margin reef fabrics indicate early lithification, providing structural integrity and differentiation into relatively distinct fore reef, reef crest, and reef flat subfacies. Reef development was a function of vertical accretion and basinward progradation in conjunction with general platform physiography around the basin. Conspicuous argillaceous slope facies which bound reef sections represent extrinsic events during normal platform margin deposition, resulting in the redeposition of eroded coastal mud on the slope. Flora and fauna within these marker beds reflect the evolution of environmental conditions culminating in the widespread exposure of platform areas.

Pinnacle reefs, initiated as shallow-water mounds rich in codiacean algae and peloids, apparently evolved a variety of reef subfacies in response to basin subsidence. The upward transition from mound facies to coral-stromatoporoid rim and stromatolite crest subfacies reflects accelerated subsidence of the basin which accompanied platform/basin decoupling. Abundant drusy cements indicate that relatively steep reef peripheries were maintained by organic binding and submarine cementation. Reef flat subfacies developed upon establishment of generally shoaling conditions. During all stages of pinnacle reef development, proximal to distal flank subfacies formed by commingling debris shed off reefs with sediment endemic to the basin floor environments adjacent to reefs.

Evaporative drawdown of the Elk Point basin at the close of Winnipegosis deposition resulted in exposure of the broad platform region as well as the upper portions of pinnacle reefs. The subsequent establishment of vadose and related diagenetic environments resulted in the creation of platform margin and pinnacle reef reservoirs, but styles of reservoir generation and reservoir host facies differ for the two regimes. The reservoir at Temple Field is developed in non-argillaceous slope mudstone facies which underlies platform margin reefs. Early lithified reefs not only served to direct dolomitizing fluids into slope facies, but also played a key role in limiting halite invasion into the slope reservoir. Vertical zonation of diagenetic environments in pinnacle reefs resulted in a variety of vadose and meteoric phreatic processes in the upper parts of reefs, including leaching, lithification, and dolomitization. Consequently, coral-stromatoporoid subfacies display the greatest diversity of pore types and magnitude of porosity. Except for occurrences of overdolomitized reefs, preserved intergranular porosity in underlying algae-peloid mound facies was not significantly altered by marine phreatic processes in either undolomitized North Dakota reefs or dolomitized Saskatchewan reefs.

INTRODUCTION

The Middle Devonian Winnipegosis Formation (fig. 1) produces from a variety of carbonate reservoirs in the northeastern Montana and northwestern North Dakota portions of the Williston Basin. Producing trends are broadly subdivided into: the western **platform interior**, including Montana's Outlook, Reserve, and North Bainville Fields, among others; the **platform margin**, including Temple and Hamlet Fields; and the **basin**, which at present is represented only by Stoneview Field in North Dakota, but having significant potential for pinnacle reef production (fig. 2). Within North Dakota, the Winnipegosis platform margin is informally subdivided into western, southern, and eastern platforms, each reflecting different subsidence and depositional histories which are recorded in stratigraphic and facies sequences. Stromatoporoid-coral reefs are sporadically developed along portions of the platform margin, with the best example of reef facies existing on the portion of the western platform which includes Temple Field.

The 1982 discovery and subsequent development of the Temple Field Winnipegosis pool in northeastern Williams County, North Dakota sparked considerable interest in the platform margin play which quickly waned after a number of dry holes were drilled in adjacent Divide County. Recent discoveries of oil-charged pinnacle reefs in the Tableland area of southeastern

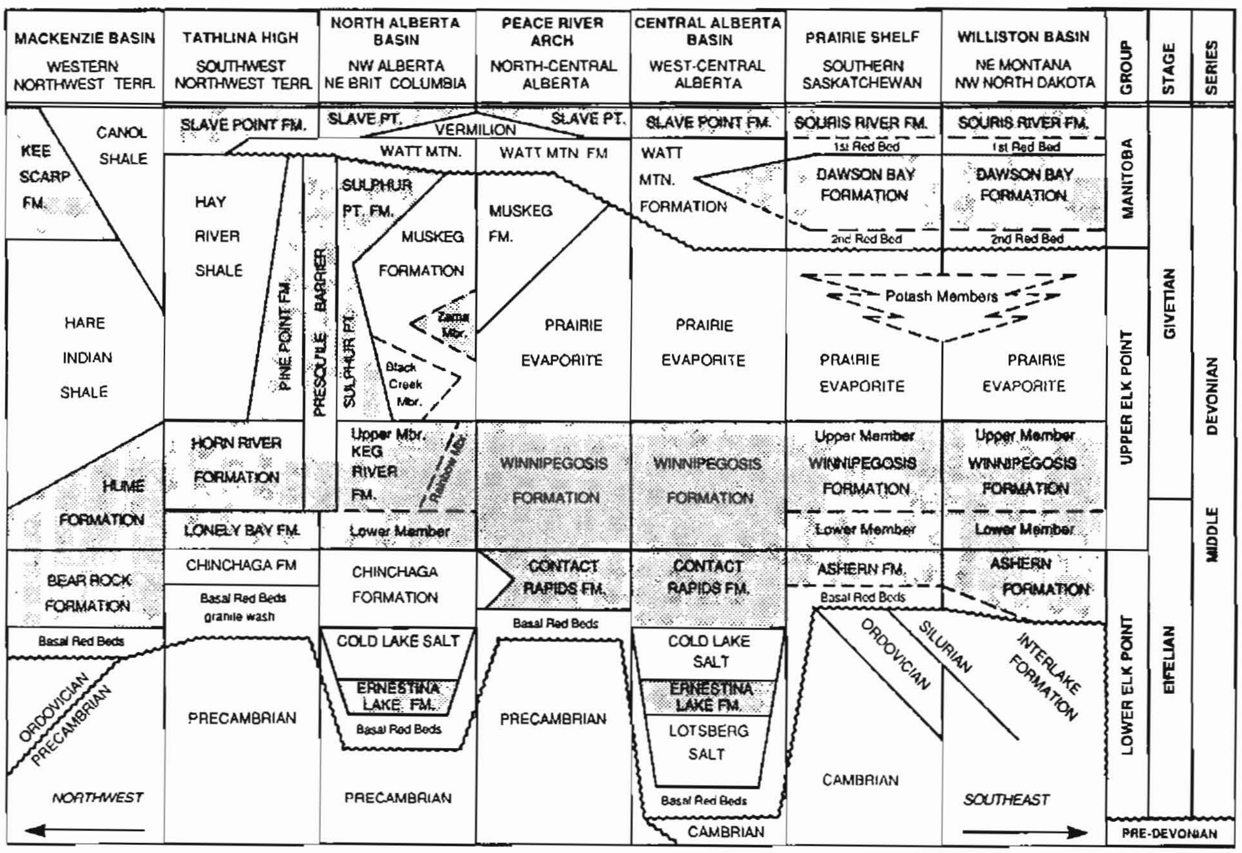

Fig. 1 - Stratigraphic nomenclature and correlation of Middle Devonian formations across the Elk Point shelf and basin. Shading denotes dominantly carbonate formations.

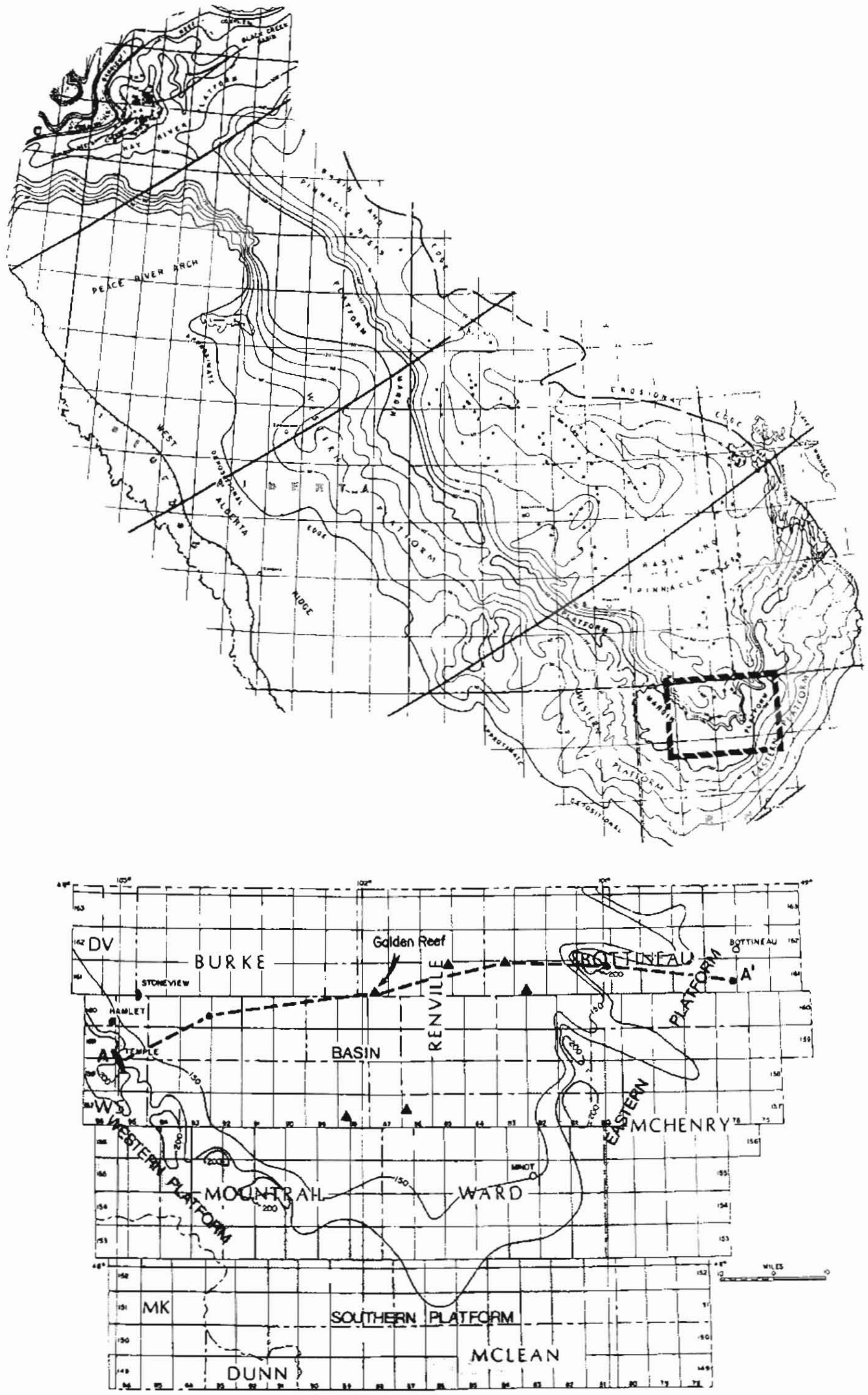

Fig. 2 - Thickness and major paleogeographic elements of the Winnipegosis Formation and its equivalents across the Elk Point shelf and basin (top), showing location of the northwestern North Dakota study area. Numerous dots in basin area represent many of the known pinnacle reefs. Enlarged map area (below) locates Temple field and the Golden pinnacle reef. Regional cross section A-A' is denoted by dashed line.

Saskatchewan have rejuvenated interest in the pinnacle reef play after 20 years and more than 50 dry holes in the search for oil-charged pinnacles. Primary recoverable reserves estimated at 5.5 MMbo for the Home et al. North Tableland #8A-22-2-9W2 discovery well, and estimates for total pinnacle reef reserves as high as one billion barrels of oil in place within the developing exploration fairway provide tremendous incentive for Saskatchewan and North Dakota operators alike.

The scope of this paper and core workshop is to illustrate and examine aspects of facies and reservoir development of two different Winnipegosis reservoir types in North Dakota. Temple Field, located on the western platform margin in northeastern Williams County, is presently the most significant Winnipegosis reservoir in North Dakota. On the other end of the spectrum, the pinnacle reef reservoir penetrated at Shell Golden #34X-34 in Renville County yielded only non-commercial oil. However, the facies sequence and style of reservoir development in the Golden pinnacle reef is similar to that in the North Tableland reef.

GEOLOGIC SETTING

Paleogeographic reconstruction of the Winnipegosis and its equivalents defines an intracratonic platform and basin complex which extended from northern Alberta southeastward into northwestern North Dakota (fig. 2). This platform and basin complex is generally referred to as the Elk Point basin. Thickness trends in the Winnipegosis are characterized by gradual basinward thickening from interior portions of the basin-rimming platform in central Alberta, southwestern Saskatchewan, northeastern Montana, and north-central North Dakota, towards platform margins where the formation reaches thicknesses of 180-225 feet (figs. 2, 3). This sedimentary wedge rapidly thins downslope into the basin where average formation thickness is approximately 60 feet. Winnipegosis thickness trends show no evidence for a subsiding Williston Basin, the structural entity which had existed prior to Winnipegosis deposition and which is expressed in isopachs of the underlying Ashern Formation. Moreover, the elongate trend of Middle Devonian sediments within the Elk Point shelf and basin most certainly represents only the preserved portion of a much broader carbonate shelf within southern Canada, as indicated by right-angle trends of platforms at both the northwestern and southeastern extents of the complex (Williams, 1984) (fig. 2).

Time-stratigraphic relationships determined from marker bed correlation across the platform and into the proximal basin indicate differentiation of the broad Prairie shelf from an early-formed carbonate ramp to a distinct platform and basin during deposition of the Winnipegosis. Pinnacle reefs had initiated as relatively shallow water mounds in the distal ramp region at some time prior to this physiographic differentiation. Subsequent to platform/basin decoupling, development, and progradation of reef and bank complexes prevailed at the platform margin. Reef development encompassing Temple Field represents the eastern extent of western platform progradation (fig. 2). During this time of platform margin progradation, pinnacle reefs experienced relatively rapid vertical accretion from their mound bases in response to basin subsidence.

At the close of Winnipegosis deposition, accumulation of finely laminated basin mudstones under progressive restriction and increasing salinity represent the combined effects of evaporative drawdown of sea level across the Elk Point basin and the confinement of the shelf sea by upward accretion

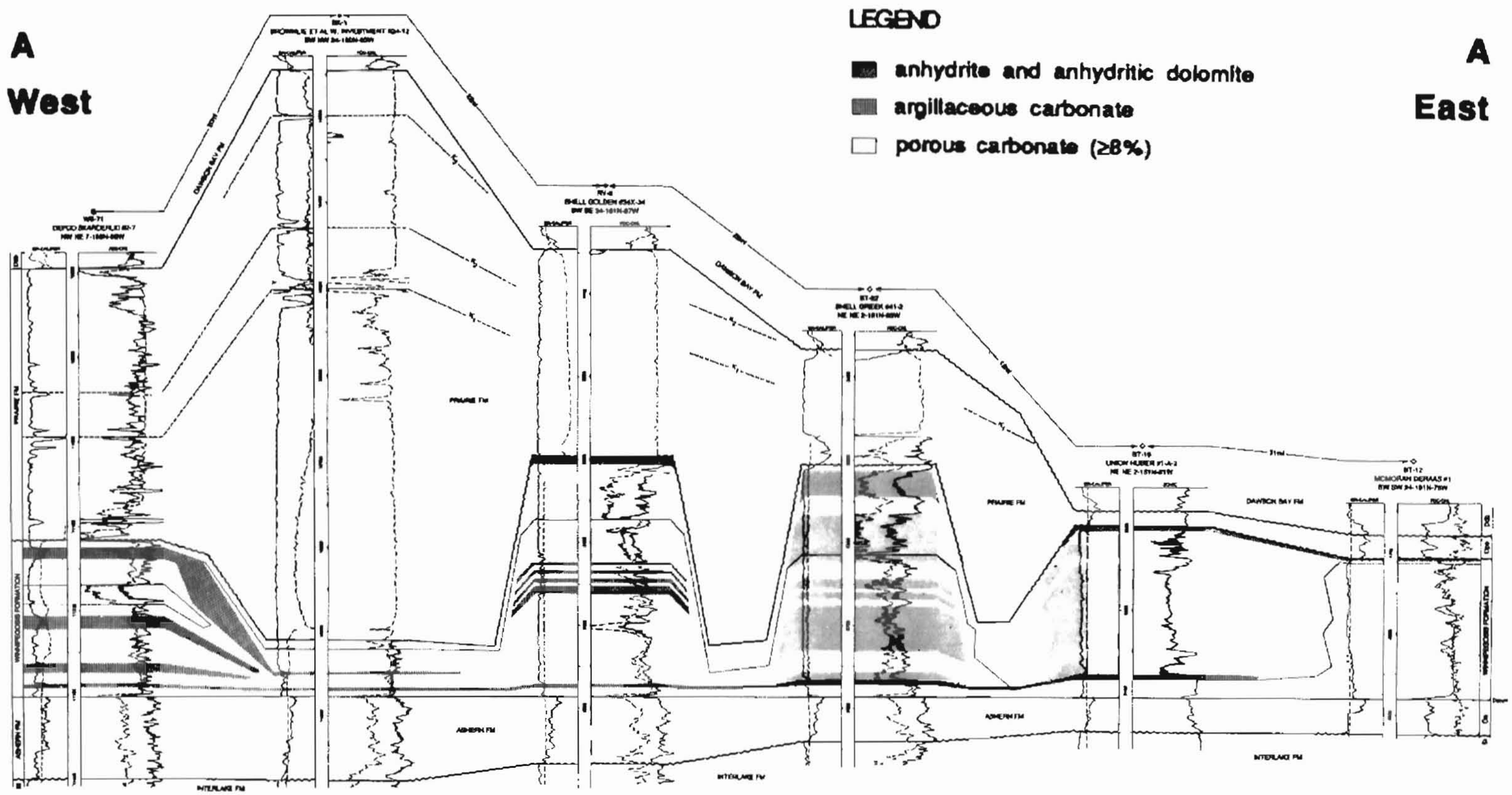

Fig. 3 - Regional stratigraphic cross section A-A', extending from Temple Field on the Western Platform to the Eastern Platform in Bottineau County. Disconformable relationships with the Prairie Formation indicated for the platforms and for the Golden and Greek pinnacle reefs illustrate interpreted extent of exposure resulting from evaporative drawdown.

of the Presqu'ile reef barrier. Maiklem (1971) presents arguments in support of late Winnipegosis evaporative drawdown of water level of at least 100 feet within the Elk Point basin as a precursor to deposition of the Prairie Evaporite. Facies distribution, leaching, and dolomitization of the Winnipegosis at platform margins and pinnacle reefs indicate that evaporative drawdown had lowered the shelf sea level approximately 140 feet by the end of Winnipegosis deposition in the North Dakota basin area (Kissling and Ehrets, 1985, 1986) (fig. 3). This mechanism was ultimately responsible for reservoir development in both platform margin and pinnacle reef facies.

TEMPLE FIELD AREA

Temple Field is a combined structural-stratigraphic trap situated along a subordinate structural limb on the northwestern flank of the Nesson Anticline (fig. 4). Initially completed in 1980 as the first Dawson Bay pool in North Dakota, interest switched to the Winnipegosis Formation upon discovery of a larger stratigraphic trap updip of the Dawson Bay pool. To date, 18 wells have been completed as Winnipegosis oil and gas producers, defining primary recoverable reserves of about 6.5 MMbo equivalent. Most recently, the completion of Dallas Hamlet Unit #3 in NWSWsec 30, T159N, R95W has further extended production in the Winnipegosis reservoir, exemplifying the irregular, lobate nature of the updip porosity pinchout (fig. 4). The Temple reservoir trends roughly northwest-southeast along the platform margin, ranging in width from approximately one mile up to three miles in the vicinity of Temple Field. Net pay thickness of 8% porosity averages about 15 feet and ranges up to 40 feet (figs. 4, 5).

Reservoir cross sections illustrate the development of the Temple reservoir beneath reef facies which ranges between 20 and 80 feet thick (fig. 5). Only locally do the basal few feet of the reef serve as suitable reservoir. Most commonly, the reef remains as limestone and may contain appreciable halite cement in its upper half. Such halite cementation accounts for anomalous FDC-CNL log cross over characteristic of most reef sections in the field area (fig. 5). Halite cementation also occurs in facies which overlie reef sections in direct contact with the Prairie Evaporite. The upper portion of the Winnipegosis covering large areas of Divide County to the northwest of Temple Field is also characterized by partial to complete halite plugging, resulting in the degradation and destruction of earlier, well-developed reservoirs in the formation. Reservoir facies underlying reefs are apparently less susceptible to halite plugging; however, poor drill stem test recoveries suggest that halite cement may have partially plugged portions of the platform margin reservoir immediately southeast of Temple Field.

Facies Model

Facies sequences illustrated in cores from the Temple Field area and supplemented by cores from other parts of the platform margin allow for reconstruction of the Temple Field platform margin as a generalized model (fig. 6). Prior to platform/basin decoupling, the outer ramp region including the Temple Field area was most likely characterized by marine shelf facies with isolated stromatoporoid-coral banks. Transformation from ramp-style to platform/basin deposition can be intrepreted to have occurred just prior to the time represented by the T3 marker (fig. 6). Subsequent to this transformation, the platform margin evolved a distinct set of facies dominated by slope deposits, less commonly by reefs, and eventually

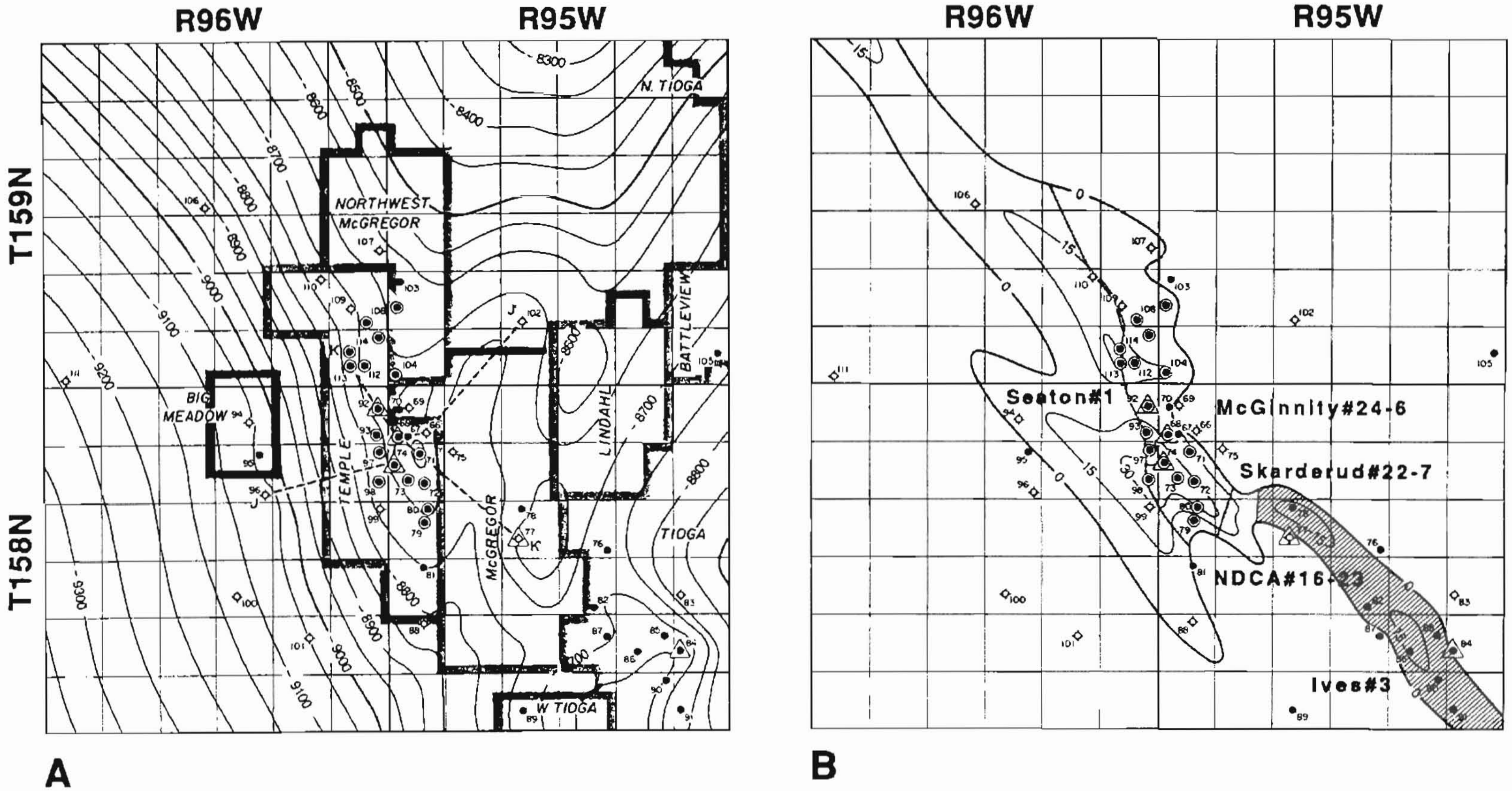

Fig. 4 - Temple Field area, northeastern Williams County. (A) General structural relationships of the Winnipegosis Formation on the western flank of the Nesson anticline. Distribution of Winnipegosis producing wells (circled) illustrate nature of combined structural-stratigraphic trap in Temple Field. Contour Interval= 50 feet. (B) Winnipegosis porosity isopach (≥8%, contour interval= 15 feet). Shading denotes oil charged reservoir; diagonal ruling indicates partly (?) salt-plugged reservoir. Triangles denote cored wells.

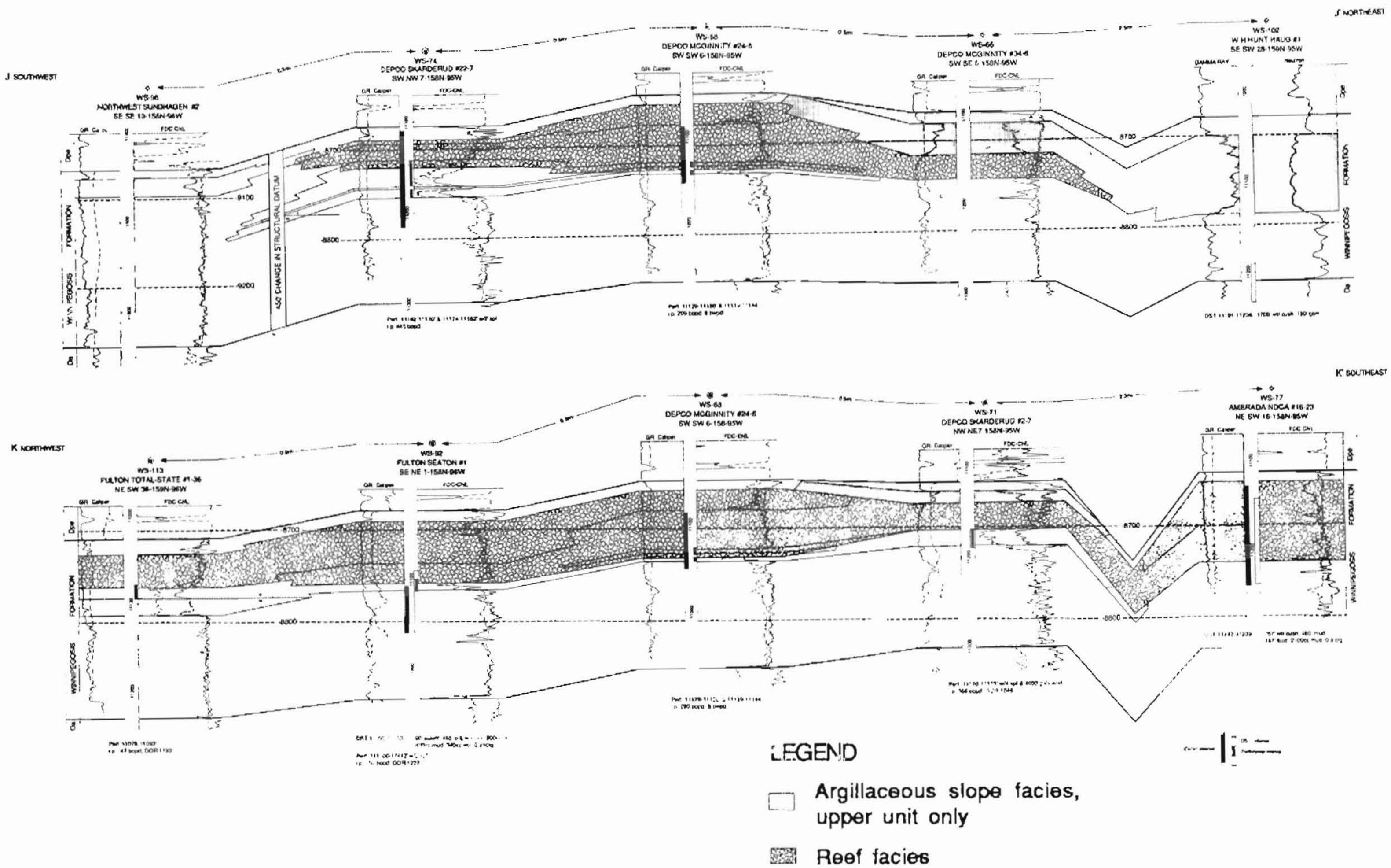

Fig. 5 - Temple Field structural cross sections J-J' and K-K' (refer to Fig. 4A). Depositional dip section J-J' illustrates stratigraphic relationships of reef and underlying slope reservoir facies. Depositional strike section K-K' illustrates variable reef development along the platform margin. FDC-CNL log cross over in upper portion of most wells indicates salt plugged carbonate. O/W denotes original oil/water contact in the reservoir.

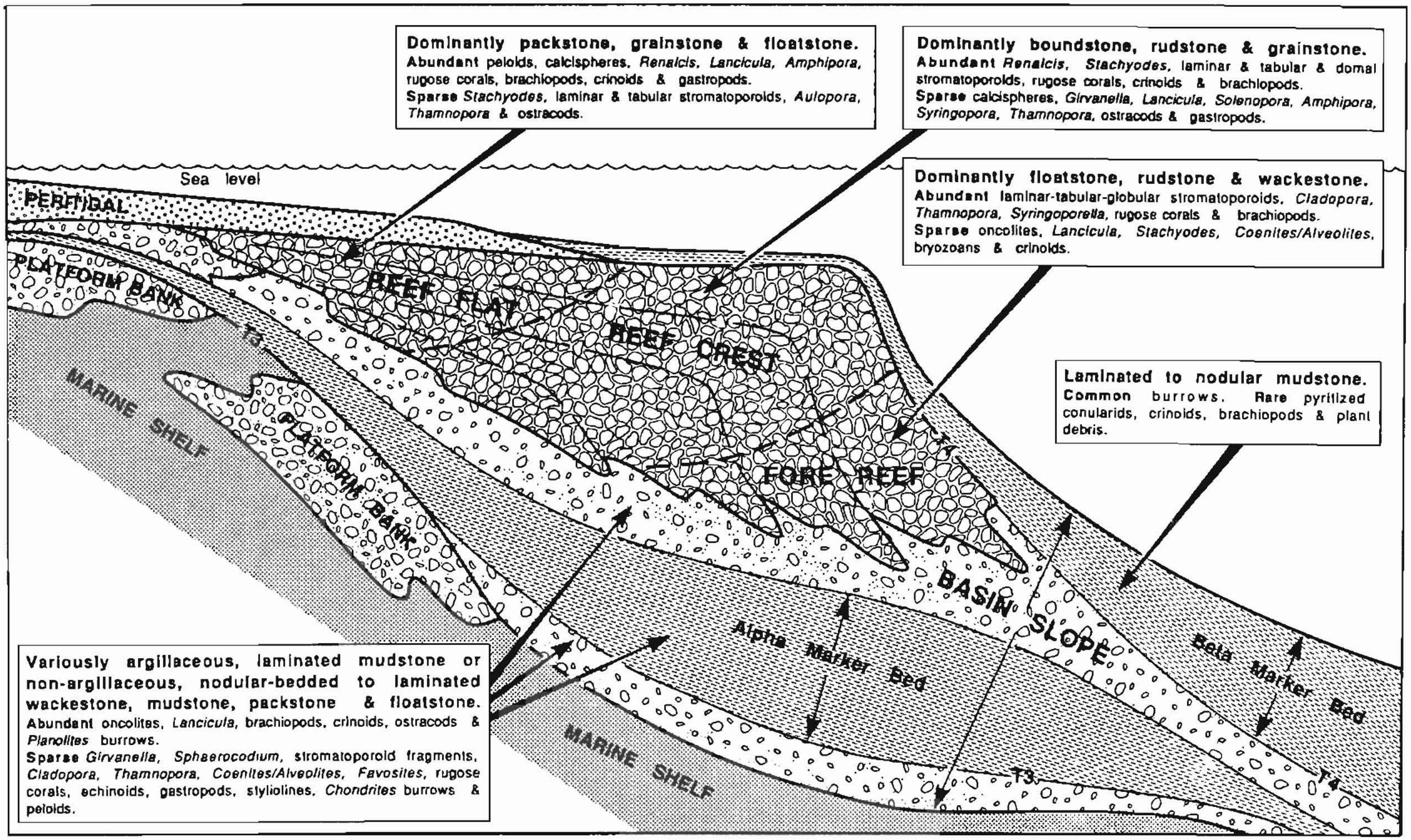

Fig. 6 - Facies model for the platform margin in the Temple Field area. Depositional textures and fossil components are summarized for each facies. Marker beds T3 and T4 represent approximated time-stratigraphic marker beds in the platform margin sequence. The point in time depicted by the model is just prior to evaporative drawdown.

overstepped by peritidal facies under progressive shoaling conditions. These facies are summarized below, with characteristic textures, faunal and floral constituents illustrated in figures 8-10. The cored interval in Depco Skarderud #22-7 is provided as an example of the platform margin facies sequence characteristic of Temple Field (fig. 7). Additional examples are drawn from other cored wells in the field area, in particular from Depco McGinnity #24-6 (fig. 4B).

Basin Slope Facies

Strata comprising the basin slope facies had been deposited as thick sediment wedges just beyond western platform margin. As the western platform prograded basinward, earlier-formed basin slopes were incorporated within it. Perhaps the most conspicuous feature of the Temple Field area is the development of a series of carbonate wedges having an appreciable clay content which had prograded eastward into the deeper basin environment. These units vary in lithology from relatively clean to argillaceous carbonates, the latter representing the mappable units frequently referred to by operators as "Winnipegosis shales" for their distinct gamma-ray log expression. The stratigraphically lower argillaceous unit, referred to herein as the "Alpha marker," is fairly well developed in the middle portion of the formation in Temple Field (figs. 3, 5, 6). It loses its gamma-ray character as it drops in stratigraphic position downslope to the east. The upper argillaceous unit, or "Beta marker," is very well developed at Temple, and reaches a thickness of about 80 feet just east of the field. The Beta marker unit is recognizable as a thin, relatively persistent marker bed on the platform to the west.

Brachiopods, crinoids, oncolites, and burrows (predominantly Planolites) are major fossil components of the Alpha marker unit. Lesser components, in order of decreasing abundance, are: ostracods, gastropods, echinoids, styliolines, fenestrate bryozoans, sponge spicules, the codiacean alga Lancicula, Thamnopora, Cladopora, Coenites/Alveolites, Girvanella, laminar stromatoporoids, Ca-phosphate bone, Syringopora, trilobites, calcispheres, Sphaerocodium, foraminifera, intraclasts, and algal peloids. Perhaps the most significant feature of the unit is its bitumen content. Although present total organic carbon content measures only a few percent, original organic content may have been sufficient to make the Alpha unit a potential oil source within the formation. On the contrary, the Beta argillaceous marker unit is largely non-bituminous and contains a remarkably different fossil assemblage than the Alpha unit. Most significant is the presence of sparse carbonized vascular plant debris, rare conularid medusae, Ca-phosphate bone or conodonts, the brachiopod Lingula and minute, pyritized gastropods. These strata display rare scour features and depositional dips ranging from 15 to 40 degrees.

Basin slope facies consist of mudstone with sparse wackestone and packstone (figs. 8B-D). Oncolite floatstone to rudstone is a common component, and represents the most distinguishing feature of the basin slope (fig. 9C). Non-argillaceous basin slope facies underlying and overlying the "Alpha marker" unit carries much the same fauna and flora, although in somewhat greater profusion and with a higher proportion of calcispheres, Lancicula, laminar stromatoporoids, Thamnopora, Cladopora, and algal peloids. These strata also contain sparse Amphipora, Stachyodes, tabular and globular stromatoporoids, Aulopora, Favosites, solitary and branching rugose corals, fistuliporid bryozoans, bivalves, and Tentaculites. Apparently the non-argillaceous slope facies contains a thoroughly mixed endemic and trans-

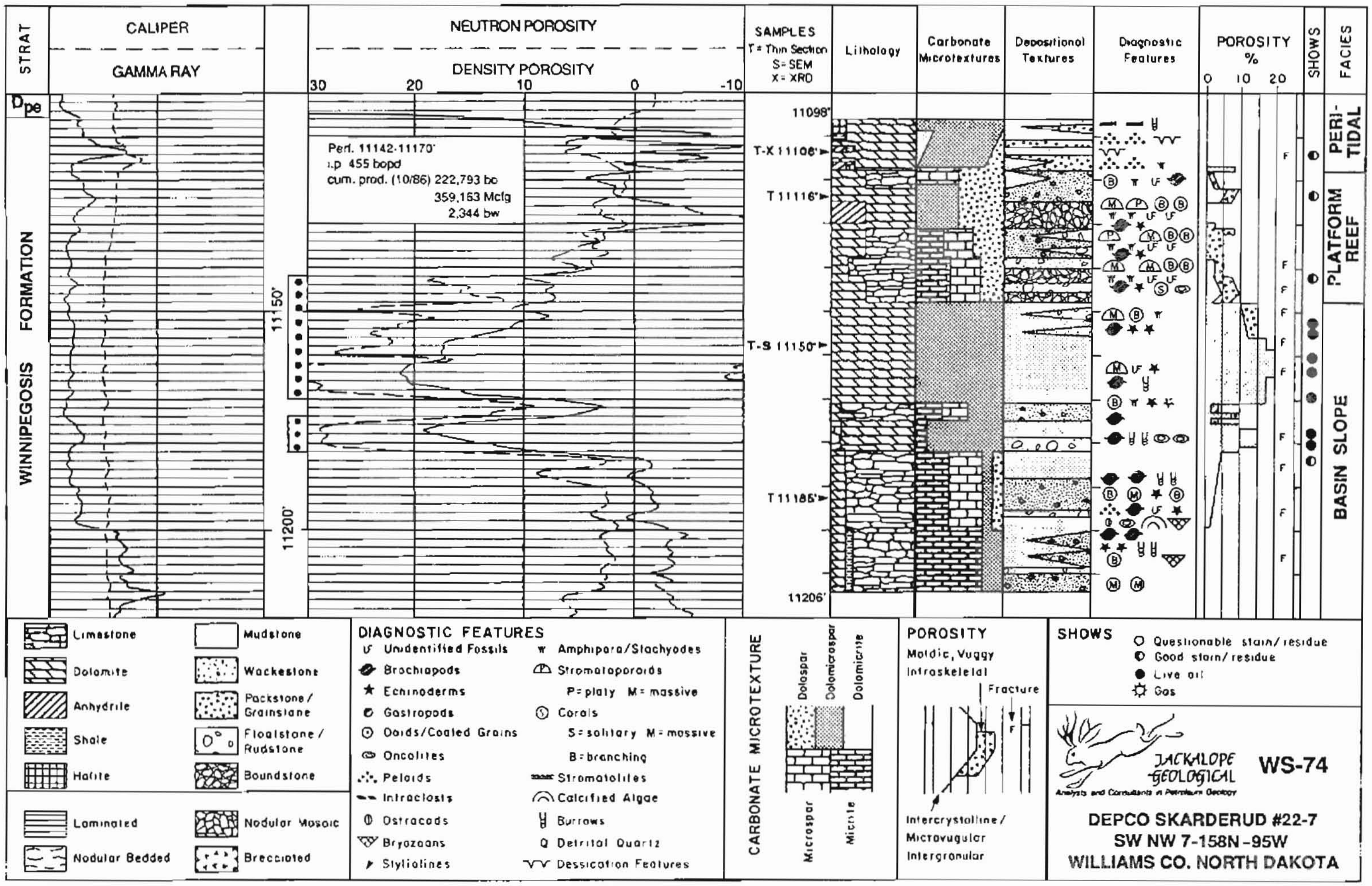

Fig. 7 - Log characteristics and core graphic column for Depco Skarderud #22-7, Temple Field.

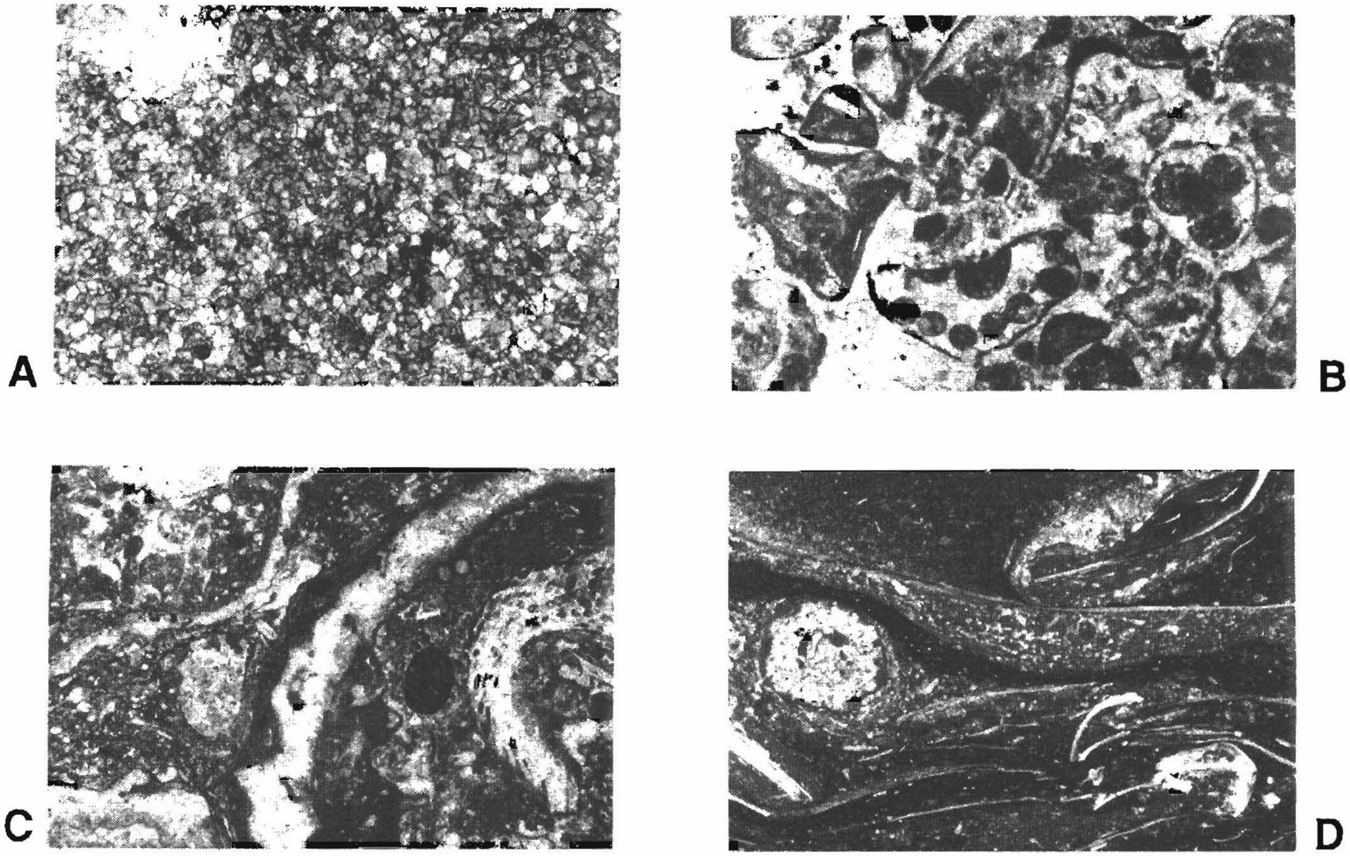

Fig. 8 - Thin section photomicrographs. Temple Field area.

(A) Slope facies. Dolomite; mudstone. Porous dolomicrospar matrix with rare, isoloated masses of anhydrite cement (upper left). Intercrystalline porosity totals 12%. Temple Field pay. Depco Skarderud #22-7; 11,150'. PPL, photo width represents approximately 1.5 mm.

(B) Slope facies. Limestone; algae-peloid grainstone. Equant calcite cements highly abraded fragments of the codiacean alga Lancicula along with other skeletal fragments. Depco McGinnity #24-6; 11,140'. PPL, photo width represents approximately 4 mm.

(C) Slope facies. Limestone; oncolite floatstone within brachiopod wackestone matrix. A large mass of skeletal debris (right) with oncolitic coating within a matrix of fine skeletal debris (left). Fulton Seaton #1; 11,132'. PPL, photo width represents approximately 8 mm.

(D) Slope facies. Dolomitic limestone; brachiopod-algae wackestone. Common thin-shelled brachiopods and less abundant codiacean algae (eg. left), some with thick oncolitic coatings, within a dense micrite matrix devoid of porosity. Amerada Ives #3; 11,190'. XN, photo width represents approximately 8 mm.

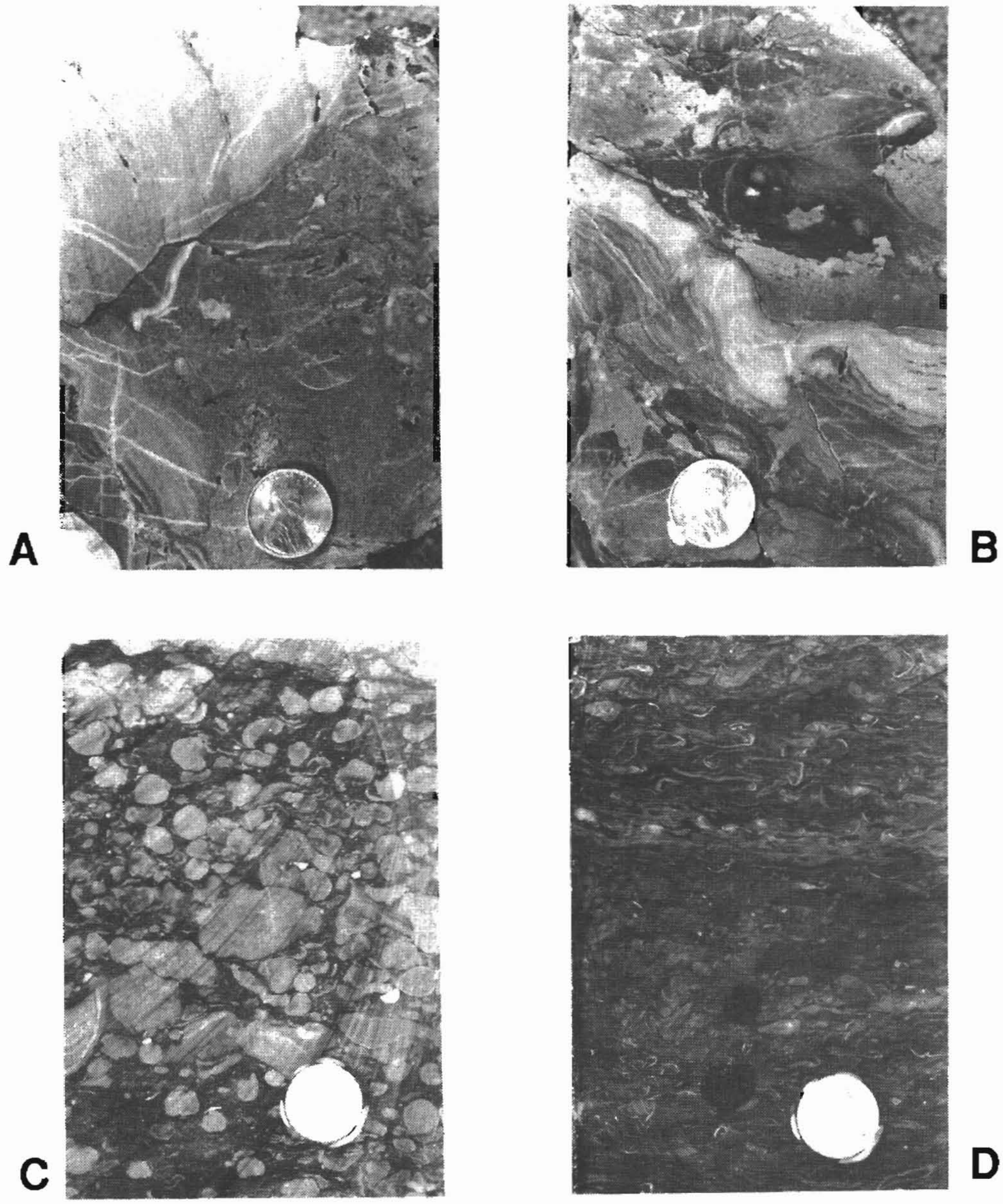

Fig. 9 - Core surface photographs. Temple Field area.

(A) Platform Margin Reef Facies. Dolomitic limestone; stromatoporoid floatstone. Displaced tabular and domal stromatoporoids within partially dolomitized matrix of skeletal wackestone. Small vugs account for about 2% porosity. Depco McGinnity #24-6; core depth 11,105'.

(B) Platform Margin Reef Facies. Calcitic dolomite; stromatoporoid boundstone. Laminar and tabular stromatoporoids bind matrix of coral-skeletal wackestone. Depco McGinnity #24-6; core depth 11,119'.

(C) Slope Facies. Slightly argillaceous and bituminous limestone; oncolite floatstone. Common oncolites and abraded fragments of the codiacean alga Lancicula within microspar matrix. Fulton Seaton #1; core depth 11,132'.

(D) Slope Facies. Dolomitic limestone; brachiopod wackestone and packstone. Abundant deformed brachiopods forming thin packstone beds. Amerada Ives #3; core depth 11,183'.

ported fossil assemblage. Presumed endemic components include unabraded brachiopods and crinoids, oncolites, Planolites and Chondrites burrows, a portion of the coral and bryozoan assemblage present in platform margin reef facies, and a variety of finer skeletal constituents present in most other platform margin facies. The remaining components, which are highly abraded and mud coated, are believed to have been transported downslope from platform reef flats and reef crests or from platform banks. These include nearly all of the algal peloids, Lancicula, stromatoporoids, rugose corals and calcispheres, and some of the corals Thamnopora and Cladopora. Rhythmic packstone and floatstone observed in some core sequences are interpreted as downslope debris flows or small-scale turbidites of reef-derived material (fig. 9D).

Basin slope deposits constitute significant basinward progradation of the western platform margin. Because deposition took place over a wide gradient during probable episodes of marked basin subsidence, a broad range of hydrographic conditions must have existed. Environmental variation is reflected in the broad scope of depositional textures and the mixed fossil assemblages. Near to the platform margin, water depths may have been as little as 30 feet. Wave energy and current velocities were sufficient to cause erosion and displacement of skeletal debris from reef and bank surfaces and, at the base of reefs, to stimulate the development of oncolites. At the distal or basinward extremity of this environment where water depths may have exceeded 200 feet, current velocities must have been exceedingly low. This is substantiated by the microlaminated fabric of mudstones, the generally unabraded condition of endemic articulated thin-shelled brachiopods and crinoids, and by the clustered rather than random distribution of sponge spicules.

Alpha and Beta argillaceous marker beds represent the interaction of extrinsic events with prevailing platform conditions. Both marker beds are partly the product of erosion of unlithified coastal mud flats in the platform interior, apparently triggered by (1) a slight lowering of sea level, at least within the Elk Point basin, or (2) by subtle uplift of all or portions of the coastal arc of mud flats. Whatever the mechanism, the result was the net transport of fine terriginous mud and minor detrital quartz across the platform and over the platform margin. This material was redeposited with carbonate mud as part of the basin slope facies. The bituminous character of the Alpha argillaceous marker, together with the conspicuous presence of presumably planktonic styliolines and conodonts, suggest that surface waters just beyond the platform margin had been rich in phytoplankton. The exceptional fauna and flora of the Beta argillaceous marker suggest dysaerobic bottom waters and significant subaerial exposure of major portions of the platforms.

Platform Margin Reef Facies

Platform margin reefs overlie either marine shelf or basin slope facies, and are clearly gradational in character with the proximal basin slope. Reef intervals most commonly consist of limestone or dolomitic limestone, and only rarely do reef facies grade to dolomite in their upper and lower parts although adjacent to thoroughly dolomitized peritidal and slope facies (fig. 7). Depositional textures are dominantly boundstone, rudstone, and floatstone, interbedded by wackestone, packstone, and grainstone. Mudstone intervals appear only near the base of reefs. The platform reef facies is characterized by an abundant and diverse assemblage of stromatoporoids, corals, and algae, including many forms and genera that are rare in other platform and marine shelf facies. Because of the several cores which have penetrated this facies, it has been possibie to distinguish three different platform reef subfacies: (1) reef flat, (2) reef crest, and (3) fore reef (fig. 6).

The reef flat subfacies consists of packstone, grainstone, and floatstone textures. Dominant constituents are algal peloids, calcispheres, Renalcis, Lancicula, Amphipora, solitary and branching rugose corals, crinoids, brachiopods, and gastropods. Less common skeletals include Stachyodes, laminar and tabular stromatoporoids, Aulopora, Thamnopora, ostracods, intraclasts, and mud-coated and bored skeletal fragments. Other forms of algae and stromatoporoids are rare, as are fenestrate bryozoans, echinoids, bivalves, and trilobites. Skeletal debris and peloids comprising packstone and grainstone exhibit a high degree of fragmentation and abrasion.

Depositional textures in the reef crest subfacies are predominantly boundstone, rudstone, and floatstone with interbedded packstone and grainstone (figs. 9B, 8B-C). The fossil assemblage is characterized by abundant Renalcis, Stachyodes, laminar stromatoporoids, tabular stromatoporoids, domal stromatoporoids, Syringoporella, solitary and branching rugose corals, crinoids, and brachiopods. Less common components include calcispheres, Girvanella, Lancicula, Amphipora, Syringopora, Thamnopora, gastropods, and ostracods. Fistuliporid bryozoans, large bivalves, serpulids, and trilobites are relatively rare. Algal peloids are also rare, but mud-coated and bored skeletals are fairly well represented.

The deeper fore reef portions of platform margin reefs are especially characterized by a diverse assemblage of corals. Floatstone, rudstone, wackestone, and sparse mudstone textures are dominated by laminar, tabular, and globular stromatoporoids, Syringoporella, Cladopora, Thamnopora, solitary and branching rugose corals, Coenites/Alveolites, and brachiopods (figs. 9A-B). Less common constituents include Stachyodes, Syringopora, Favosites, Michelinia, Hexagonaria, crinoids, and fenestrate, fistuliporid, and ramose bryozoans. Stromatolitic oncolites, Girvanella, and Lancicula segments are also well represented. Echinoids, gastropods, large bivalves, and ostracods are relatively rare. Rare Amphipora fragments are invariably abraded or mud coated. Many corals and stromatoporoids are in situ, but large, tumbled, or overturned colonies exhibiting broken but unabraded surfaces have also been observed (fig. 9A).

Platform reefs evidently had developed in well circulated marine waters of normal salinity, in physiographic settings that had insured relatively strong wave action and current flow. Certain fabrics and textures provide evidence of the structural integrity of platform margin reefs. These include: a prevalence of in situ or growth positions among stromatoporoids and corals; skeletal encrustation (especially by Renalcis, Girvanella, and laminar stromatoporoids, resulting in boundstones); the presence of large shelter or growth cavities; inclined depositional surfaces with apparent dips from 35 degrees to nearly vertical; brecciated fabric and large, sediment-filled fractures apparently caused by post-depositional slumping; and the presence of well developed drusy cements. These features, together with the relative lack of dolomitization, indicate that these reefs had been lithified early in the diagenetic sequence and had the capacity to maintain topographic relief and slopes under conditions of relatively high wave climate. Actively accreting fore reef subfacies of established reefs and perhaps reefs at their early stage of development probably occupied water depths ranging from 30 feet to 90 feet or more. Reef crest and back reef subfacies probably accomplished their final accretion in water depths less than 30 feet. Back reef subfacies were eventually overstepped by peritidal peloid and ooid shoals. Platform margin reef tracts were approximately 0.5 to 3 miles wide, with maximum reef thickness reaching approximately 100 feet. Reef width and height are decidedly a function of vertical accretion and basinward progradation (fig. 6).

Peritidal Facies

Peritidal sediments constitute final Winnipegosis deposition over the platform margin as well as over the upper portion of the basin slope (fig. 6). This facies forms the upper 10-25 feet of the formation on the western platform margin, and thickens westward into the platform interior where it represents a major part of the formation. In the producing trend of northeastern Montana, peritidal facies incorporate bedded anhydrite which serves as a seal for underlying platform bank reservoirs.

Anhydritic and halitic dolomite and limestone comprising this facies consist of two dissimilar but often interbedded depositional textures: (1) finely laminated, occasionally stromatolitic mudstone and (2) peloid or ooid packstone and grainstone (fig. 10A). Laminated mudstone textures are composed of dolomicrite, micrite, and dolomicrospar. These strata contain numerous laminae and lenses of felted anhydrite. Soft-sediment deformation, fenestrae, mudcracks, and brecciation are common features. Stromatolites are dominantly planar and commonly incorporate laminae of algal peloids or intraclasts, or display undulating or disrupted fabric. Packstone and grainstone are present as laminae or thin beds within mudstone, or as thick, fining-upwards units of algal peloids and ooids. Peloids and ooids are associated with larger intraclasts, composite grains, pisolites, and rare oncolites. Peloid and ooid grainstone is commonly current bedded and may exhibit scoured surfaces and low-angle crossbedding. Planar stromatolites, *Renalcis*, ostracods, calcispheres, rare gastropods, bivalves, and *Chondrites* burrows constitute the endemic fossil assemblage. Other skeletal taxa, including rare *Amphipora*, laminar stromatoporoids, brachiopods, and crinoids, probably represent debris transported from adjacent banks or reefs.

The peritidal facies encompasses a complex of related shallow subtidal, intertidal, and supratidal depositional environments. Principal among these were: (1) vast intertidal mud flats exposed on a daily basis or for more prolonged periods, and colonized by algal stromatolites; (2) shallow, ephemeral lagoons subjected to high temperatures, high salinities, periodic stagnation, evaporation, and exposure; and (3) intertidal peloid-ooid shoals and foreshore bars which were subjected to moderately strong waves or currents. Additionally, all of these subenvironments had been subjected to supratidal exposure and prolonged residence in the vadose zone, as indicated by the prevalence of brecciation, fenestral fabric, extensive leaching, and, in northeastern Montana, their intimate association with facies assigned to sabkha environments.

Diagenesis and Ø-k Relationships

To a large extent, reservoir potential in the Winnipegosis Formation is a measure of the development and retention of secondary porosity and permeability. Except in reef facies, preserved primary porosity is exceedingly rare and contributed little to existing reservoirs. Nearly all reservoir-quality porosity on the western platform and along the platform margin occurs in dolomite or calcitic dolomite. Limestone intervals in other

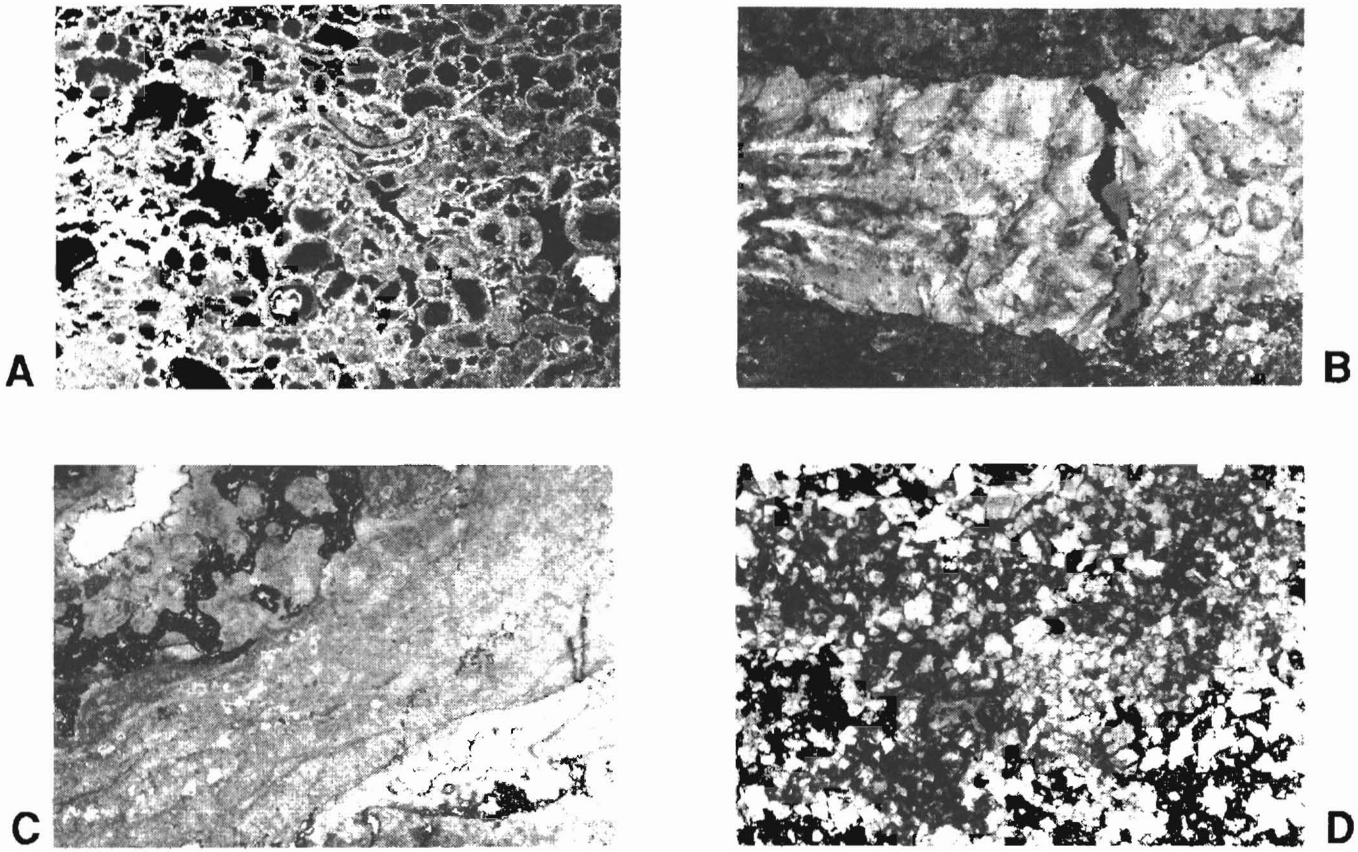

Fig. 10 - Thin section photomicrographs, Temple Field area.

(A) Peritidal Facies. Very halitic dolomite; ooid-skeletal grainstone. Halite cement (black) fills molds of common ooids and peloids. Depco Skarderud #22-7; 11,106'. XN, photo width represents approximately 8 mm.

(B) Platform Margin Reef Facies. Dolomitic limestone; stromatoporoid-coral floatstone/boundstone. Fragment of the coral Cladopora in fine skeletal wackestone matrix. Depco McGinnity #24-6; 11,110. PPL, photo width represents approximately 8 mm.

(C) Platform Margin Reef Facies. Limestone; stromatoporoid-coral boundstone. Stromatoporoid fragment with oil residue in intraskeletal pores. Depco McGinnity #24-6; 11,125'. XN, photo width represents approximately 4 mm.

(D) Slope Facies. Dolomite; mudstone. Dolomicrospar matrix bearing 14% oil stained, fine intercrystalline/microvugular porosity. Temple Field pay zone. Depco McGinnity #24-6; 11,131'. PPL, photo width represents approximately 4 mm.

facies are either devoid of porosity or possess only traces up to a few percent. Matrix porosity and fractures are rare in the Alpha and Beta argillaceous marker units. The non-argillaceous basin slope reservoir is largely composed of dolomicrospar mudstone with rare fine dolospar (figs. 10D, 8A). Intercrystalline/microvugular porosity is the dominant pore type, with pore diameters measuring 0.01-0.3 mm. Other forms of porosity such as molds and vugs are relatively rare in the reservoir facies. Fractures are relatively common, and certainly contribute to overall reservoir permeability in Temple Field.

As a result of sea level drawdown, the Temple Field reservoir was fully developed soon after the culmination of Winnipegosis deposition while the western platform was exposed and elevated above the hypersaline Elk Point sea. Except for structural reversal and the implacement of oil, this reservoir had undergone little change since its creation. Sandwiched between relatively impermeable strata represented by underlying argillaceous slope facies and overlying reef facies, non-argillaceous slope facies were leached and dolomitized in a mixing zone created by downward and seaward movement of meteoric water into connate marine water. The lateral extent of dolomitization was undoubtedly a measure of the significant hydraulic head generated by an estimated 140 feet of sea level drop. The effects of subsequent deep-burial diagenesis are seen in the development of near-vertical fractures and reduction of average porosity from about 25 percent to 15 percent, largely by pressure solution compaction and minor anhydrite cementation.

Early lithification and dolomitization of some peritidal facies could have taken place by episodic wetting or constant immersion in highly saline water or Ca-depleted, Mg-enriched brine. Of greatest importance is the significant reduction of vertical permeability by penecontemporaneous lithification of individual laminae or layers. Appreciable vertical fluid passage could be maintained only by fractures, most of which were eventually cemented. Where lacking impermeable seals, porous peritidal facies overlying platform reefs were significantly invaded by Prairie brine, with resultant halite precipitation destroying most reservoir potential.

Perhaps the most important diagenetic process related to development and preservation of the Temple slope reservoir was the early cementation of platform margin reef facies. The initial effect of early permeability reduction in reef facies was to channel dolomitizing fluids into underlying slope facies. Upon transgression of the platform by hypersaline Prairie waters, concentrated brines would have found ready access into porous Winnipegosis dolomites that were not isolated by intervening impervious anhydrite or lithified carbonate. As a result of early lithification, platform margin reefs served to limit brine invasion and halite precipitation in the underlying slope reservoir.

Ø-k plots for western platform representative of the Temple Field area illustrate the relative importance of slope facies as the principal reservoir in this regime (fig. 11). While only 18 percent of all slope facies Ø-k analyses are of reservoir quality (8% Ø and 3 md k), more than 50 percent of those samples in non-argillaceous slope facies fall within the region of reservoir quality. Porosity in these non-argillaceous mudstones averages approximately 15 percent, with core analyses and porosity logs frequently indicating values over 20 percent. Associated permeability most commonly ranges 10-70 md. On the contrary, only 4 percent of reef facies Ø-k analyses are of reservoir quality,

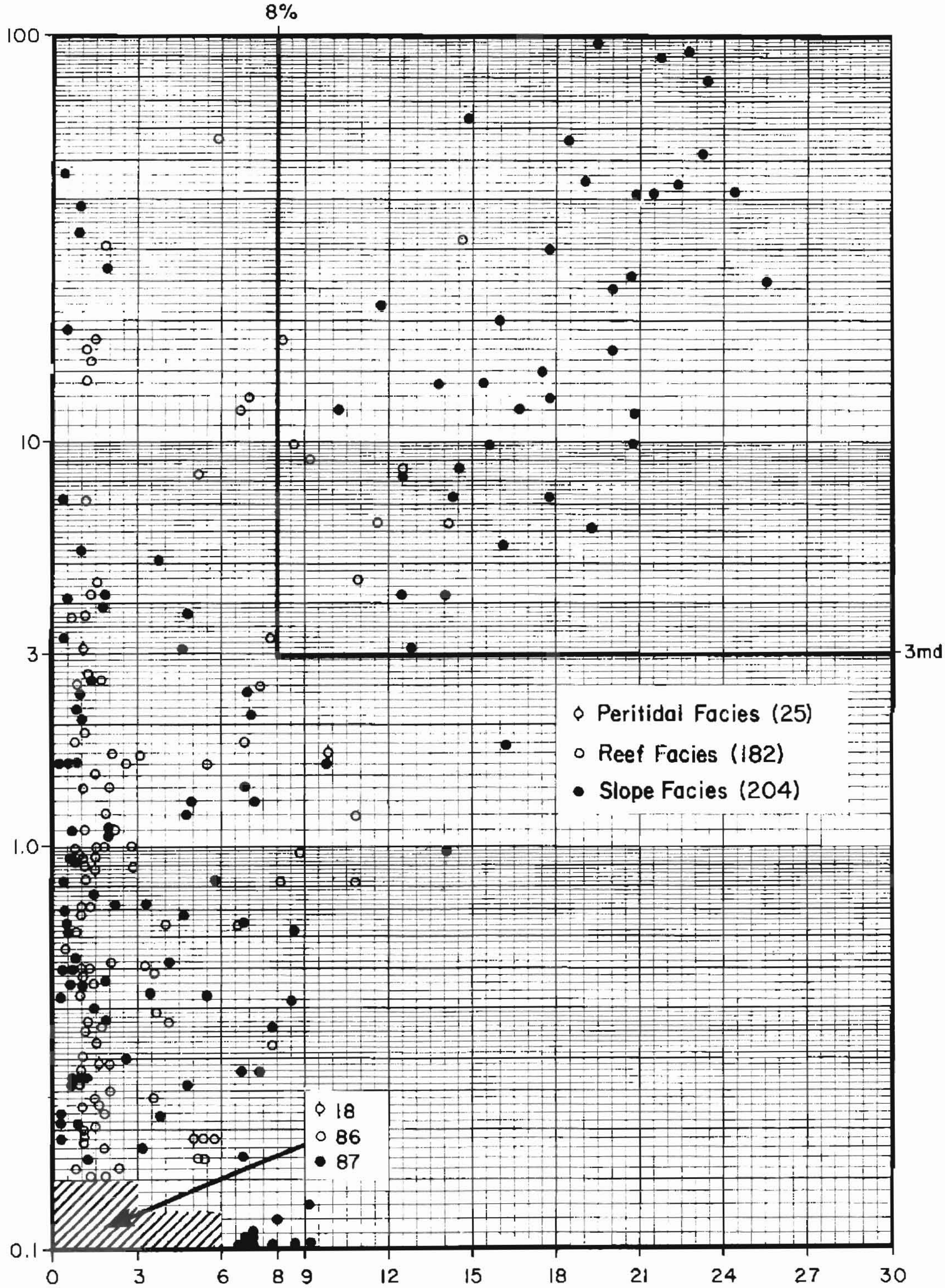

Fig. 11 - Ø-k plots for 411 core analyses from six wells on the Western Platform margin. 8% porosity and 3 md permeability denote approximate lower reservoir limits.

which emphasizes the importance of platform margin reefs as seals for underlying slope reservoirs.

PINNACLE REEFS

The basin regime of the Elk Point shelf in northwestern North Dakota and southeastern Saskatchewan was the site of prolific pinnacle reef development during Winnipegosis deposition. Regionally, these broad, flat-topped, steep-sided pinnacle reefs range approximately 0.3 to 3.0 miles across and 150 to 340 feet thick. They overlie 20 to 30 feet of pre-reef Winnipegosis consisting of burrowed, nodular-bedded mudstone and crinoid-brachiopod wackestone to packstone. The numerous pinnacle reefs encountered in southeastern Saskatchewan (fig. 2) are typically 150 to 200 feet thick, but to the northwest, in the vicinity of Saskatoon, pinnacle reefs range 220 to 340 feet thick. Throughout the region the non-reef Winnipegosis basin sequence ranges 50 to 80 feet thick.

To date, six pinnacle reefs have been penetrated by wells in North Dakota (fig. 2). Marathon Adams #1 (NWSWsec 33, T161N, R82W) and Challenger Alvstad #31-29 (NWNEsec 29, T157N, R88W) pinnacle reefs lie nearest to the margin of the basin and display the least relief, being 225 feet thick. In contrast, Shell Osterberg #22X-1 (SENWsec 2, T161N, R85W) and Shell Golden #34X-34 (SESWSEsec 34, T161N, R87W) pinnacle reefs lie nearest to the basin center and had attained heights of 270 feet and 285 feet, respectively. Shell Creek #41-2 (NENEsec 2, T161N, R83W) and Inexco Erickson #1-18 (SESEsec 18, T157N, R86W) pinnacle reefs are intermediate in height and in location with respect to basin margins. Proportional thicknesses of principal reef facies similarly correspond to distance from basin margins. These systematic variations in reef thickness and relative facies development suggest that vertical reef accretion had been a function of laterally gradational subsidence rates, in which the focus of maximum subsidence was located in central Burke County.

Facies Model

The general model for Winnipegosis pinnacle reefs and adjacent non-reef basin sequence discussed here is based on examination of cores and thin sections from 37 wells within the basin regime of North Dakota and southeastern Saskatchewan. A casual synthesis of North Dakota data suggests a simple model comprised of two successive reef facies (fig. 12). However, this interpretation may be largely the function of the lack of multiple penetrations in a single reef. Information from the more abundant Saskatchewan reefs, in particular from a few which have been penetrated by two or more wells, indicates that either distinctly different types pinnacle reefs exist in the southeastern Saskatchewan basin area, or that facies relationships in North Dakota reefs might be more complex than modeled. For discussion purposes, the Winnipegosis is subdivided into six more or less distinct reef subfacies along with two non-reef basin facies.

The cored interval in the Shell Golden #34X-34 is provided as an example of pinnacle reef facies and reservoir characteristics (figs. 13, 14). The Golden reef represents one of two North Dakota pinnacles which contained free oil, having produced 1,700 barrels over a few months after completion. The other reef, Inexco Erickson #1-18, yielded a small amount of oil during a drill stem test. Reservoirs in both reefs were nearly entirely water charged. Supplemental facies and reservoir examples are provided by the Home et al. North Tableland #8A-22-2-9W2 well (fig. 15), which was com-

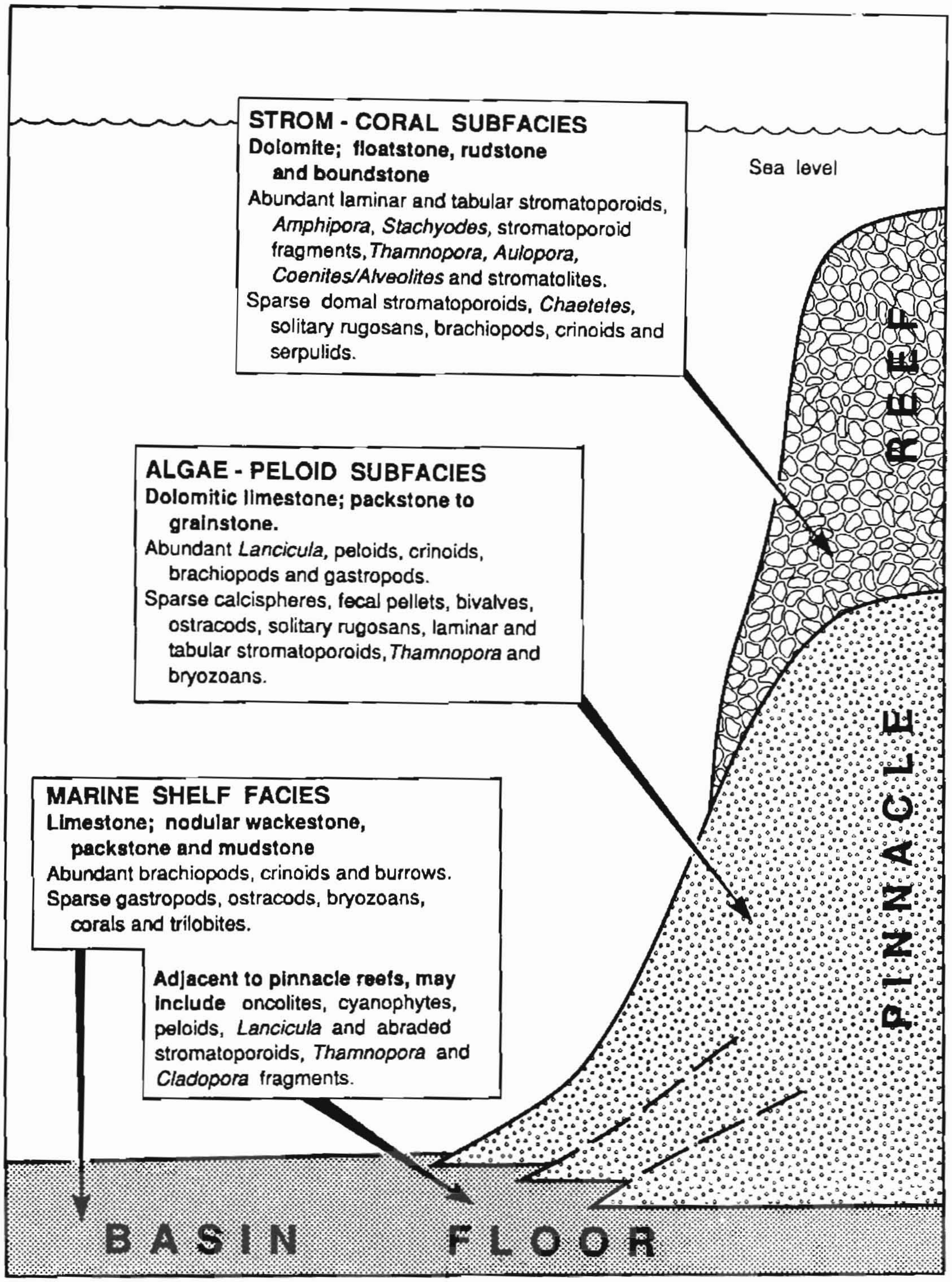

Fig. 12 - Idealized facies model for pinnacle reefs in northwestern North Dakota. Depositional textures and fossil components are summarized for each facies.

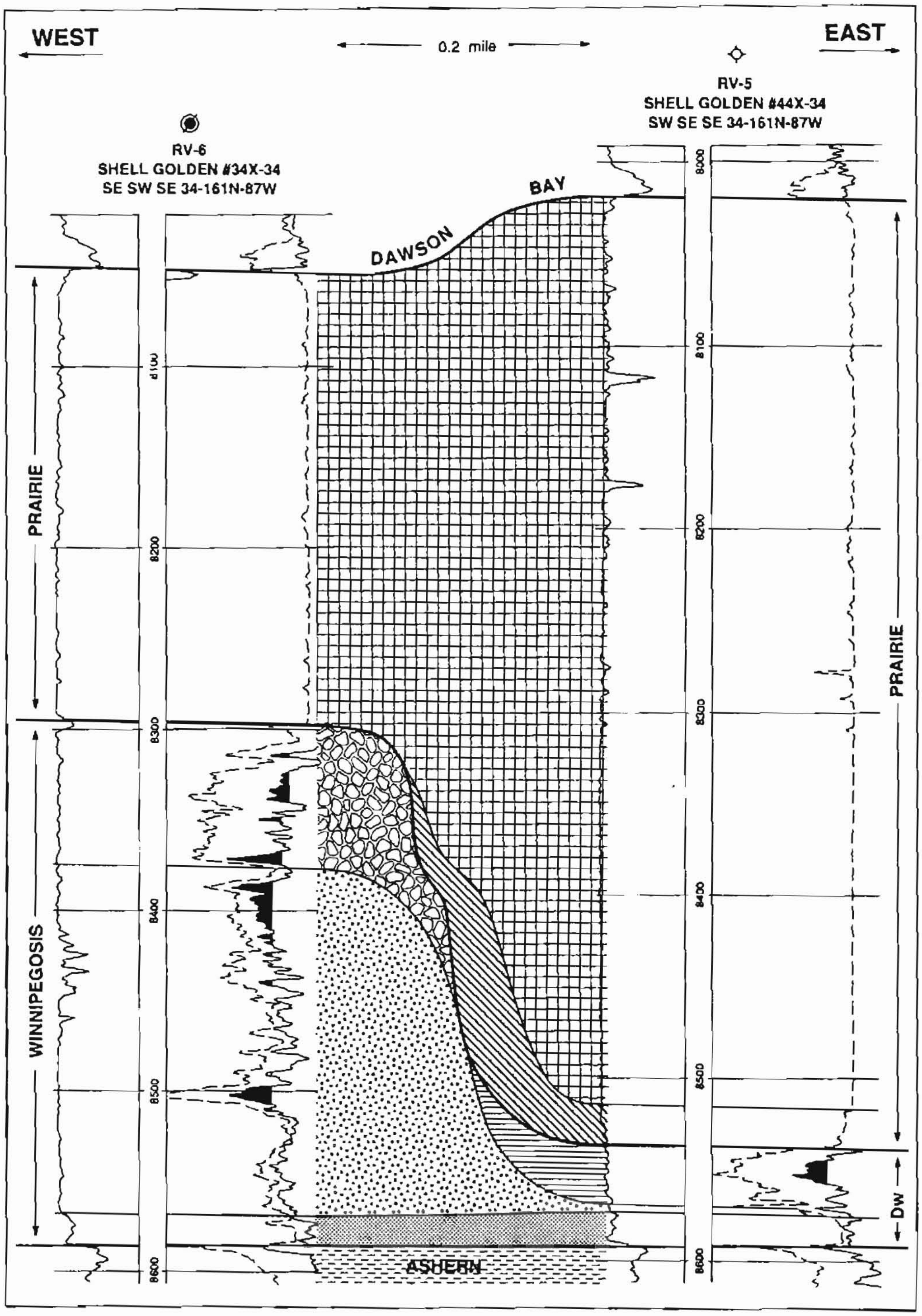

Fig. 13 - Stratigraphic and facies cross section of the Golden pinnacle reef, Renville County. Refer to Fig. 13 for summary of reef facies. Off-reef facies include basin laminite (horizontal ruled), Prairie anhydrite (diagonal ruled) and Prairie halite. Darkened portions of logs indicate ≥ 8% Ø.

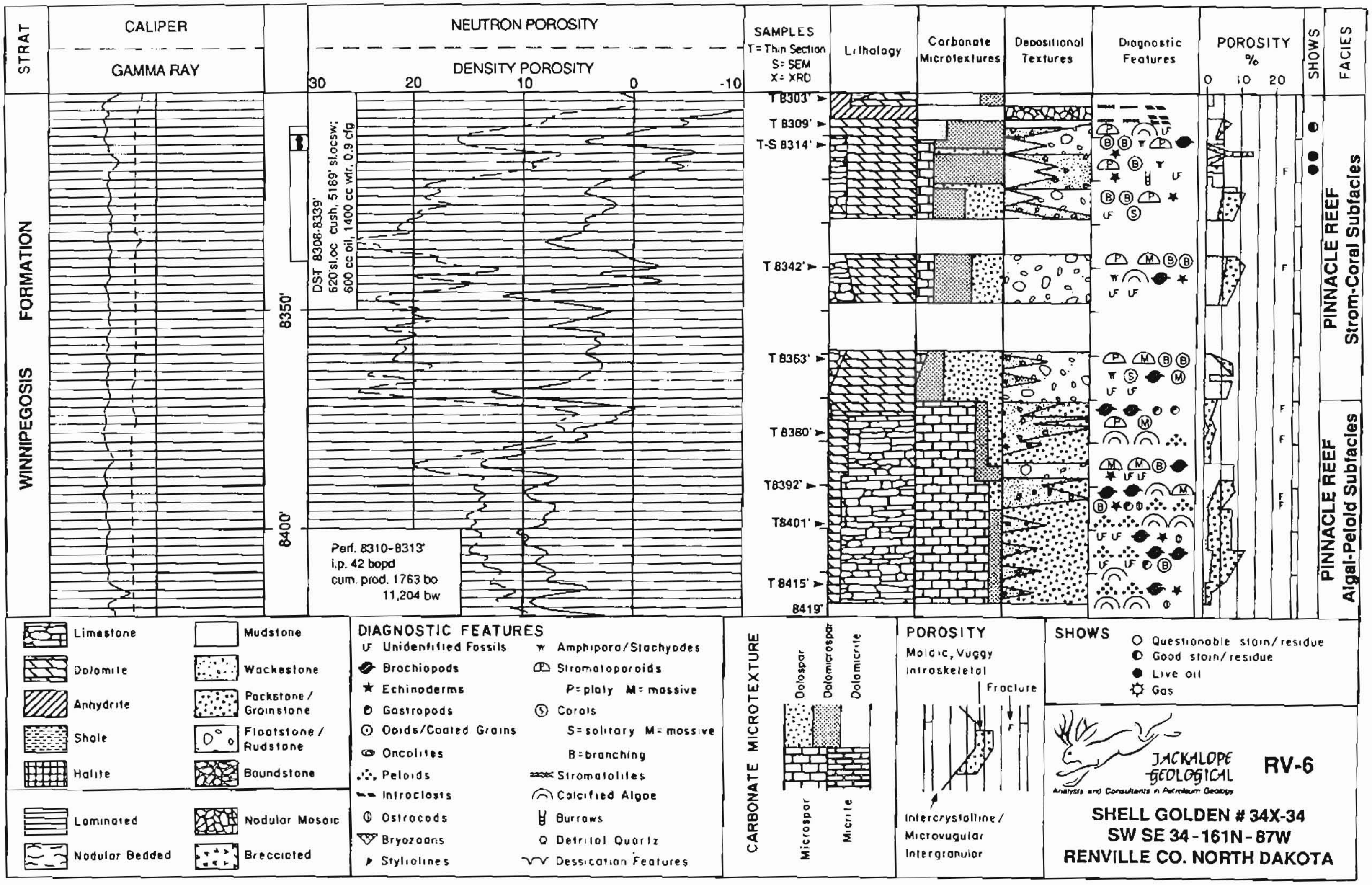

Fig. 14 - Log characteristics and core graphic column for Shell Golden #34X-34 pinnacle reef.

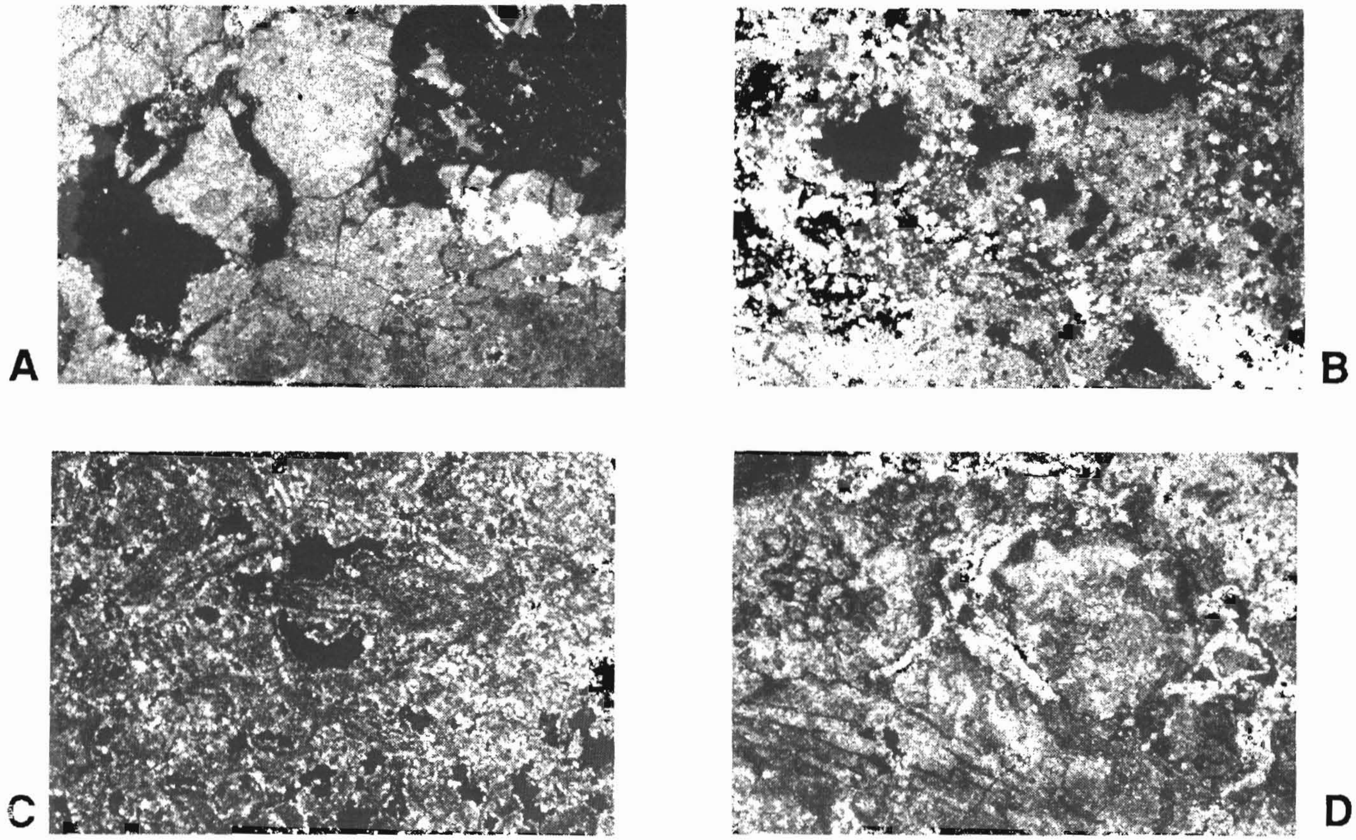

Fig.15 - Thin section photomicrographs, North Tableland pinnacle reef. All photo widths represent approximately 8 mm.

(A) Dolomite; coral-stromatolite floatstone/boundstone. Oil residue fills an irregular vug (left) and intraskeletal pores within a partly leached fragment of the branching coral Thamnopora (upper right). Total porosity is 10%. Sample depth 8448'; PXN.

(C) Dolomite; algae-peloid grainstone. Abundant, highly leached and altered fragments of codiacean algae and peloids. All intergranular pores are lined by drusy cement. Intergranular, moldic and vuggy porosity totals 18%. Sample depth 8528'; PPL.

(B) Dolomite; apparently stromatoporoid-coral floatstone/boundstone, largely obscured by leaching and dolomitization. Stromatoporoid fragment (upper left) and anhydrite-filled bivalve (lower right) within porous matrix. Total porosity is 14%. Sample depth 8474'; PXN.

(D) Dolomite; algae-peloid grainstone to rudstone. Large cross sections (left and center) and a transverse section (lower left) of codiacean algae within dolomicrospar matrix bearing 5% largely unconnected, intergranular porosity. Sample depth 8542'; PPL.

pleted for 1,000 bopd in the upper ten feet of approximately 120 feet of gross pay.

Marine Shelf Facies

This widespread, dominantly limestone facies comprises the Winnipegosis strata beneath pinnacle reefs, the lower half of the Winnipegosis in adjacent non-reef basin sequences, and the lower part of the Winnipegosis within the platform regime. The fossil assemblage distinguishing this nodular-bedded mudstone, wackestone, and packstone facies is dominated by crinoids, brachiopods, and *Chondrites* burrows, but also includes gastropods, ostracods, trilobites, echinoids, *Tentaculites*, and rare corals. The major part of this facies was deposited prior to physiographic differentiation of platform and basin regimes and initiation of pinnacle reefs. The depositional environment is viewed as mud-rich, level-bottom, or gently sloping shelf floors under normal marine salinity and circulation, at water depths ranging from less than 30 feet to several times that following platform/basin decoupling and basin subsidence.

Algae-Peloid Mound Subfacies

The lower, earlier-formed portions of Winnipegosis pinnacle reefs invariably consist of grainstone and packstone, dominated by fragments of codiacean algae and peloids (presumably derived from disaggregation of cyanophyte-bound mud). Crinoids and brachiopods are typically present in the lower part of this facies, but diminish upward. Other, less common constituents include gastropods, bivalves, ostracods, calcispheres, and fecal pellets (figs. 15C-D, 16D, 17C). Sparse platy stromatoporoids or massive stromatolites and few corals are concentrated in rare, thin floatstone to boundstone zones. Despite winnowed depositional textures, steeply inclined or current bedding is sporadic, although drusy cements within grainstone are fairly well developed.

The algae-peloid mound subfacies is thoroughly dolomitized in southeastern Saskatchewan. However, it is preserved as dolomitic limestone in North Dakota where it accounts for the lower 55 to 220 feet of pinnacle reefs, with proportionally greater development increasing toward the basin center. Probably these mounds, as massive precursors to pinnacle reefs, had begun as relatively shallow calcarenite shoals. Upward accretion of the mounds with time and gradual basin subsidence was probably maintained by prolific biogenic carbonate production and a degree of structural integrity provided by syndepositional submarine cementation.

Coral-Stromatoporoid Rim Subfacies

The upper 60 to 160 feet of most North Dakota pinnacle reefs consist of thoroughly dolomitized floatstone, rudstone, and boundstone, dominated by displaced and in situ platy and massive stromatoporoids, *Amphipora*, *Stachyodes*, solitary and fasciculate rugose corals, and the tabulate corals *Thamnopora*, *Aulopora*, *Syringopora*, *Cladopora*, and *Coenites* or *Alveolites* (figs. 15A-B, 16C, 17B). Interstitial matrix consists of skeletal wackestone to grainstone. More complete core data from southeastern Saskatchewan indicate that this facies does not occupy the entire crest of pinnacle reefs as modeled in figure 13. Instead, it is apparently confined to the upper peripheries or rims of pinnacle reefs.

The upward transition from the algae-peloid mound subfacies to the coral-stromatoporoid rim subfacies evidently reflects accelerated basin subsidence that had accompanied the later stage of platform/basin decoupling. Although the coral-stromatoporoid rim subfacies was manifestly formed under conditions of

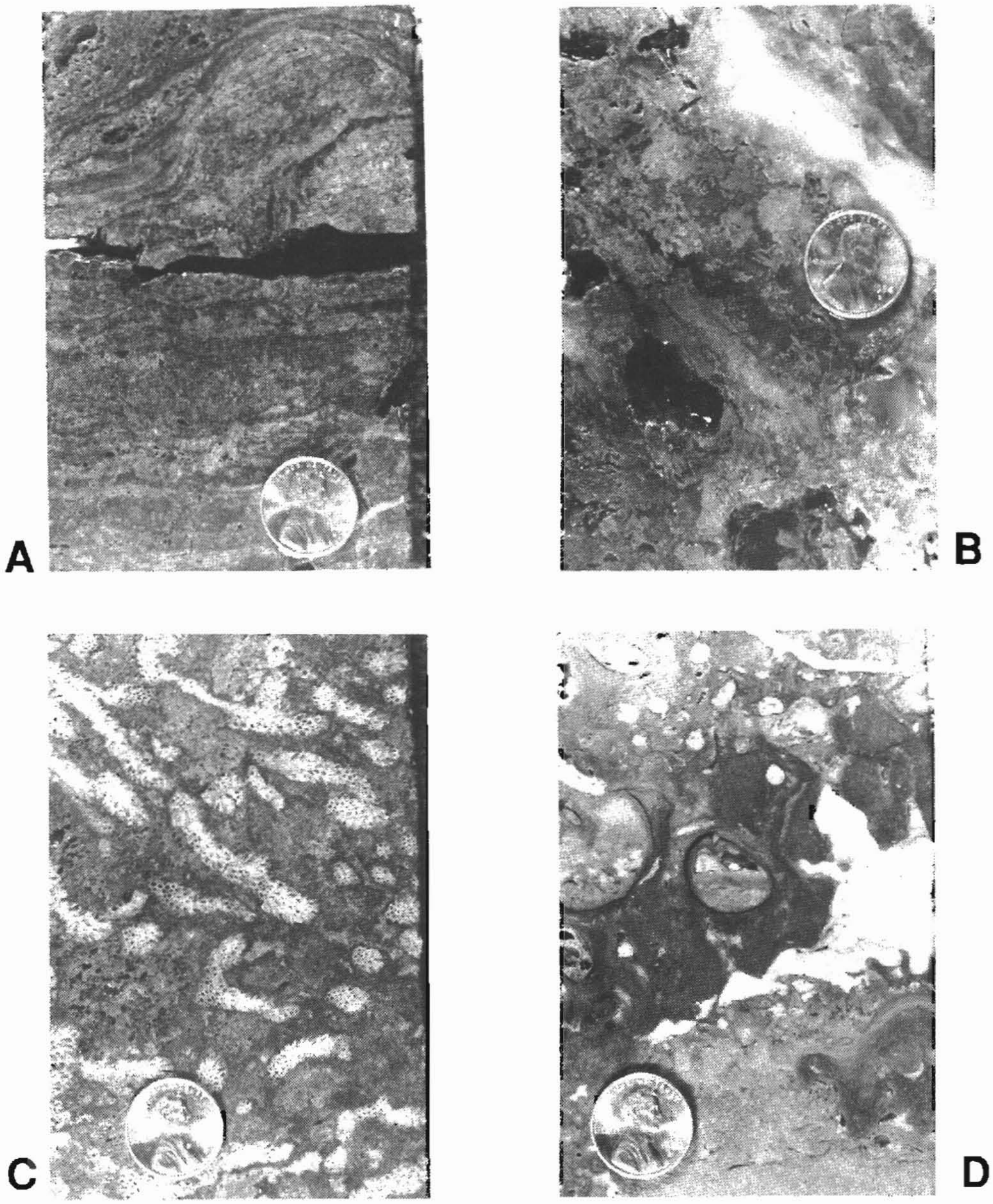

Fig. 16 - Core surface photographs, Golden pinnacle reef.

(A) Dolomite; laminated and stromatolitic mudstone. Deformed stromatolite laminae (top) are interbedded with apparent thin zones of peloid grainstone. Porosity consists of 5% poorly connected molds, shelters and intergranular pores; core depth 8310'.

(B) Anhydritic dolomite; apparently laminated and stromatolitic mudstone. Anhydrite cement fills some of the large, irregular vugs, while others remain open although poorly connected. Golden reef pay zone; core depth 8312'.

(C) Slightly calcitic dolomite; coral floatstone. Essentially unbroken colonies of the branching coral Thamnopora are nearly evenly distributed in a porous dolospar and dolomicrospar matrix; core depth 8325'.

(D) Slighlty dolomitic limestone; skeletal-peloid packstone. Sparse bivalves within a matrix of peloids, codiacean algae fragments and stromatolites. Moldic, fine vuggy and intercrystalline porosity totals 8%; core depth 8415'.

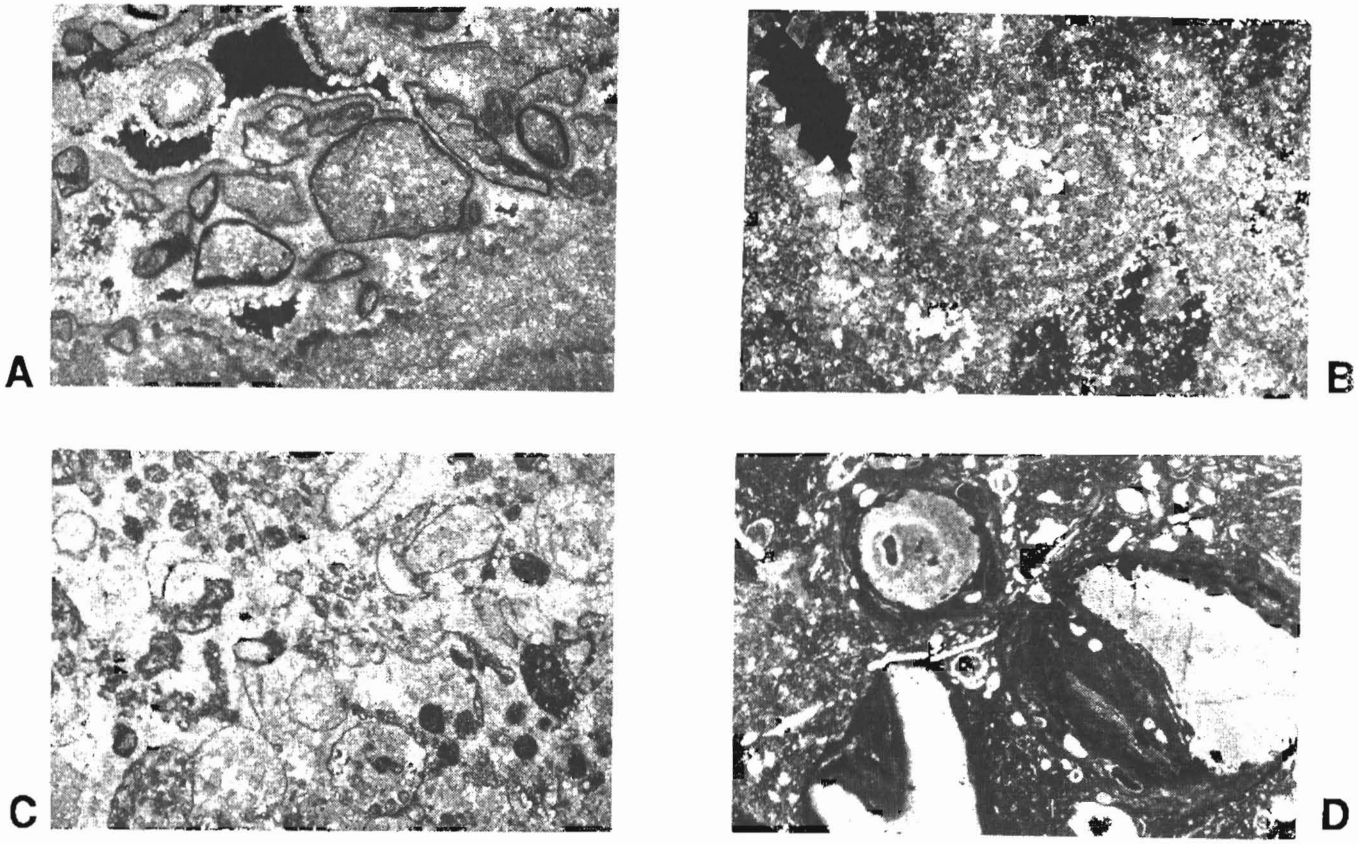

Fig. 17- Thin section photomicrographs, Golden pinnacle reef. All photo widths represent approximately 8 mm.

(A) Dolomite; intraclast grainstone. A thin zone of coated intraclasts and rare ooids (e.g., upper left) within laminated/stromatolitic mudstone and skeletal wackestone. Most intergranular pores are lined by dolomicrospar druse; total porosity is 8%. Sample depth 8309'; PPL.

(B) Dolomite; stromatoporoid floatstone, skeletal wackestone matrix highly is obscured by dolomitization. Altered branching stromatoporoid fragment (center) within mixed dolospar/dolomicrospar matrix. Total porosity is 12%. Sample depth 8363'; PPL.

(C) Dolomitic limestone; highly neomorphosed algae grainstone. Numerous codiacean algae fragments and less common dark peloids in microspar matrix or cement. Most pores are lined and filled by calcite druse. Total porosity is 2%. Sample depth 8380'; PPL.

(D) **Distal Flank Facies.** Dolomitic limestone; crinoid-brachiopod-oncolite packstone. Oncolites, algae and calcified algal-coated crinoids are typical of off-reef basin facies. Sample from Shell Osterberg #21X-2, Renville County. Sample depth 7511'; PPL.

normal marine circulation in active wave or current movement, the coral assemblage suggests at least moderate water depths. Relatively steep reef peripheries (20 to 40 degrees or more) were probably maintained by organic binding and submarine cementation. Drusy cements are common in this facies.

Stromatolite Crest Subfacies

The upper third of most pinnacle reefs examined in southeastern Saskatchewan consist of thick intervals of essentially in situ massive or bulbous stromatolites, interbedded by subordinate intervals of peloid grainstone. This facies also constitutes the upper half of the Challenger Alvstad pinnacle reef in North Dakota. Numerous stromatactis-like shelter cavities within these laterally linked hemispherical or "cabbage-head" stromatolites (referred to the form genus Pycnostroma) are variously filled by mud, peloid packstone, or isopachous cements, or had provided shelters for cavity-dwelling bivalves, gastropods, and brachiopods. Among corals and stromatoporoids, in situ colonies of the tabulate coral Chaetetes are the most conspicuous.

Superposition of this facies over the algae-peloid mound subfacies and interfingering with the coral-stromatoporoid rim subfacies demonstrates the depositional contemporaneity of the stromatolite crest and coral-stromatoporoid rim facies. Consequently, accretion of the massive stromatolite boundstone and partial disaggregation to create associated peloid grainstone beds are viewed as having taken place under moderate rather than particularly shallow water depths.

Reef Flat Subfacies

The uppermost several feet of the Shell Golden #34X-34 core consists of alternating thin zones of laminated mudstone comprised of planar stromatolites, stromatolite intraclast wackestone to grainstone, and nodular-mosaic anhydrite (figs. 16A-B, 17A). Equivalent lithologies are encountered at the tops of other but not all pinnacle reefs in North Dakota and Saskatchewan. The presence or prominence of dolomicrite microtextures, soft-sediment deformation, brecciation and microfaults, coated grains and caliche crusts, rare ooids or pisolites, extensive anhydrite or halite cementation of vugs and fenestrae, and well formed isopachous cements are also characteristic. These features, combined with in place and disrupted planar stromatolites and nodular-mosaic, felted anhydrite, indicate discontinuous deposition, erosion and leaching within an array of ponded, peritidal and vadose supratidal conditions. Such conditions likely prevailed over the crests of pinnacle reefs during the prolonged stage of sea level drawdown, contemporaneous with deposition of the Winnipegosis basin laminite and the lower Prairie anhydrite and halite within the surrounding euxinic to hypersaline basin.

Proximal Flank Subfacies

This mixed facies, which has not been identified with certainty in North Dakota, consists of contributions from all foregoing pinnacle reef facies. As may be expected, the lower parts of proximal flanks are dominated by codiacean algae-peloid-crinoid grainstone and packstone and displaced corals and stromatoporoids. The upper parts are dominated by steeply inclined, peloid grainstone and subordinate stromatolite boundstone. However, the uppermost proximal flank strata commonly display steeply inclined planar stromatolites and peloid-intraclast grainstone and may be interbedded with either Winnipegosis basin laminite (euxinic basin facies) or the basal Prairie anhydrite. Deposition of this dolomitized facies evidently spanned all water depths and all time during pinnacle reef accretion and exposure.

Distal Flank Subfacies

This limestone facies exhibits most attributes of the marine shelf facies with which it overlies and interfingers, but is distinctive by virtue of constituents exotic to the otherwise crinoid-brachiopod-dominated fossil assemblage. This nodular-bedded packstone and floatstone facies contains numerous small oncolites, several genera of calcified algae, abraded and mud-coated fragments of codiacean algae, corals and stromatoporoids, and crinoid ossicles markedly larger than those observed in typical marine shelf facies (fig. 17D). The distal flank facies represents both endemic and reef-derived debris that accumulated on the nearby basin floors in relatively deep water.

Euxinic Basin Facies

This dolomite and limestone facies invariably consists of finely laminated, rarely deformed mudstone. Fossils are represented solely by rare Planolites and Chrondrites burrows and by traces of crinoids, fine unidentified skeletal debris and peloids. Felted anhydrite lenses and nodules and isolated anhydrite laths are present in the upper part of the facies, and bitumen residue and pyrite are encountered throughout. This facies typically overlies marine shelf facies and comprises the upper 30-50 feet of the Winnipegosis Formation. It either grades upward to dolomitic anhydrite or is abruptly but conformably overlain by laminated anhydrite comprising the base of the Prairie Evaporite. Where this facies onlaps the flanks of pinnacle reefs, it is typically much thinner and may be interbedded by current-bedded, peloid packstone and grainstone belonging to closely adjacent, contemporaneous proximal flank and stromatolite crest facies.

Euxinic basin sediments were deposited during an episode of progressive basin constriction and stagnation that accompanied evaporative drawdown of basin water level. This eventually led to exposure of Winnipegosis platforms and pinnacle reefs and the establishment of hypersaline basin waters. Presumably water depths within the basin had diminished from maxima of 200-300 feet to low stands of 50-150 feet at the onset of Prairie Evaporite precipitation. The finely laminated mudstone, having varve-like grading, preserved organic carbon, high pyrite content, and a paucity of shelly benthic fossils, suggests the prevalence of density-stratified basin waters and dominantly toxic or anaerobic bottom conditions during deposition.

Diagenesis and Ø-k Relationships

Shallow burial diagenetic processes related to prolonged subaerial exposure of pinnacle reefs near the climax of Winnipegosis deposition are most responsible for reservoir development. Under postulated conditions of sea level drawdown, a vertical zonation of diagenetic environments would have been established within pinnacle reefs. From the sediment surface downward, these environments were: (1) the vadose zone, in which void spaces were occupied alternately by air and by percolating meteoric water undersaturated in calcium carbonate; (2) the meteoric phreatic zone, saturated by fresh water becoming increasingly enriched in carbonate toward its base; and (3) the much depressed marine phreatic zone saturated by connate brine. The vertical extent of each zone would vary with respect to crestal and flank positions on any particular reef, as well as with respect to frequency of rainfall, density of pore fluids, and permeability of the buried sediment.

Leaching of the less stable carbonate phases by downward percolating meteoric waters, resulting in the formation of vugs and molds and concommittant lithification of the limestone host, was certainly the most effective vadose process. Among pinnacle reef facies, the highest percentages of vuggy porosity are found in the coral-stromatoporoid rim subfacies. Molds are likewise best developed in this facies. That the lower portions of North Dakota pinnacle reefs are poorly dolomitized demonstrates that this style of leaching and lithification was a vadose-zone process unrelated to dolomitization.

In North Dakota pinnacle reefs, the coral-stromatoporoid subfacies displays the best developed porosity by virtue of high values of intercrystalline/microvugular, moldic and vuggy porosity. The diversity of pore types indicates that this subfacies had also experienced appreciable vadose-zone leaching prior to dolomitization. Also, the proximity to overlying evaporites may have also subjected this subfacies to both mixing zone and seepage reflux dolomitization processes.

Although halite cementation can be detrimental to pinnacle reef reservoirs, many reefs do not show evidence of significant halite cements. This may be partly a function of the low permeability in parts of reef flat subfacies (sometimes including thin anhydrite beds) which separate the underlying reservoir from the Prairie Evaporite. The distribution of the lower Prairie anhydrite over the flanks of pinnacle reefs also served as a seal, but this facies may only rarely entirely envelope reefs. A secondary mechanism for limiting halite cementation may exist in the form of increased fluid pressures in the reefs as a result of dissolution and compaction. Such pressures may have been sufficient to counteract downward infiltration of dense, hypersaline brine.

Ø-k plots for three of the six North Dakota pinnacles illustrate the relative reservoir capacity of strom-coral subfacies compared with algae-peloid mound subfacies (fig. 18). In North Dakota, Ø-k relationships are partly the function of the reef lithology, the lower algae-peloid facies being largely limestone. Despite the thorough dolomitization of southeastern Saskatchewan reefs, algae-peloid mound facies still reflect relatively lower permeability compared with coral-strom rim subfacies, a relationship which is undoubtedly linked to the inherent intergranular porosity and associated lower permeability of the algae-peloid mound facies. Another factor which is evident in several Saskatchewan reefs is the near total destruction of reef reservoirs as a result of overdolomitization. This may be related to Prairie salt solution and subsequent deeper-burial dolomitization, a phenomenon which may have occurred on both regional and local scales.

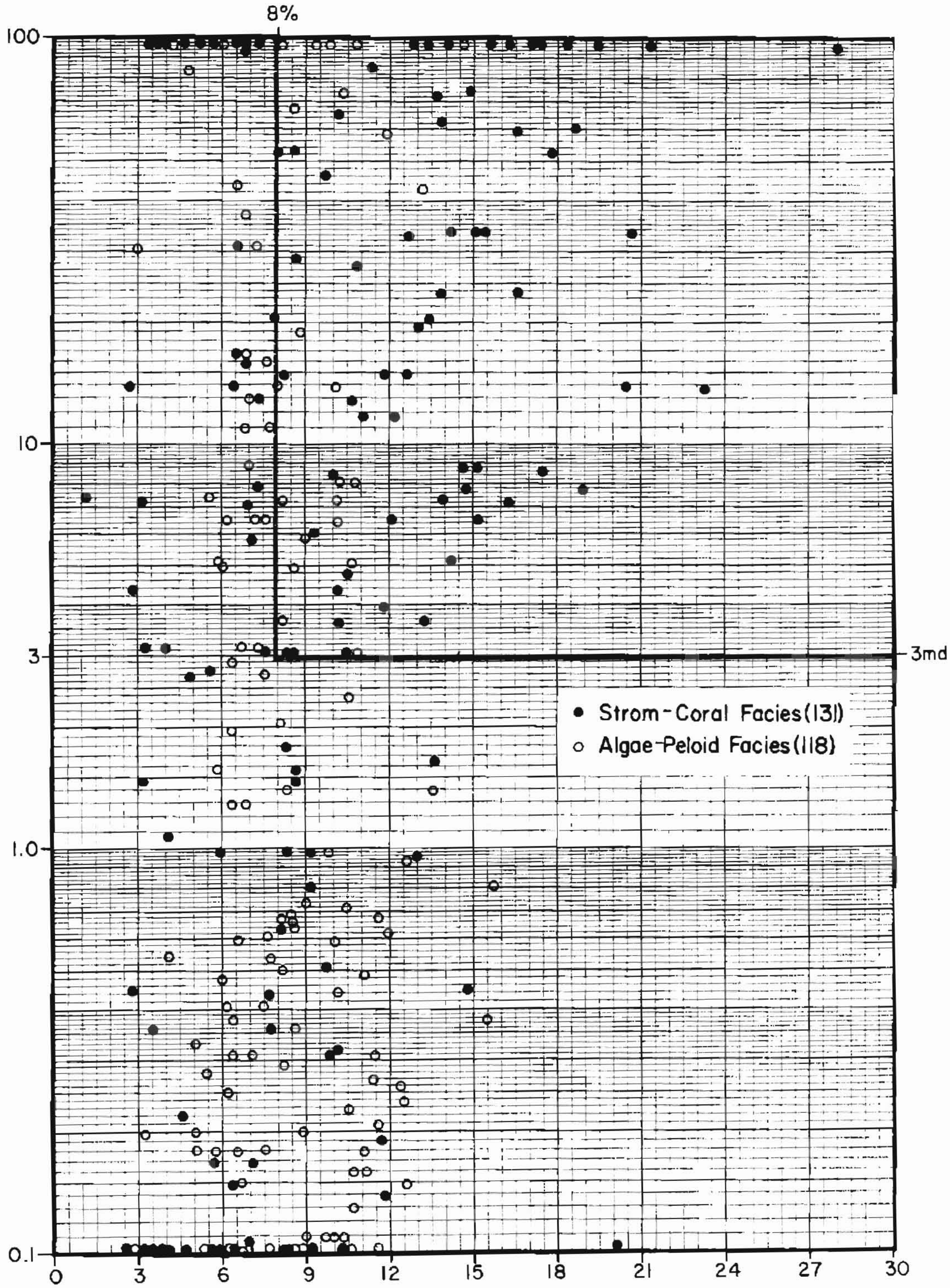

Fig. 18 - Ø-k plots for 249 core analyses from three wells penetrating pinnacle reef facies. 8% porosity and 3 md permeability denote approximate lower reservoir limits.

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THE LOWER RATCLIFFE INTERVAL (MISSISSIPPIAN) IN WILLIAMS AND MCKENZIE COUNTIES, NORTH DAKOTA

by
Michael L. Hendricks
Hendricks and Associates, Inc.

ABSTRACT

The lower Ratcliffe interval in Williams and McKenzie Counties, North Dakota is a carbonate to evaporite regressive sequence. The lower Ratcliffe has been informally divided into Midale, Berentson, Alexander, and Flat Lake subintervals based on lithologies and wireline log responses. The Alexander and Flat Lake beds are locally productive along southeast plunging anticlines in the central Williston Basin. The Alexander subinterval consists principally of shallowing upward, shallow shelf, and restricted subtidal depositional facies. Production is associated with partially dolomitized mudstones and wackestones of the restricted subtidal facies. The Flat Lake subinterval is a complex assemblage of restricted subtidal, intertidal, and supratidal-sabkha depositional facies. Production is from intergranular and pinpoint vuggy pores associated with shoaling sequences.

INTRODUCTION

The Ratcliffe interval in McKenzie and Williams Counties, North Dakota is a carbonate to evaporite regressive sequence characterized by shallowing upward depositional environments. Productive intervals are principally dolomitic mudstones and wackestones and peloidal and pisolitic lime packstones.

Location and Structural Setting

The area discussed in this paper is in the central portion of the Williston Basin (U.S.), including most of Williams and McKenzie Counties, North Dakota (fig. 1). The present synclinal axis of the basin lies along the eastern edges of Williams and McKenzie Counties, directly west of the Nesson anticline. A series of southeast plunging anticlines and synclines are present west of the syncline. Ratcliffe beds are locally productive along some of the anticlinal structures.

Stratigraphic Setting and Nomenclature

The Ratcliffe beds are part of the Charles Formation (Madison Group). The Charles was first named by Seager (1942) for an 800-foot-thick section of evaporites and carbonates in the Carter Northern Pacific #1 test well on the Cedar Creek anticline. Madison Group sedimentation in the Williston Basin is characterized by complex intertonguing of basinal, shallow shelf, and shoreline carbonates, and evaporite beds. The Ratcliffe interval

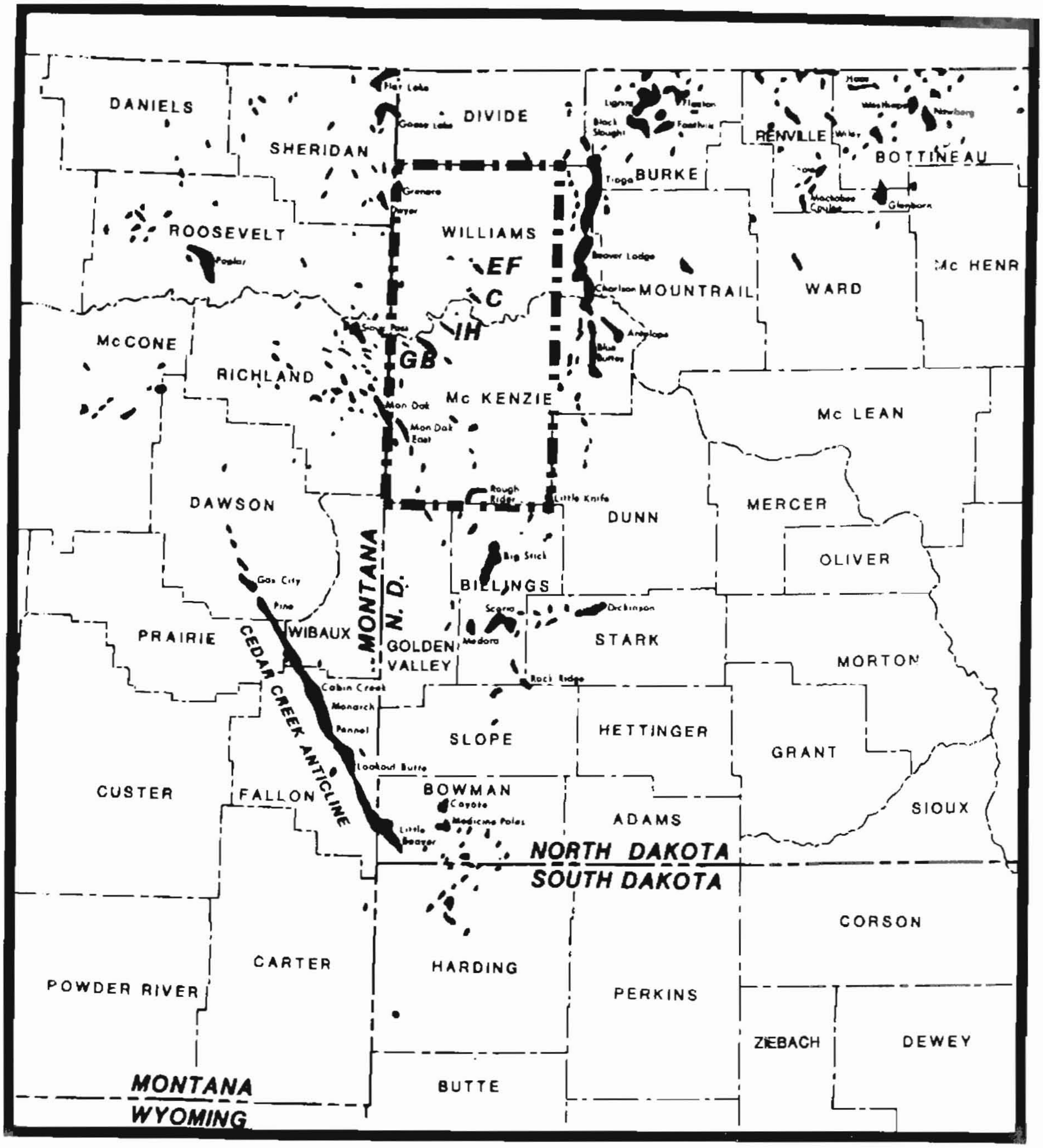

Figure 1. Outline of the area discussed in this paper. EF = East Fork Field, C = Catwalk Field, IH = Indian Hills Field, GB = Glass Bluff, Elk, and Sioux Fields.

records major regressive sedimentation and restriction of the basin.

Fuller (1956) divided the Madison Group, as defined by Sloss 1952), into five units. In ascending order, these beds are the MC-1, Forget-Nottingham, Hastings-Frobisher, Midale, and Ratcliffe beds. In 1956, the Saskatchewan Geological Society redefined Fuller's divisions. In ascending order, these units were named the Souris Valley, Tilston, Frobisher-Alida, Midale, Ratcliffe, and Poplar beds (fig. 2).

Smith (1960) was the first to use the term "interval" instead of "bed" to define widespread, correlative marker units. Smith's five intervals in ascending order are the Bottineau, Tilston, Frobisher-Alida, Ratcliffe, and Poplar. The Midale subinterval forms the base of the Ratcliffe interval. Bluemle et al. (1980) defined the Ratcliffe interval as beds from the base of the Midale marker to the base of the Greenpoint anhydrite. This interval contains the "last" or lowermost Charles salt.

In the central basin, the lower Ratcliffe has been informally divided into the Midale, Berentson, Alexander, and Flat Lake subintervals (fig. 3). This paper focuses on the Alexander and Flat Lake subintervals. The Alexander subinterval is named for beds below the lowest (oldest) Ratcliffe anhydrite in the Alexander Field, sec24, T151N, R101W (North Dakota). These beds are locally productive to the northwest in the Glass Bluff Field.

The Flat Lake subinterval is named for beds from the top of the Alexander interval to the base of the "y" marker (a distinct lithologic change from shallow water carbonates to deeper water carbonates) in the Flat Lake Field, T38N, R58E (Montana).

Major Core Lithofacies

The following core lithofacies were described in the Alexander and Flat Lake subintervals, and are summarized on a composite stratigraphic column (fig. 4). Some lithofacies are locally absent because of lateral facies changes produced by paleostructure, sea level fluctuations, and varying rates of subsidence. These changes are reflected in the local and regional cyclic nature of the Ratcliffe interval.

Facies 1

The base of the Alexander subinterval is characterized by brown to black, slightly bioturbated, skeletal wackestone to packstone (facies 1). Fossils are normal marine and include both whole and fragmented crinoids, brachiopods, rugose and tabulate corals, and sparse bryozoans and foraminifers (figs. 5, 6). Trace fossils are: subhorizontal burrow structures with slightly curved spreiten (Zoophycos), irregularly branched and inclined burrow structures lacking spreiten (Planolites and Thalassinoides), and sparse ramifying burrow systems (Chondrites). Irregular, wispy laminae, which may be compressed burrow outlines, are common to absent.

Facies 1 was deposited below storm wave base along a very low gradient, open shelf or ramp. The presence of normal marine fossils and burrow structures of the Cruziana ichnofacies support this interpretation.

Facies 2

Overlying the skeletal wackestones and packstone of facies 1 are light-brown to gray, bioturbated, dolomitic, and sparsely skeletal mudstones and

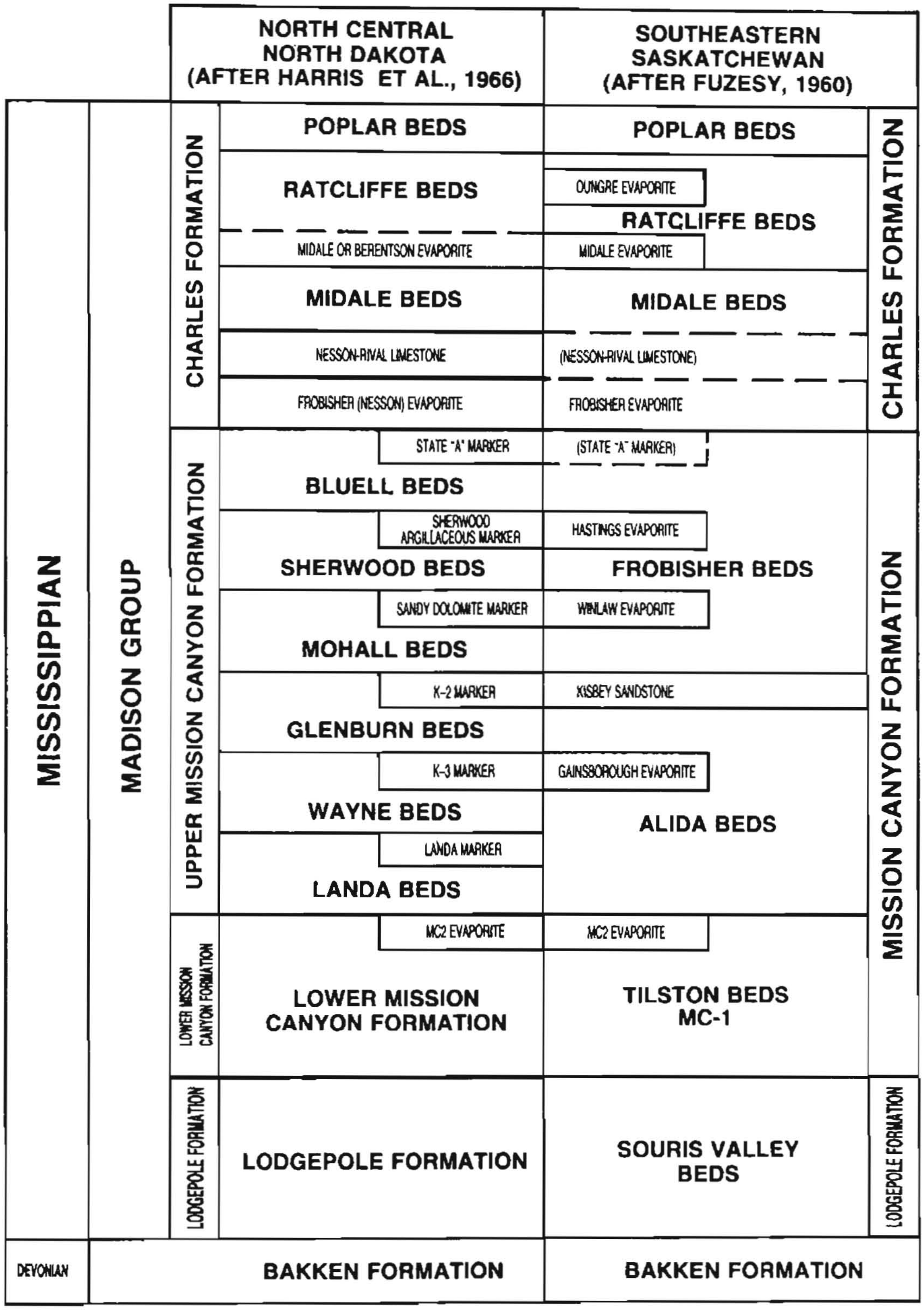

Figure 2. Summary of Mississippian stratigraphic nomenclature in the Williston Basin. In the North Dakota portion of the basin, interval instead of beds is more commonly used.

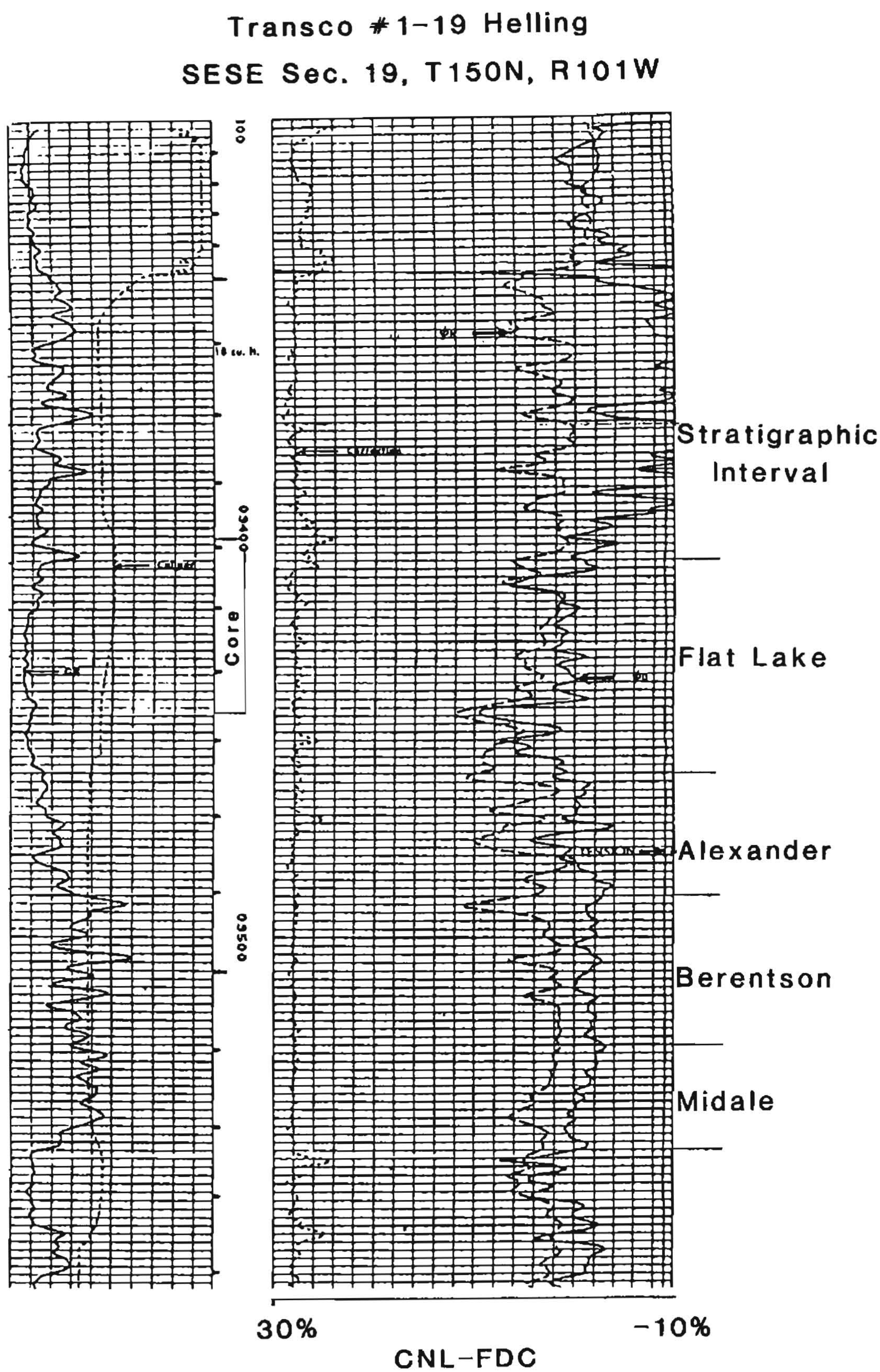

Figure 3. Type log showing the subintervals of the Ratcliffe in the central basin. Production is from the Alexander and Flat Lake intervals.

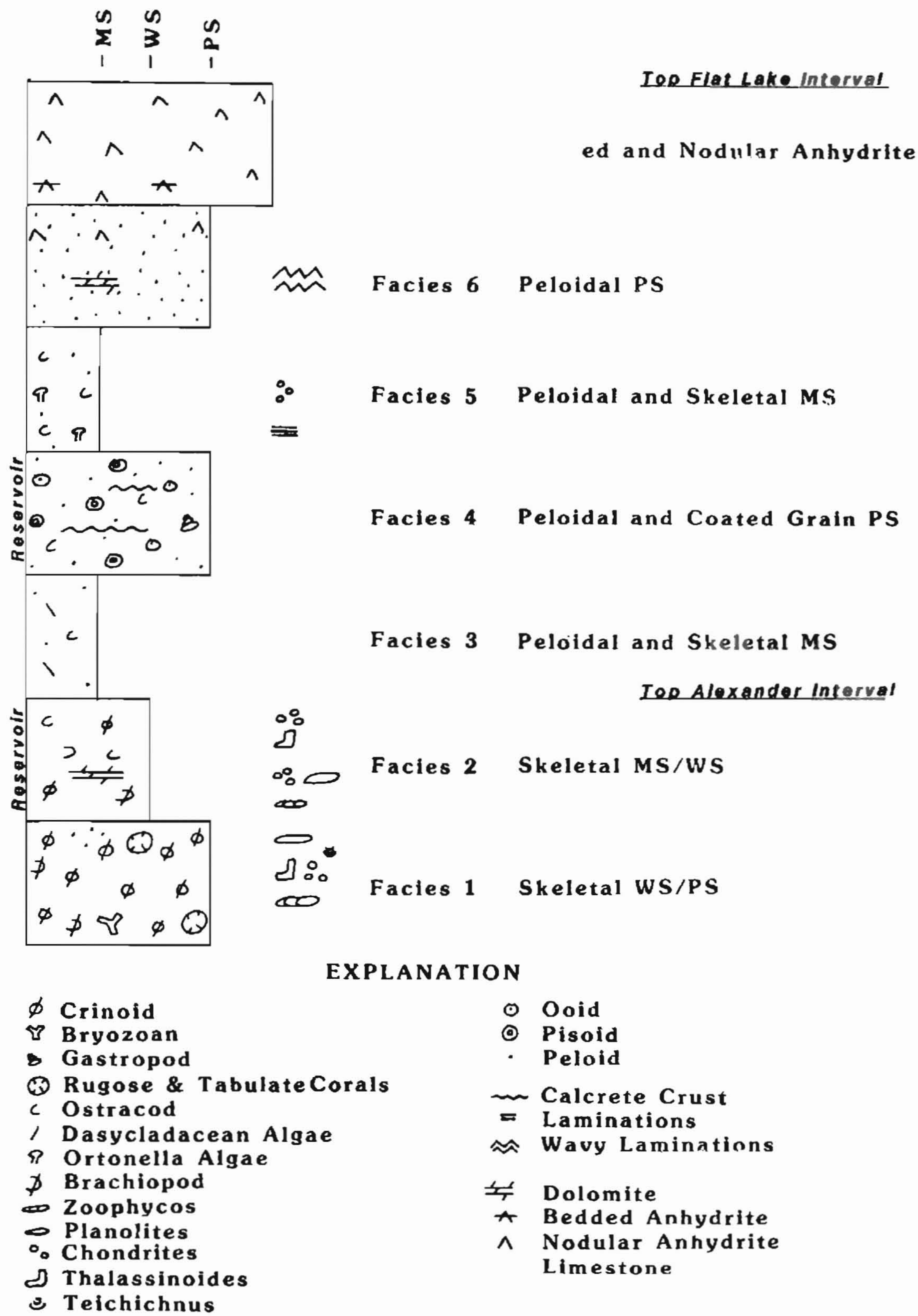

Figure 4. Type stratigraphic section from the Alexander and Flat Lake intervals in the central basin. Production in the Alexander interval is from dolomitic wackestones, while Flat Lake production is from lime packstones. Facies shown correspond to those discussed in the text.

Figure 5a. (Facies 1). Crinoidal and burrowed wackestone of the shallow shelf, BWAB, 10-31X Federal, NWNEsec10, T147N, R104W.

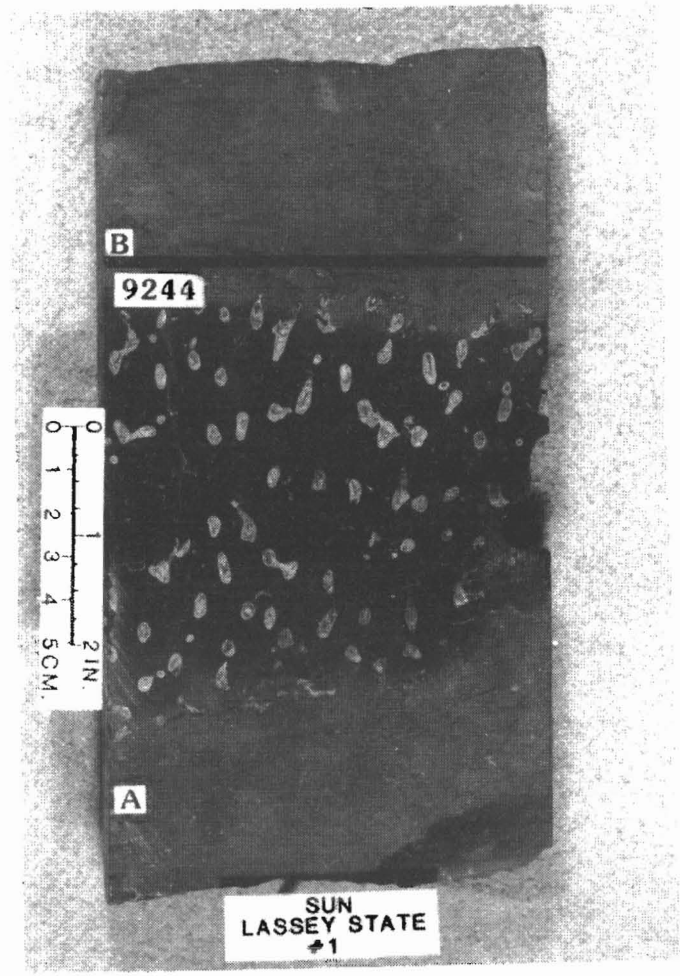

Figure 5b. (Facies 1). Tabulate corals in a burrowed and skeletal wackestone of the shallow shelf, Sun Exploration and Production, #1 Lassey State, SWSWsec28, T152N, R103W.

Figure 5c. (Facies 1). Large rugose corals in a crinoidal wackestone. The skeletal allochems are typical of shallow shelf environments. Sun Exploration and Production, #1 Zimmerman Seel, SWNEsec 3, T152N, R104W.

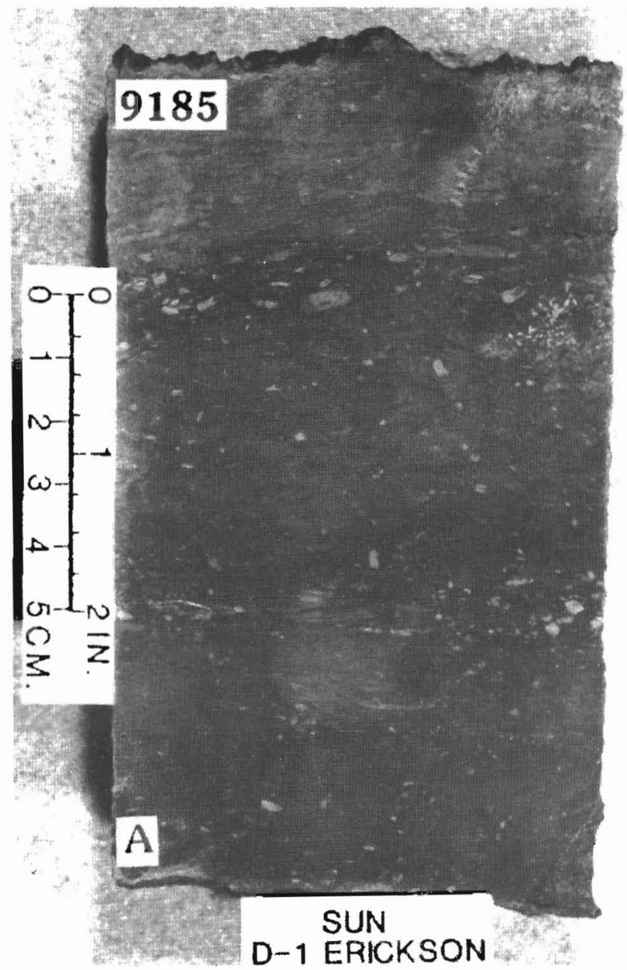

Figure 5d. (Facies 1). A crinoidal wackestone from the shallow shelf facies. Sun Exploration and Production, #1 D. Erickson. SENWsec 27, T152N, R103W.

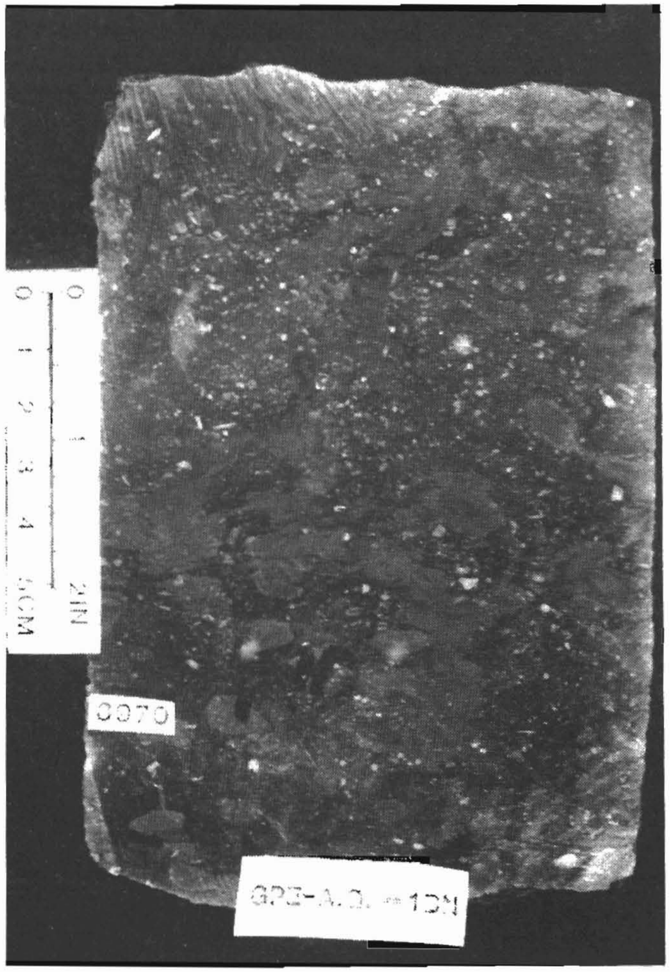

Figure 6a. (Facies 1). A burrowed and skeletal wackestone. Burrow structures are of the Cruziana ichnofacies, which are part of the shallow shelf, GPE, #1 BN, SESEsec 1, T147N, R105W.

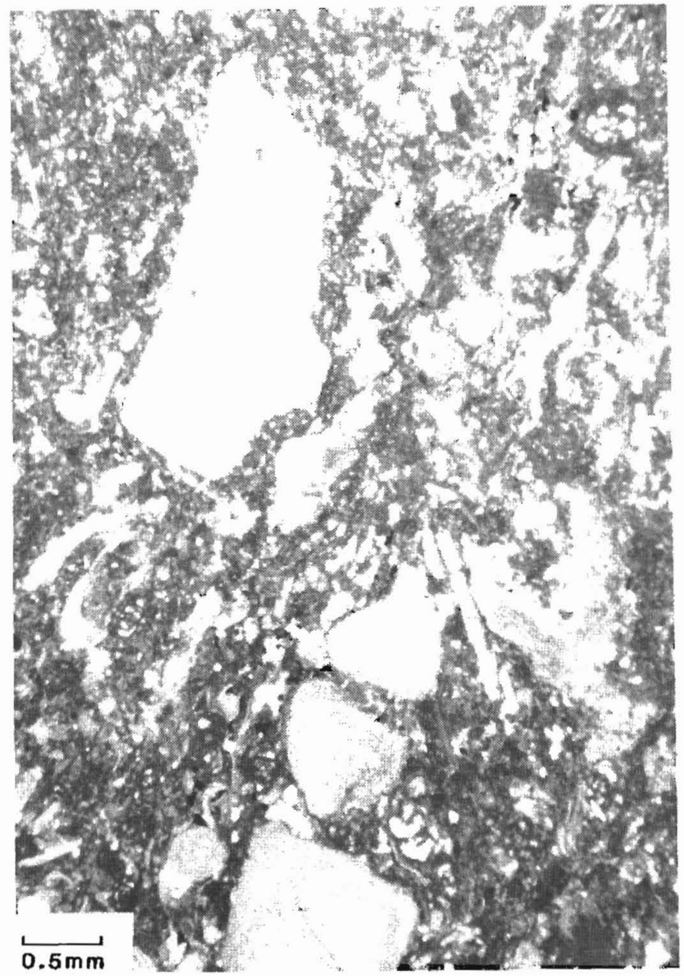

Figure 6b. (Facies 1). A photomicrograph of skeletal fragments typical of the shallow shelf facies. From 8767 feet in the Arco, #1 State Gafkjen, SESEsec 36, T158N, R100W.

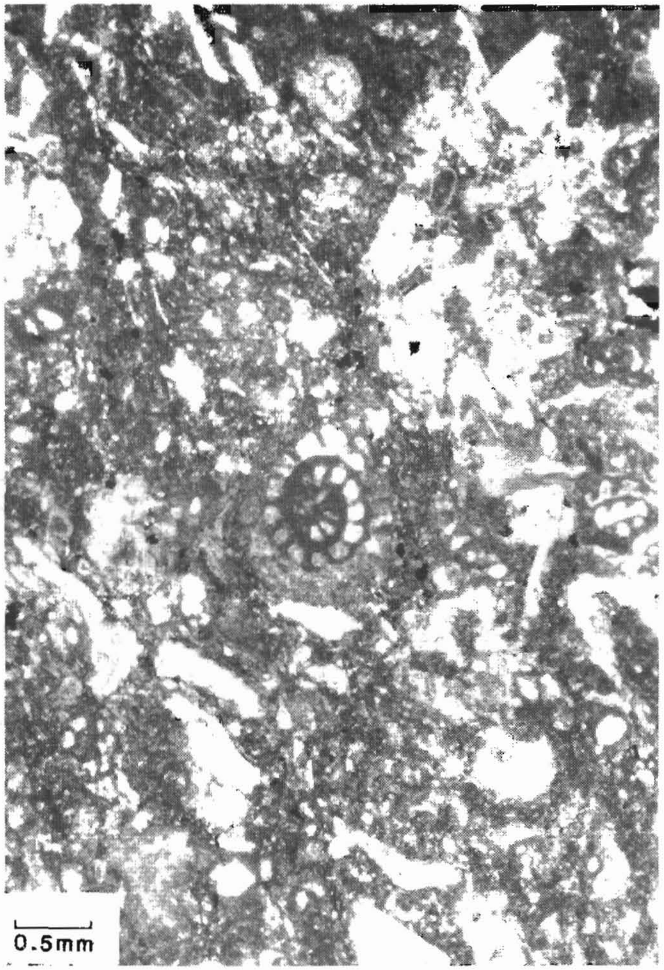

Figure 6c. (Facies 1). An endothyrid foraminifer (center) is surrounded by crinoid, brachiopod, and other skeletal fragments. From 8767 feet in the Arco, #1 State Gafkjen, SESEsec 36, T158N, R100W.

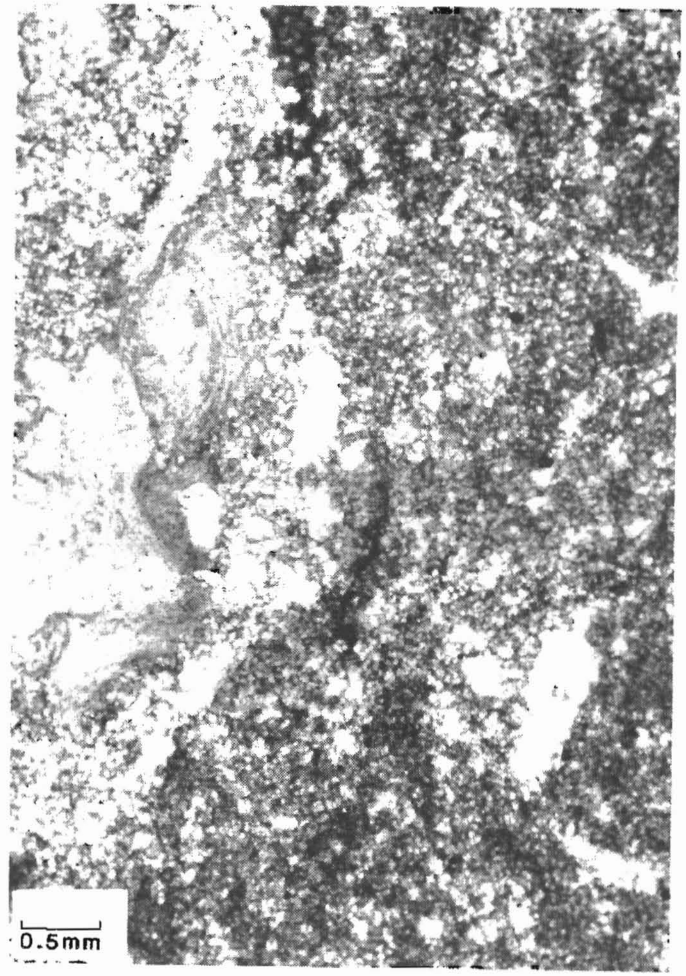

Figure 6d. (Facies 1). A brachiopod fragment (left center) is unaffected by the partial dolomitization (white specks) of this skeletal wackestone. Preferential dolomitization of the mud matrix is common in shallow shelf facies.

wackestones (facies 2). Fossil constituents are mainly ostracods and rare, thin-shelled brachiopods, crinoids, and rugose corals (figs. 7, 8). Trace fossils are predominantly small ramifying burrow systems (Chondrites). Thalassinoides, Planolites, and Zoophycos, are less common. Wispy laminations are common.

Facies 2 was deposited in a shallow, normal to restricted marine environment. The wispy laminations may be either clay laminae produced by episodic fallout of suspended sediments or microstylolites. Facies 2 is the reservoir facies within the Alexander subinterval.

Facies 3

Continued restriction of the basin resulted in the deposition of facies 3, a gray to light-brown, slightly dolomitic, sparsely skeletal, and peloidal mudstone to wackestone (fig. 9). Ostracod and dasycladacean algal debris is sparse. The overall massive texture of this facies may indicate complete bioturbation. Trace fossils are rare and consist of small, irregular, subhorizontal, and slightly inclined burrow structures lacking spreiten (Planolites).

Facies 3 was deposited in a highly restricted, subtidal environment as indicated by the paucity of skeletal material.

Facies 4

Gradual shallowing is indicated in the sediments of facies 4, a shoal sequence. This lithofacies is a light-brown to brown, coated-grain packstone. Fossils are sparse ostracod or gastropod fragments. Trace fossils are not present. Non-skeletal allochems are poorly sorted peloids and irregularly shaped coated grains (ooliths and pisoliths). These grains display multiple generations of breakage and rim cementation (figs. 10, 11). Cores of many of the grains appear to be fragments of Ortonella algae (Codiacean). Individual grain units contain both normal and inverse graded beds. This facies is usually massively bedded with rare cross-stratification. The lack of cross-stratification, incomplete winnowing of mud, and poor sorting of grains suggest a low energy depositional environment.

Micritic crusts and fenestral fabric are common in this shoal sequence. Fenestrae are mostly occluded with calcite, baroque dolomite, and anhydrite cements. Micritic crust may have developed during periods of subaerial weathering or during periods of fallout sedimentation associated with storm events.

Facies 4 is the reservoir facies in the Flat Lake subinterval.

Facies 5

Shoal sequences are locally overlain by dark-brown, slightly dolomitic and anhydritic, algal and peloidal mudstones and wackestones (facies 5). Fossils are ostracods, calcispheres, and whole and fragmented grains of Ortonella algae (fig. 12a). Small Chondrites burrow structures are common. Peloids are micritized and inferred to be algal in origin. Dark organic-rich laminations are common.

Facies 5 was deposited in lagoons which developed behind (east-northeast) of the main shoal trends. The presence of both ostracods and algae indicate restricted conditions.

Facies 6

Lagoonal deposits of facies 5 are locally overlain by light-brown to light-gray, peloidal, dolomitic and anhydritic wackestones to packstones (facies 6). Wavy laminations are possibly stromatolites (figs. 12b, 12c). No fossils or trace fossils are present.

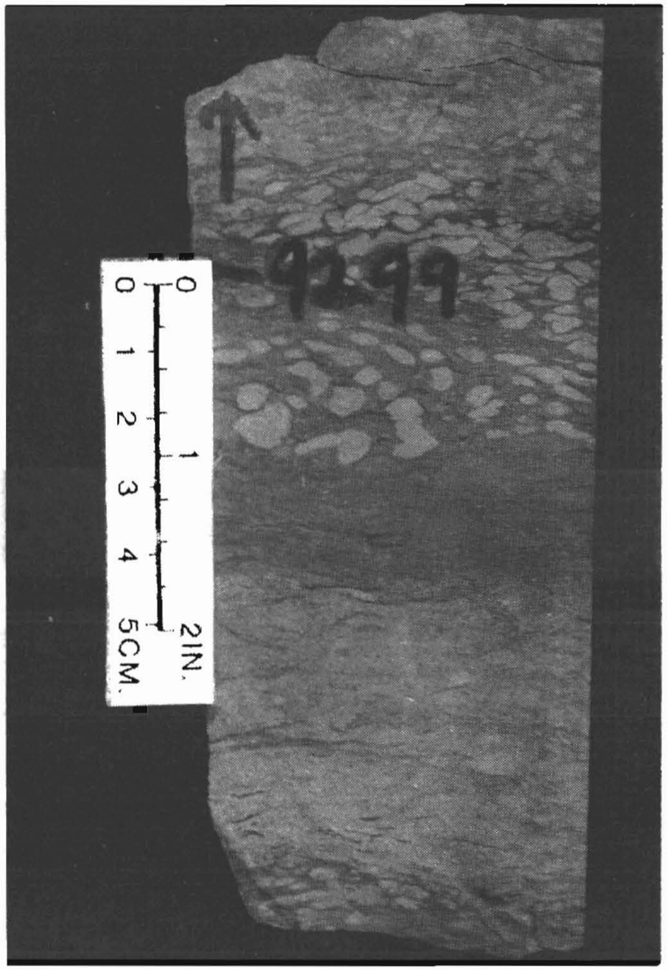

Figure 7a. (Facies 2). Well preserved Chondrites burrow structures from the restricted subtidal facies, Depco-Pennzoil, #22-32 Federal, SWNEsec 22, T147N, R101W.

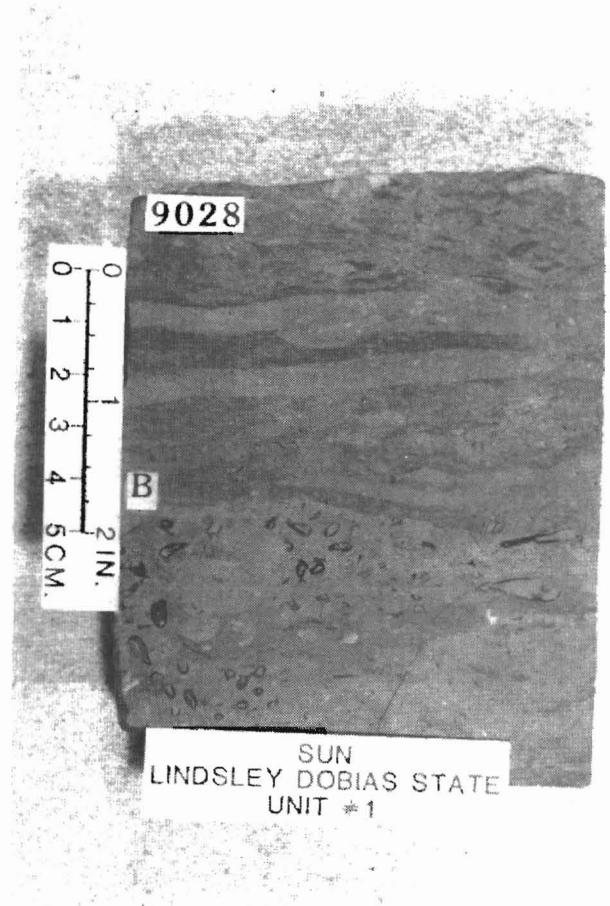

Figure 7b. (Facies 2). Elongate Planolites and Zoophycos burrow structures in a skeletal wackestone. These types of burrows are typical of the restricted subtidal. Sample from the Sun Exploration and Production, #1 Lindsley Dobias State, NESWsec 29, T152N, R103W.

Figure 7c. (Facies 2). Large Thalassinoides burrow structures in a slightly dolomitic mudstone, from the Sun Exploration and Production, #1 Zimmerman Seel, SWNEsec 3, T152N, R104W.

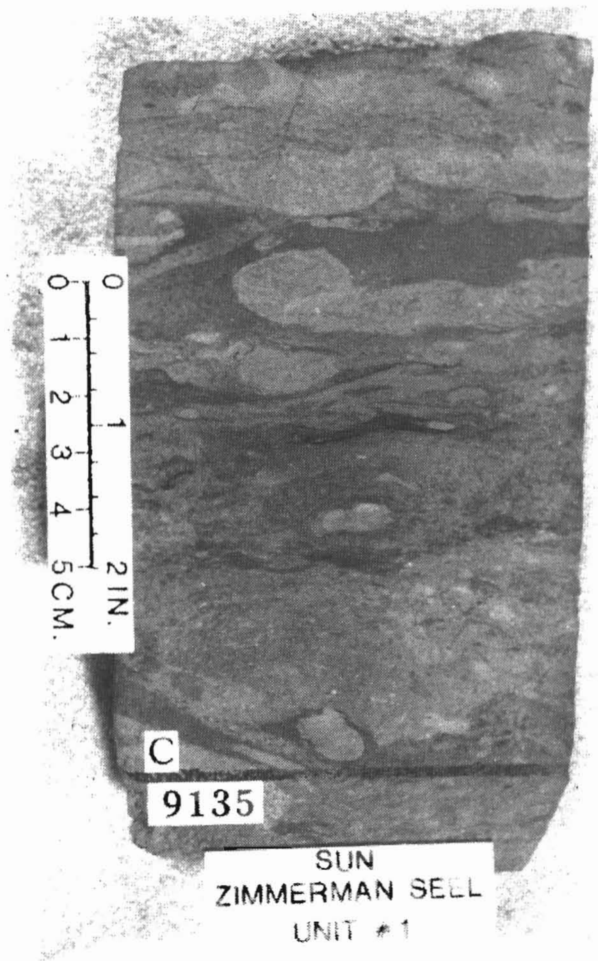

Figure 7d. (Facies 2). Thalassinoides and Teichichnus burrow structures in the restricted subtidal, Sun Exploration and Production, #1 Zimmerman Seel, SWNEsec 3, T152N, R104W.

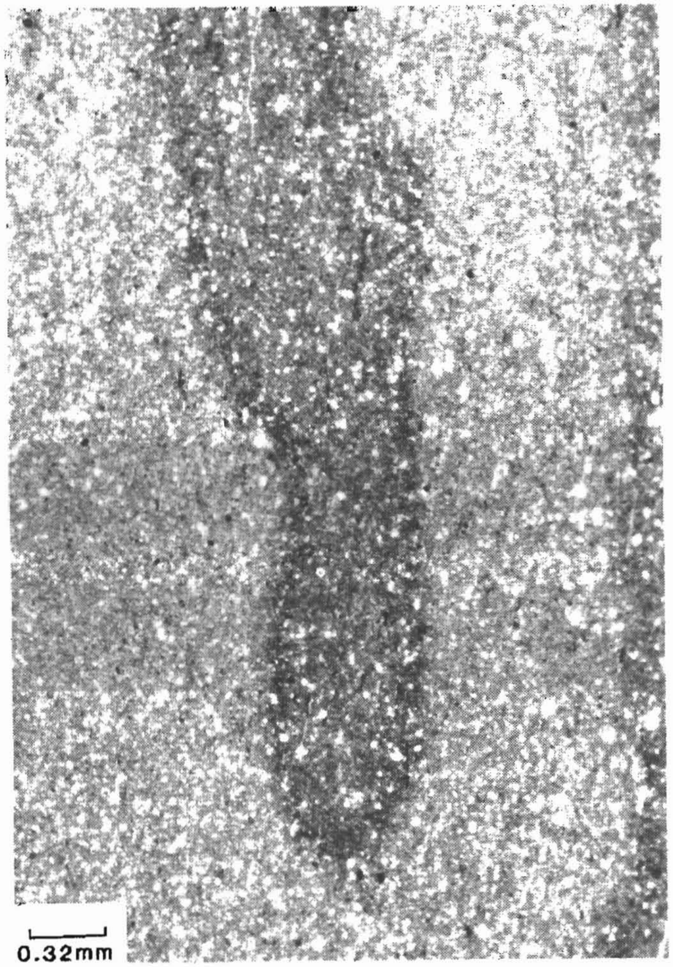

Figure 8a. (Facies 2). A <u>Chondrites</u> burrow structure in a photomicrograph from 9204 feet in the Sun Exploration and Production, #1 D. Erickson, SENWsec 27, T152N, R103W. Partial dolomitization is shown by the moderately abundant white specks (small dolomite rhombohedrons).

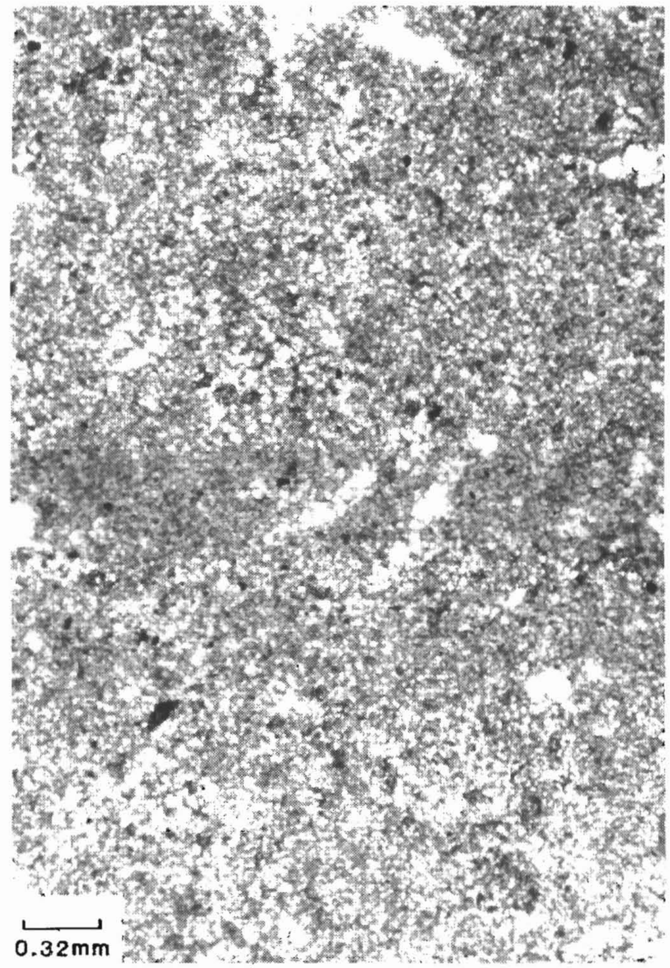

Figure 8b. (Facies 2). Dolomitization has produced sparse intercrystalline porosity in this restricted subtidal sample. From 9178 feet in the Sun Exploration and Production, #2 Erickson, NWNEsec 27, T152N, R102W. The dark specks in this photomicrograph are small pyrite crystals.

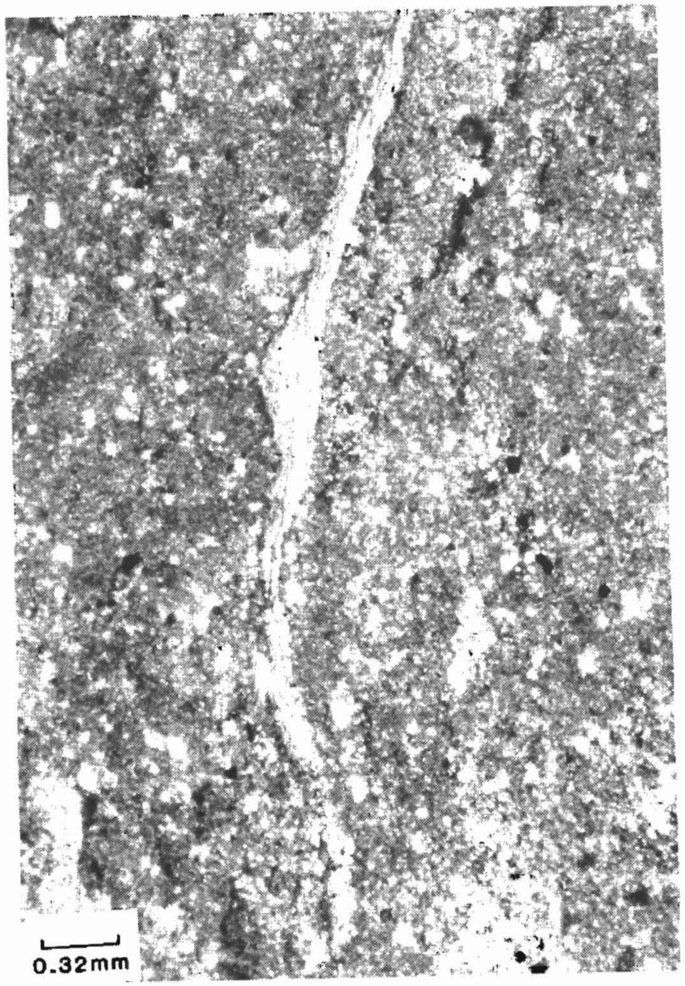

Figure 8c. (Facies 2). An elongate brachiopod fragment is well preserved in this slightly dolomitic mudstone. Dolomite has selectively replaced the lime mud fraction of this sample from 8738 feet in the Arco, #1 State Gafkjen, SESEsec 36, T158N, R100W.

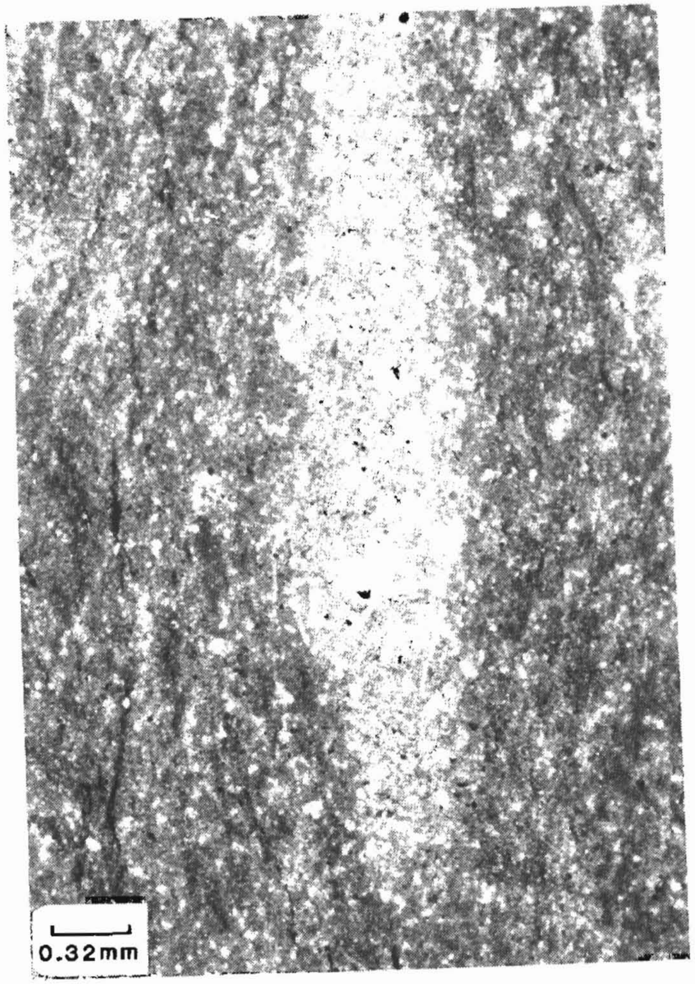

Figure 8d. (Facies 2). The lime mudstone within a Chondrites burrow structure has been preferentially replaced by dolomite in this photomicrograph from 9441 feet in the Superior, #1 Monson, NWSWsec 35, T152N, R102W. This is the principal reservoir type in the Alexander subinterval.

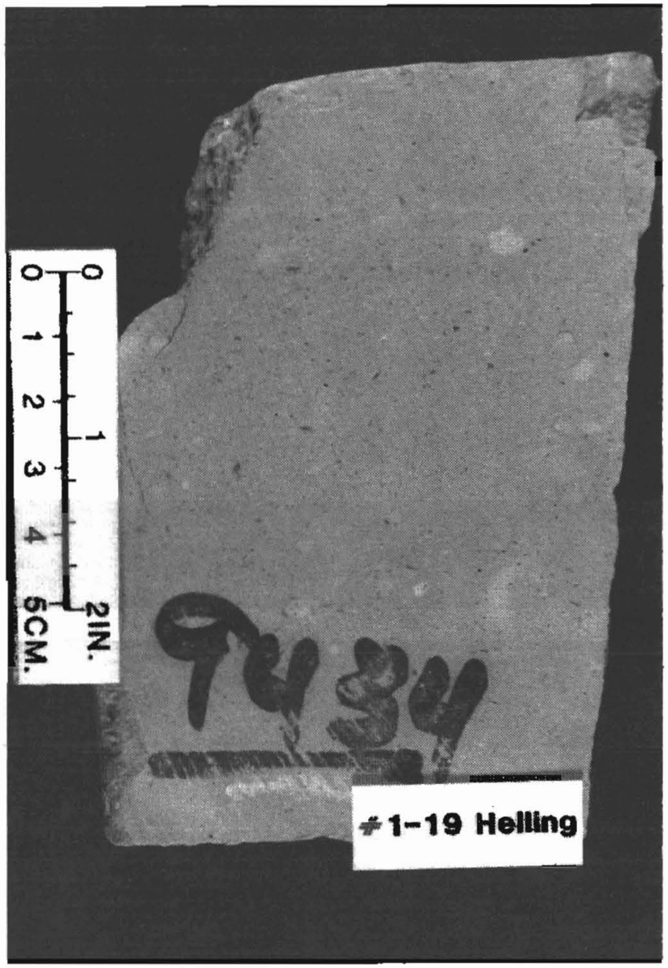

Figure 9a. (Facies 3). Massive-appearing lime mudstone from the restricted subtidal facies of the Flat Lake subinterval in the Transco #1-19 Helling, SESEsec 19, T150N, R101W. Massive appearance may be due to complete bioturbation. Porosity in this facies is locally good, but permeability is normally poor due to poor interconnection of pores.

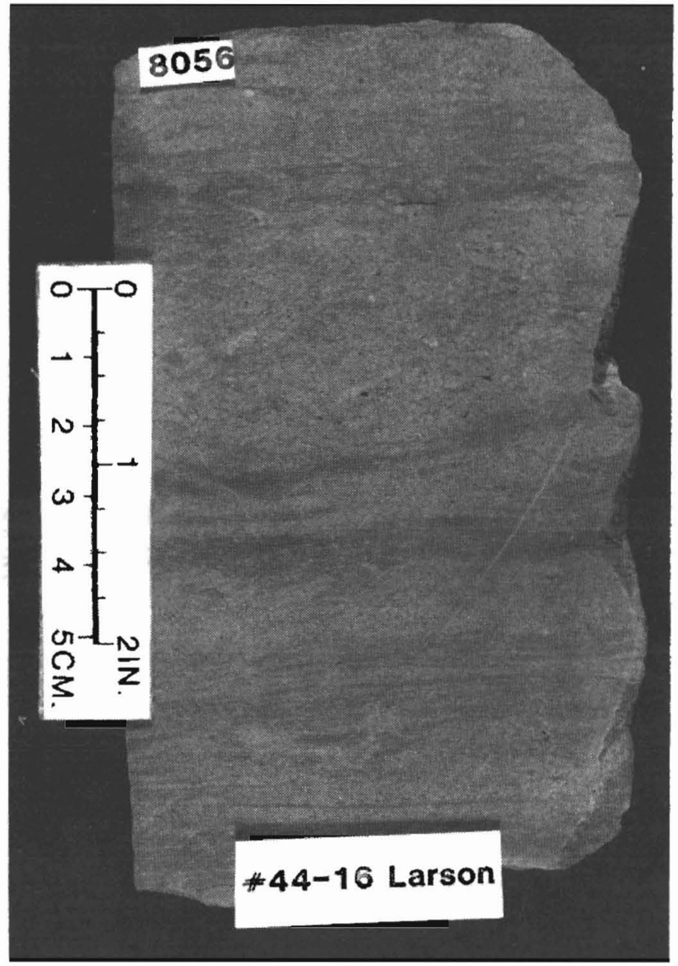

Figure 9b. (Facies 3). Subhorizontal laminations are well preserved at the base of this restricted subtidal sample from the Flat Lake subinterval in the Depco, #44-16 Larson, SESEsec 16, T159N, R102W. Small Chondrites burrow structures and wispy laminations are present in the upper portion of the sample.

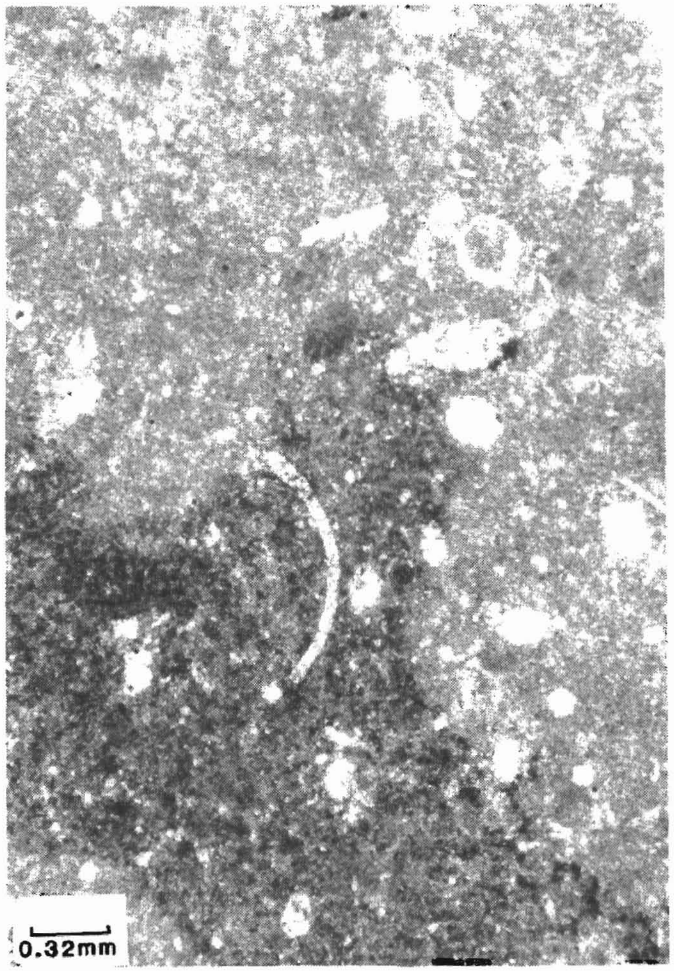

Figure 9c. (Facies 3). Part of an ostracod carapace is shown in a matrix of slightly dolomitized lime mudstone from 9185 feet in the Sun Exploration and Production, #1 D. Erickson, SENWsec 27, T152N, R103W. Some of the subcircular skeletal debris are calcispheres and transverse sections of dasycladacean algae. Deposition of this sample was in a restricted subtidal environment below effective wave base.

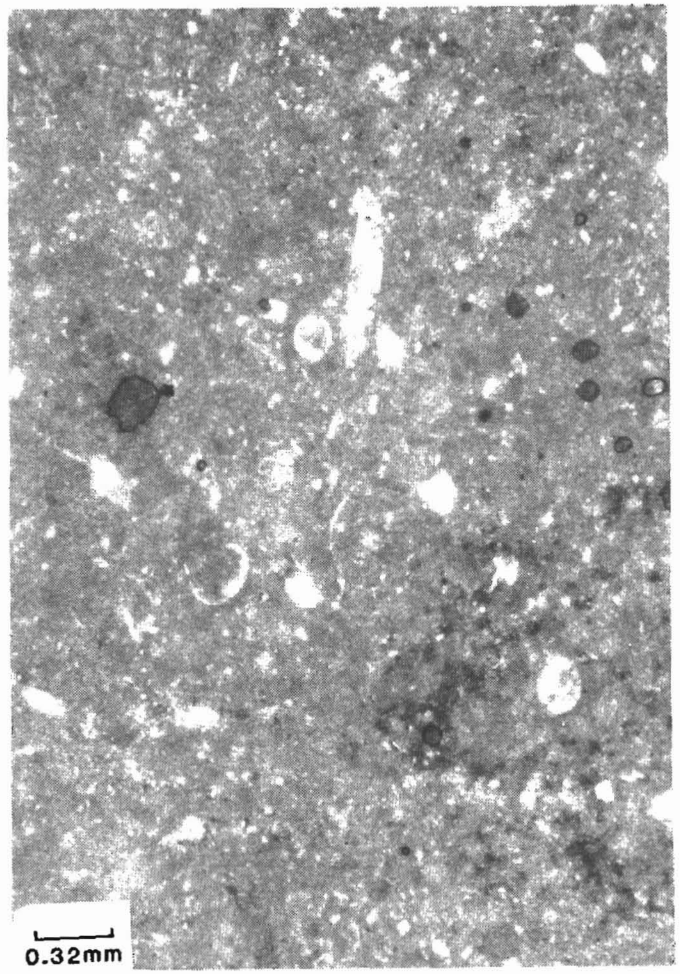

Figure 9d. (Facies 3). Another example of restricted subtidal deposition from the Flat Lake subinterval shows very small skeletal fragments (mostly ostracods and calcisheres) in a lime mudstone matrix. Some of the small white specks are dolomite rhombohedrons. Sample from 9185 feet in the Sun Exploration and Production, #1 D. Erickson, SENWsec 27, T152N, R103W.

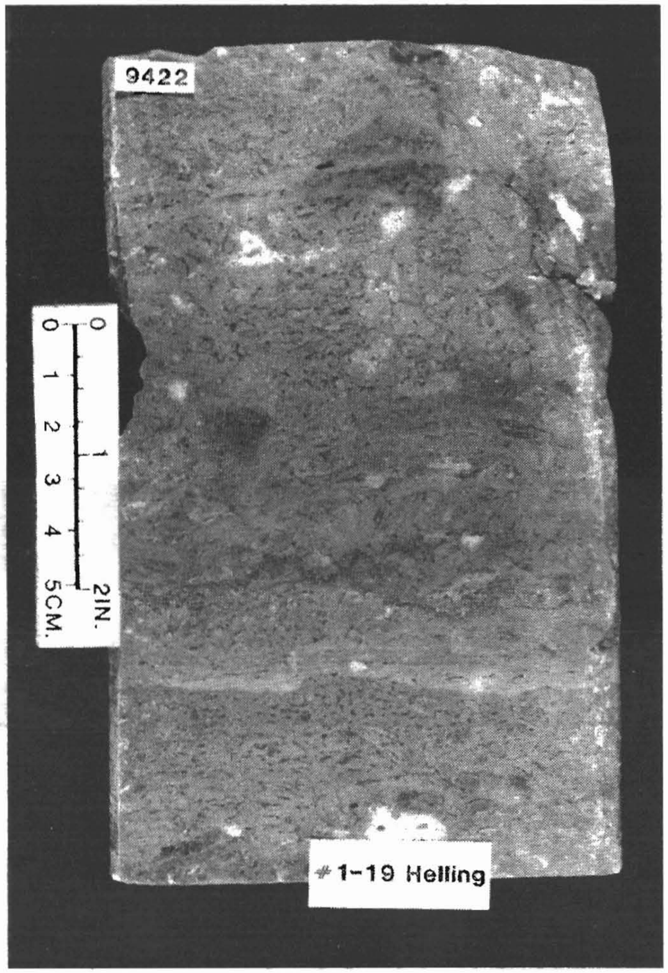

Figure 10a. (Facies 4). A peloidal and coated grain packstone with occluded fenestral fabric is part of the shoal facies of the Flat Lake subinterval. The large white patches are anhydrite and baroque dolomite cements. Transco, #1-19 Helling, SESEsec 19, T150N, R101W.

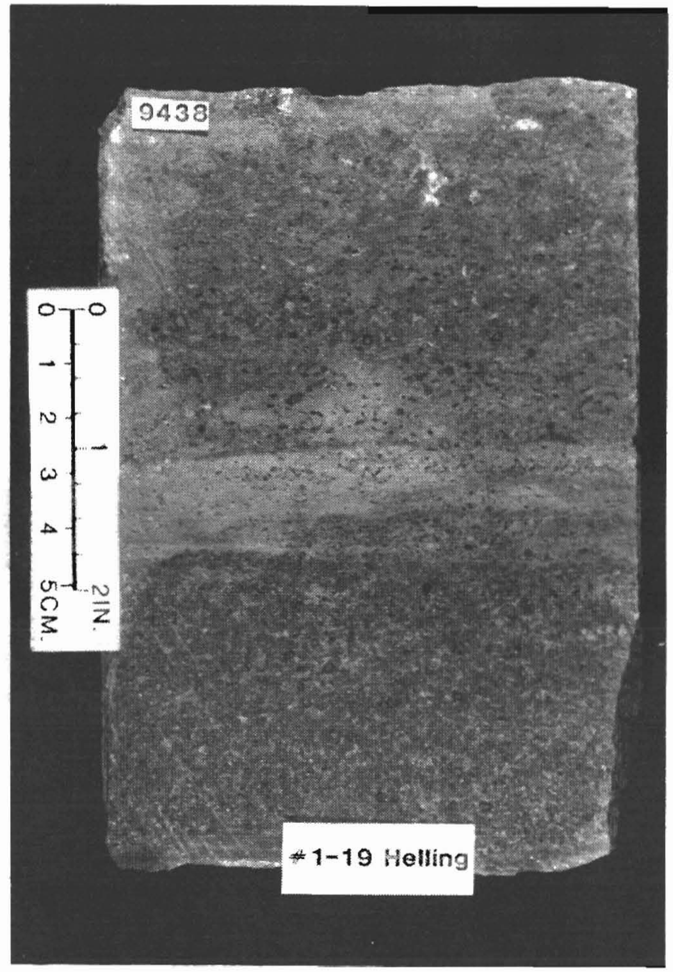

Figure 10b. (Facies 4). A peloidal and coated grain grainstone at the base of the sample grades upward into a wackestone. The grainstone bed is capped by a thin lime mudstone laminae which was probably produced by fall-out sedimentation during slack water deposition, from the Transco, #1-19 Helling, SESEsec 19, T150N, R101W.

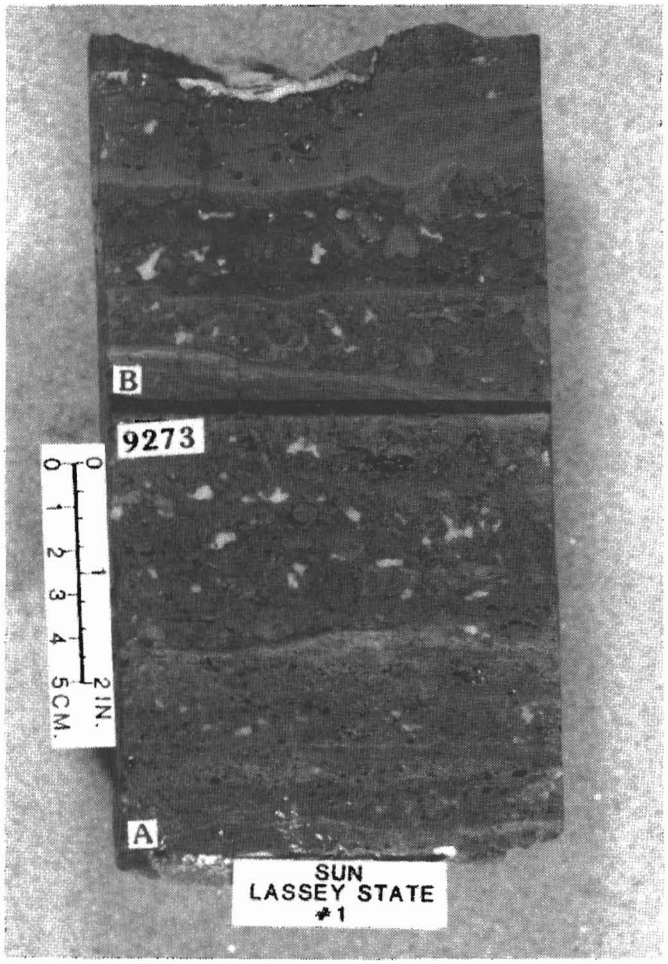

Figure 10c. (Facies 4). A peloidal and coated grain packstone from the Sun Exploration and Production, #1 Lassey State, SWSWsec 28, T152N, R103W, shows thin, shallowing upward beds typical of the grain-rich portions of the Flat Lake subinterval. The white occluding cements are baroque dolomite and sparse anhydrite. Lack of interconnection has rendered most vuggy pores ineffective.

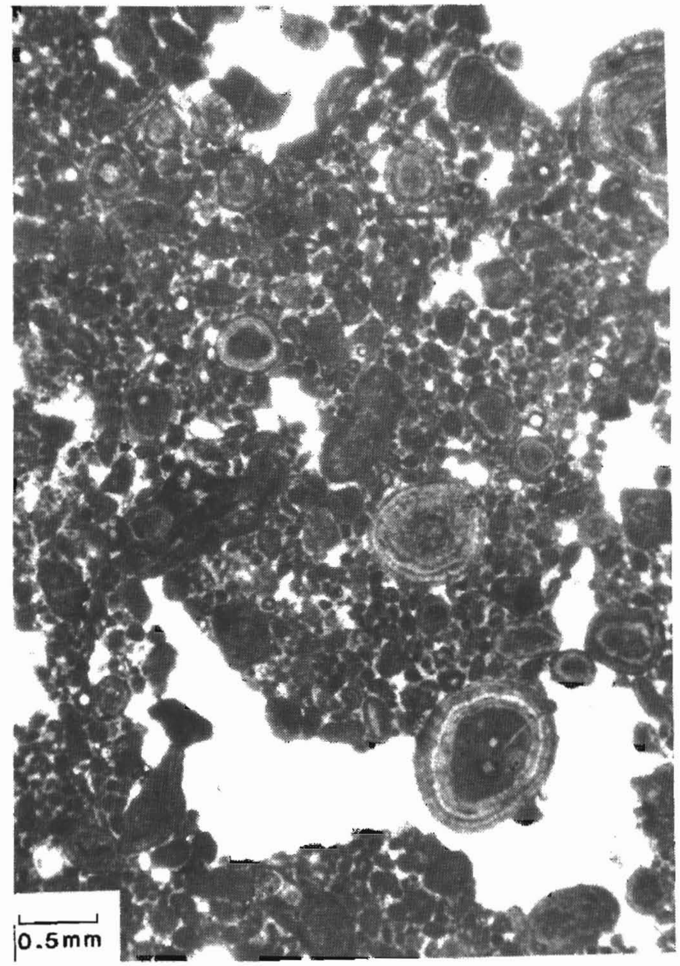

Figure 10d. (Facies 4). A photomicrograph from a shoal sequence shows small peloids and various sizes of coated grains. Fenestral pores are occluded with prismatic calcite spar and baroque dolomite cements. Sample from 9144 feet in the Sun Exploration and Production, #2 Erickson, NWNEsec 27, T152N, R102W.

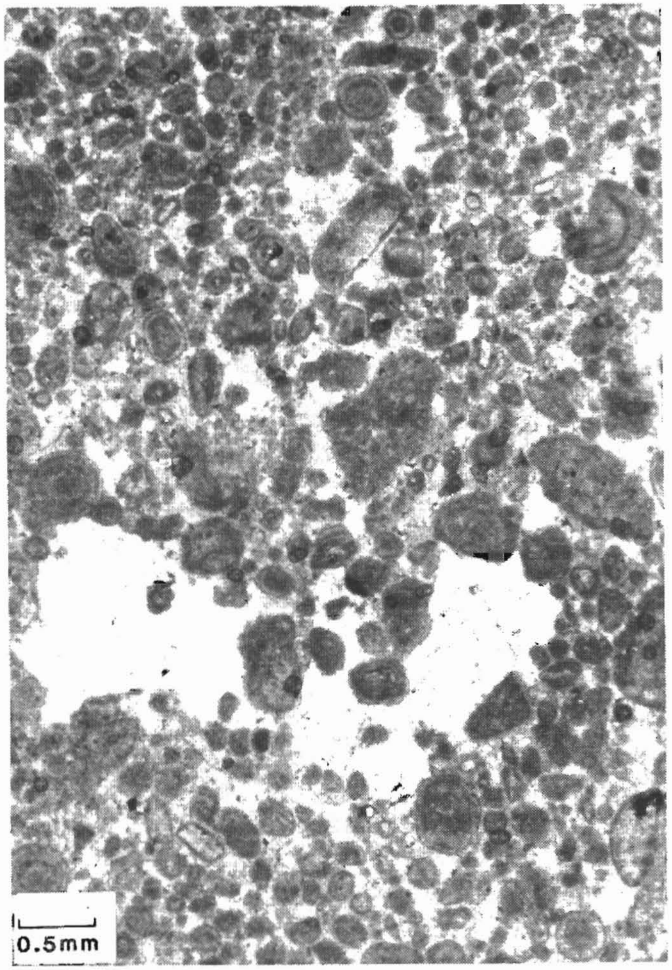

Figure 11a. (Facies 4). Fibrous calcite occludes intergranular porosity in this peloidal and ooiditic packstone. The large vuggy pore at the base of this photomicrograph is occluded with prismatic calcite spar and baroque dolomite cements. Sample is from 8045 feet in the Depco, #44-16 Larson, SESEsec 16, T159N, R102W.

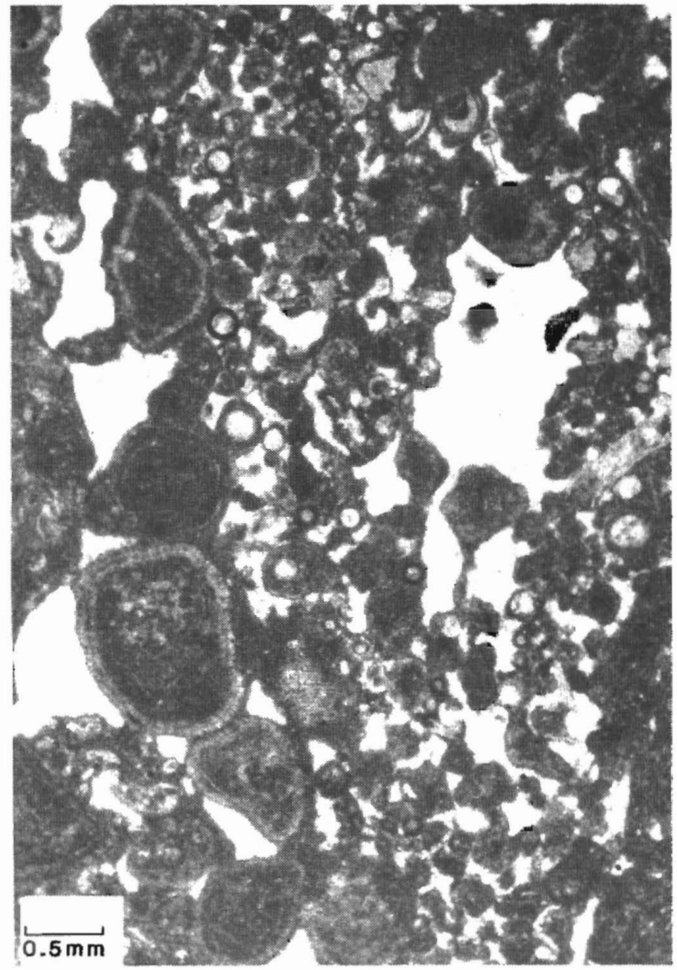

Figure 11b. (Facies 4). Calcispheres, peloids, and coated grains are part of the allochem assemblage in this packstone. Fenestral porosity is occluded with calcite spar and baroque dolomite cements. Intergranular porosity is partially preserved near the top of this photomicrograph. Sample from 9145 feet in the Sun Exploration and Production, #2 Erickson, NWNEsec 27, T152N, R102W.

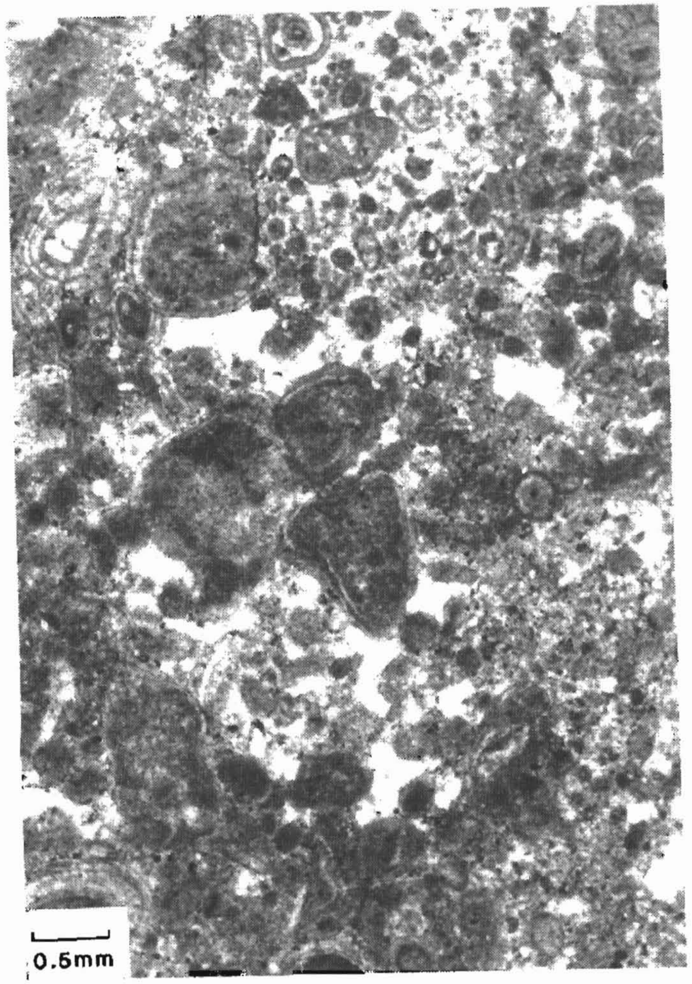

Figure 11c. (Facies 4). Intergranular pores are occluded with fibrous calcite cement in this packstone from 8045 feet in the Depco, #44-16 Larson, SESEsec 16, T159N, R102W. Baroque dolomite cement (large white spots) has further reduced porosity and permeability in this sample.

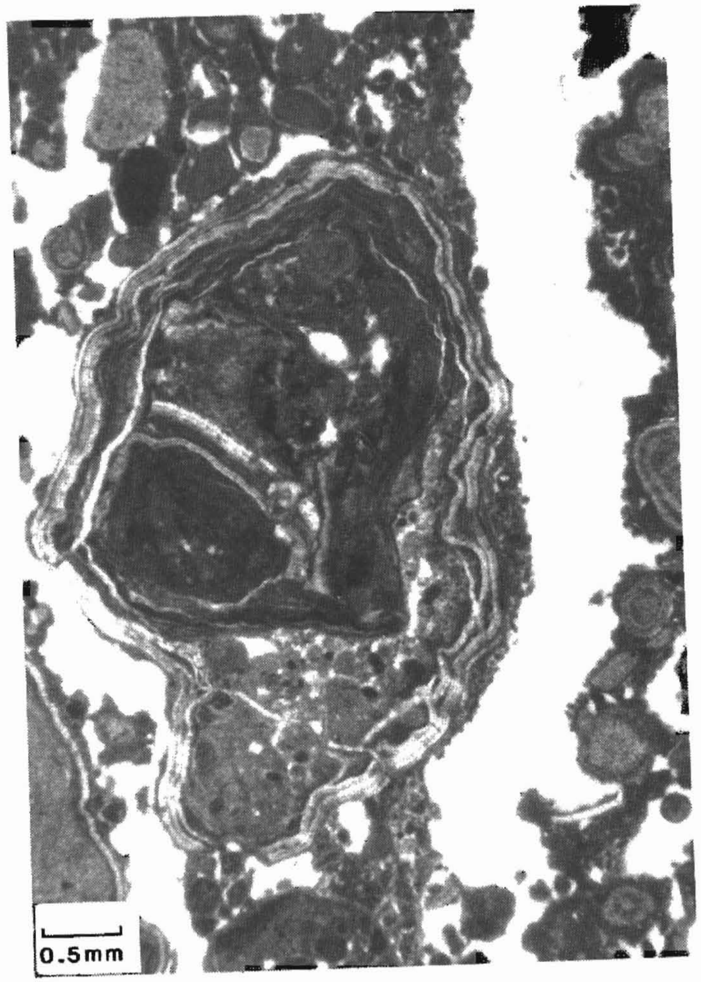

Figure 11d. (Facies 4). A large composite grain (center) shows multiple coatings indicating a complex origin. The occluded fenestral pore at right contains both fibrous calcite, lining the exterior of the pore, and sparry calcite which lines the interior. Sample from 9396 feet in the Superior, #1 Monson, NWSWsec 35, T152N, R102W.

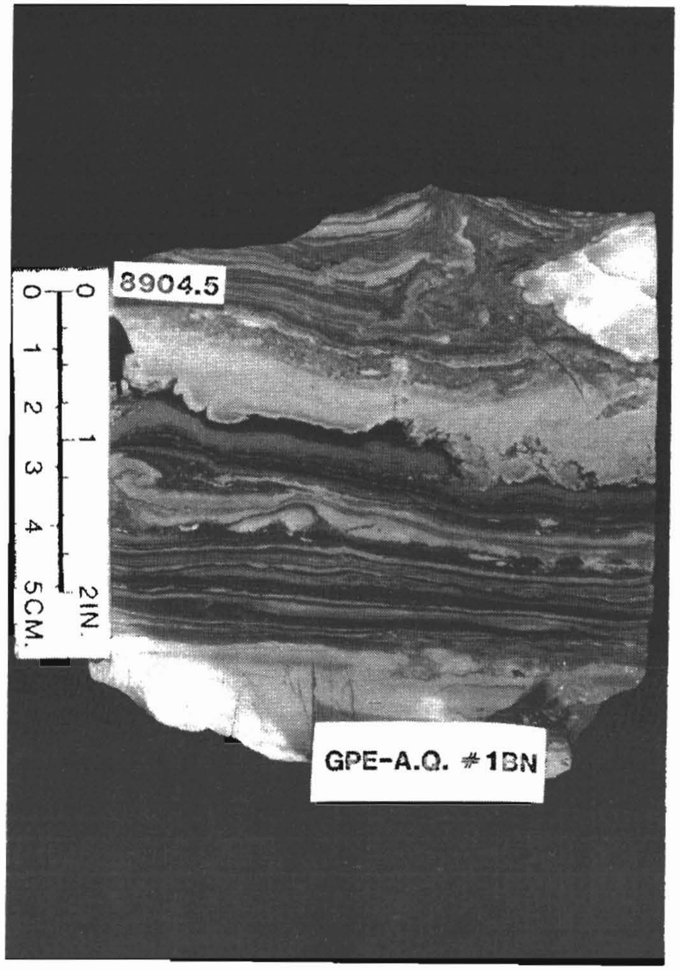

Figure 12a. (Facies 6). Wavy laminated dolomudstone of the intertidal-supratidal facies of the Flat Lake sub-interval. Some of the laminations may be stromatolites. Note the displacive anhydrite nodule at upper right indicating proximity to the sabkha. Sample from the GPE Al Aquitaine, #1 B.N., SESEsec 9, T146N, R103W.

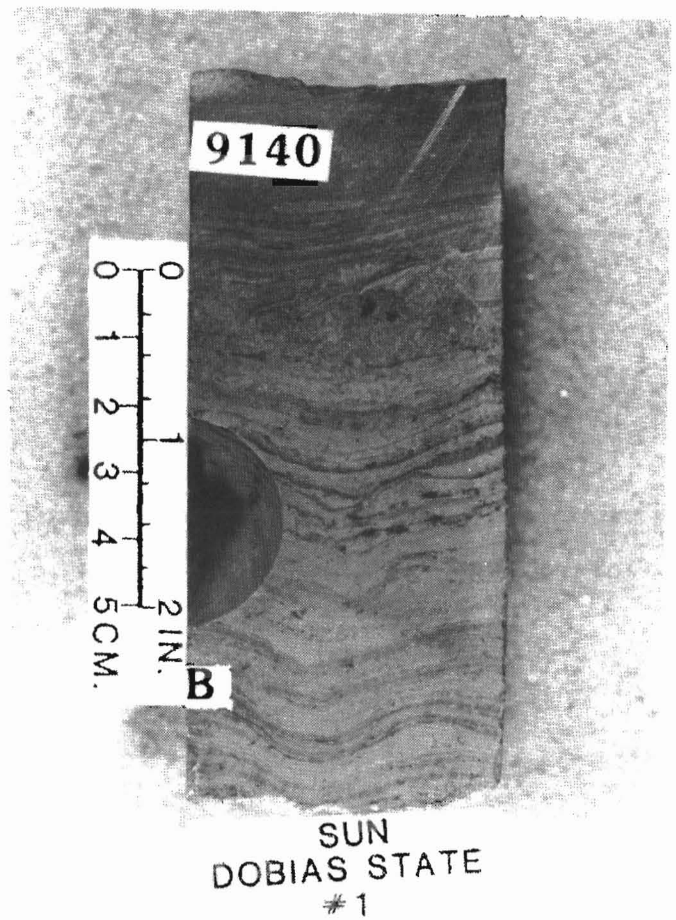

Figure 12b. (Facies 6). Another example of wavy laminated dolomudstones which were probably deposited in the high intertidal to supratidal. Some lamination may be stromatolitic. Sample from the Sun Exploration and Production, #1 Dobias State, NWNEsec 31, T152N, R103W.

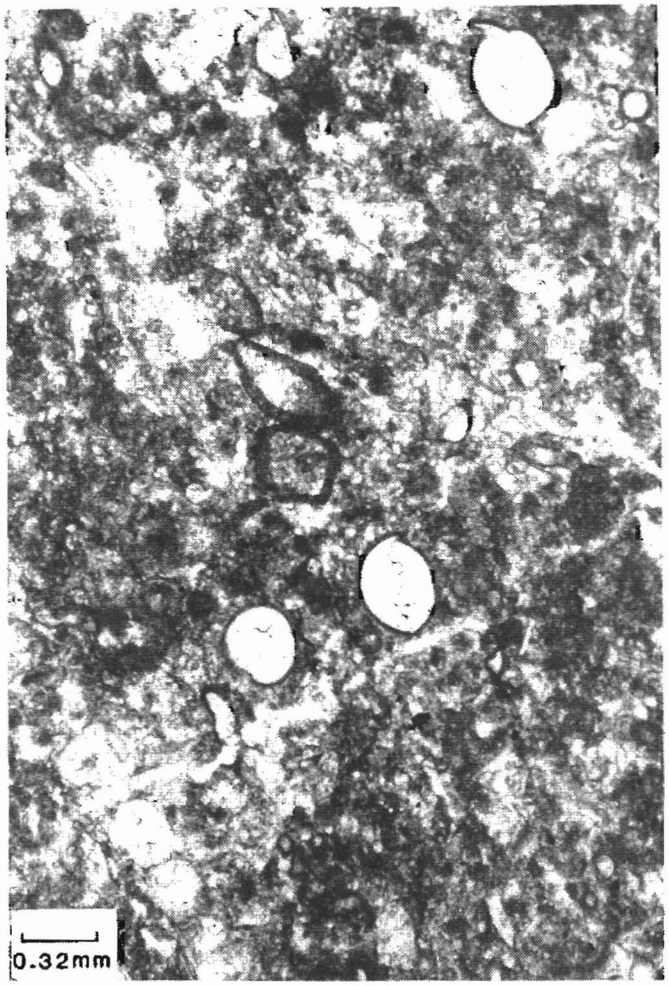

Figure 12. (C) (Facies 5 and 6). A photomicrograph shows ostracods and calcispheres in a dolomitic and anhydritic mudstone from 9141 feet in the Sun Exploration and Production, #1 Dobias State, NWNE 31, T152N, R103W. This sample may be a thin lagoonal deposit directly overlain by intertidal-supratidal deposits.

Facies 6 was deposited in intertidal to supratidal (tidal flat) environments. Thin peloidal grainstone beds may be storm washovers.

Facies 7

Bedded and nodular anhydrites (facies 7) overlie and intertongue with the stromatolitic beds of facies 6. The anhydrite beds were deposited as gypsum in supratidal or sabkha environments, and display both bedded and nodular or "chicken-wire" structures (fig. 13).

Depositional Model

The Alexander and Flat Lake subintervals of the lower Ratcliffe are shallowing upward, shoaling sequences. The Alexander subinterval in the central and western portions of Williams and McKenzie Counties was deposited within shallow shelf and restricted subtidal environments. These

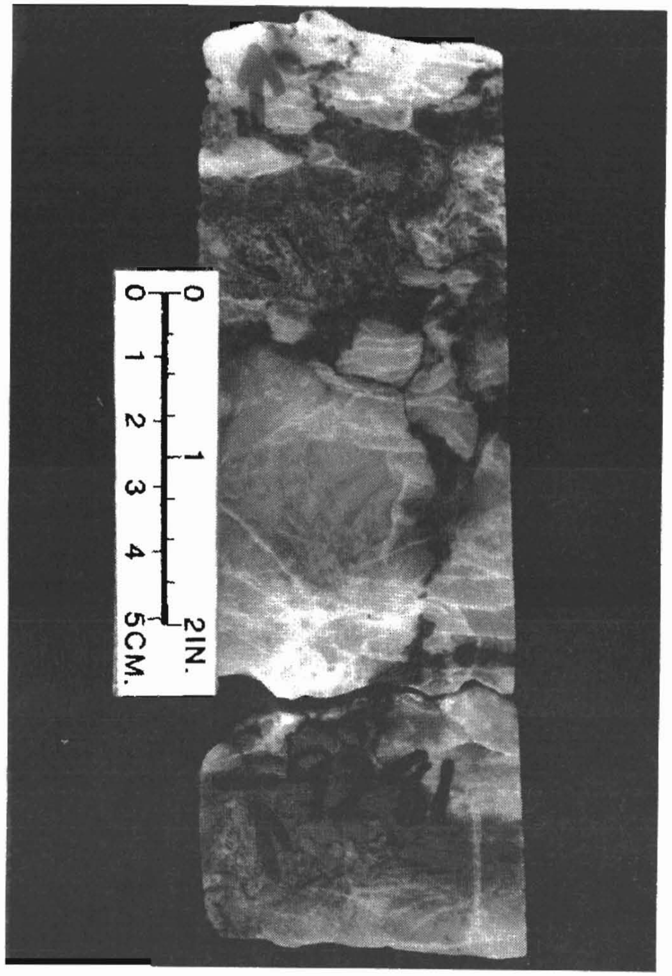

Figure 13a. (Facies 7). Nodular anhydrite from a sabkha sequence in the Depco-Pennzoil, #22-32 Federal, SWNEsec 22, T147N, R101W.

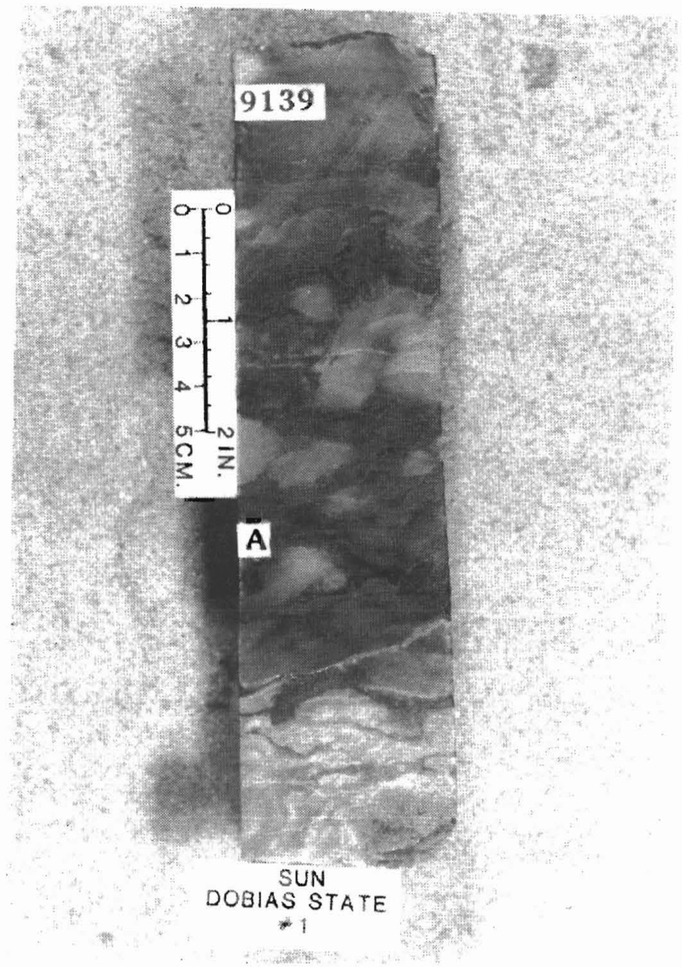

Figure 13b. (Facies 7). Nodular anhydrite from a sabkha sequence in the Sun Exploration and Production, #1 Dobias State NWNEsec 31, T152N, R103W.

sediments were deposited along a shallow carbonate ramp or shelf which was periodically restricted. Dolomitization of restricted subtidal beds (facies 2) by a seepage-reflux mechanism produced localized lenses of porosity associated with paleostructures. These beds are locally productive in the Alexander, Glass Bluff, and Indian Hills fields.

The Flat Lake subinterval contains shallowing upward, restricted subtidal, intertidal, and supratidal sequences. Some shallowing upward sequences contain laminated calcrete crusts indicating possible subaerial exposure of shoals. Nodular anhydrite in the subinterval was probably precipitated as gypsum within a sabkha.

The Flat Lake subinterval is locally productive in Elk, Sioux, Glass Bluff, and Indian Hills fields.

The presence or absence of coated grains indicates the position of the Flat Lake subinterval relative to bathymetry and paleostructure. Coated-grain sequences (facies 4) are normally found near or along the tops of paleostructures. Original intergranular and fenestral porosity has been solution enhanced and is locally productive in Elk, Sioux, Glass Bluff, and Indian Hills.

The depositional environments of the Alexander and Flat Lake subintervals are summarized in figure 13. This figure shows typical depositional environments of these subintervals across a structural nose.

CONCLUSIONS

The lower Ratcliffe interval in the central and western portions of Williams and McKenzie Counties has been informally divided into the Midale, Berentson, Alexander, and Flat Lake subintervals. These shallowing upward subintervals prograded from sabkha environments in the east to normal marine environments in the central and western portions of the basin.

The Alexander and Flat Lake subintervals are locally productive in the central basin. Both subintervals are shallowing upward sequences, but are productive in different lithofacies.

Intercrystalline porosity in the Alexander subinterval was produced by partial dolomitization. Intergranular and fenestral porosity is partially preserved in the Flat Lake subinterval. Solution-enhancement of these pores and the preservation of vuggy porosity have produced good reservoirs locally.

ACKNOWLEDGMENTS

John Grube and Bruce Birge read the manuscript and offered helpful suggestions. Tom Hendricks, SRG, Inc., helped in photographing core samples. Special thanks are given to the many companies who have contributed cores and core data for studies in the central Williston Basin.

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SILURIAN INTERLAKE GROUP: A SEQUENCE OF CYCLIC MARINE AND FRESHWATER CARBONATE DEPOSITS IN THE CENTRAL WILLISTON BASIN*

by
Esther R. Megathan
Esther R. Magathan & Associates
Consulting Geologists
535 Garfield Street
Denver, Colorado 80206

ABSTRACT

Dramatic paleoenvironmental changes are recorded by Interlake facies, fossil assemblages, diagenetic textures, and cements in the central Williston Basin. They demonstrate that depositional conditions during the Silurian initially oscillated between open marine and hypersaline, but were ultimately replaced by freshwater environments. These changes significantly affected the hydrocarbon potential of Interlake rocks because they resulted in geographically and stratigraphically confined source beds and seals, and in a variety of reservoirs whose properties were influenced both by facies and diagenesis.

Seven Interlake formations, represented in three cores from the Nesson anticline area, illustrate the carbonate facies sequence typical of the central part of the basin. The Lower Interlake Strathclair, Fife Lake, and Guernsey Formations incorporate turbidites, organic-rich basin laminites, anhydrites, and quartz-bearing 'event' markers, recording depositional cycles initiated in deep waters of normal marine salinity, and terminated in shallower, hypersaline water. The Middle Interlake Cedar Lake Formation typically is of dolomite sequences alternately rich in, and barren of, marine fossils, suggesting that salinity variations continued but were less extreme than in Lower Interlake time. The Upper Interlake Mendenhall, Missouri Breaks, and Sherven Formations contain only freshwater fossils, and document the filling of a terrestrial inland basin by lake, marsh, and stream sediments cannibalized from older carbonates exposed around the basin margin.

These highly variable depositional regimes have resulted in excellent source, reservoir, and seal facies within Interlake formations. Rocks with source rock potential accumulated during several phases of marine and freshwater deposition. Reefs and associated skeletal deposits, when dolomitized, form good reservoirs in Lower and Middle Interlake formations, and porous marsh, stream, and karst deposits, where flushed by undersaturated groundwaters, are excellent reservoirs in the Upper Interlake. Interlake seals are products both of facies and diagenesis: several depositional evaporites confine Lower Interlake reservoirs, whereas Upper Interlake reservoirs are confined both by tightly cemented quartzites and by halite remobilized during late burial diagenesis. Regionally, the entire Interlake sequence is confined by impermeable facies of the overlying Ashern Formation.

Major discoveries in recent years have established several Interlake formations as attractive exploration targets, yet wildcatting has been limited due to the lack of coherent regional stratigraphic, facies, and diagenetic models. Core studies offer the only sound basis for developing these models, and have been successfully integrated with sample studies and log suites to regionally correlate and map prospective reservoir, source, and seal facies in the most prospective central part of the basin.

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*This paper is derived from a proprietary study developed for a client base which includes Anadarko Production Company, Conoco, Inc., Marathon Oil Company, Sun Exploration and Production Company, and Texaco, Inc. Their permission to release this information is greatly appreciated.

INTRODUCTION

Significant new oil and gas discoveries in the Silurian Interlake Group over the past decade have led to renewed efforts to map and interpret the cryptic lithologies of this dolomitic carbonate sequence in North Dakota and Montana. Extensive coring has accompanied recent drilling, particularly along the Nesson anticline, and this coring, combined with facies and diagenetic analogs discovered since 1970, has made it possible to elucidate a depositional and diagenetic history which logically explains the genesis, migration, and entrapment of hydrocarbons in Interlake rocks.

Interlake rocks record a succession of dramatic paleo-environmental changes across the Williston Basin in which salinity shifts were particularly pronounced. Driven by recurring arid climates, Lower Interlake seas changed cyclically from normal marine to hypersaline, while Middle Interlake seas appear to have oscillated between normal marine and mildly hypersaline (or brackish). By contrast, humid conditions accompanied Upper Interlake sedimentation and deposition was exclusively by freshwater systems. This changing climatic scenario greatly influenced the hydrocarbon potential of various Interlake strata, resulting in the accumulation of numerous strati-graphically confined source beds, a variety of facies- and diagenetically-controlled reservoirs, and a number of stratigraphic seals.

Cores from three producing wells along the southern Nesson anticline display lithologies representative of Interlake beds in the central part of the basin and emphasize the facies contrasts which distinguish Lower, Middle, and Upper Interlake strata there. These cores are:

1. Texaco Inc., #1 Missouri Breaks (SWSEsec 10, T153N, R96W): intervals 11,780' - 11,880' 12,656' - 12,680', and 12,768' - 12,890'.

2. Home Petroleum #1 Sherven (NWSWsec 26, T153N, R95W): interval 12,101' - 12,037';

3. Prosper Energy #27-1 Sherven (NWSEsec 27, T153N, R95W): interval 12,025' - 12,208.5'.

Figure 1 shows the stratigraphic positions of these three cores, numbered as above, with respect to a typical gamma log signature and the formations described in this paper.

STRATIGRAPHY AND FACIES SEQUENCE

Interlake Nomenclature: Not a 'Formation', But a Group of Formations

The name 'Interlake' was first assigned by Baillie (1951) to a <u>group</u> of Silurian carbonate formations he mapped from outcrops in the 'Interlake' region of central Manitoba between Lake Manitoba and Lake Winnipeg. By recognizing the Interlake sequence as a Group of formations, Baillie ranked it in magnitude with the Devonian Elm Point Group and the Mississippian Madison Group. This ranking is appropriate, given the time span encompassed by Interlake deposits, and the fact that lithologically distinct formations can be discriminated within it. For these reasons, the Interlake is referred to here as a <u>Group</u> in preference to the common practice of referring to it as a formation. Apart from adhering to the rule of precedence in stratigraphic nomenclature, most geologists will find that this usage eliminates some practical problems associated with referring to the Interlake as a formation:

(a) referencing the Interlake as a formation leads one to think of it as a

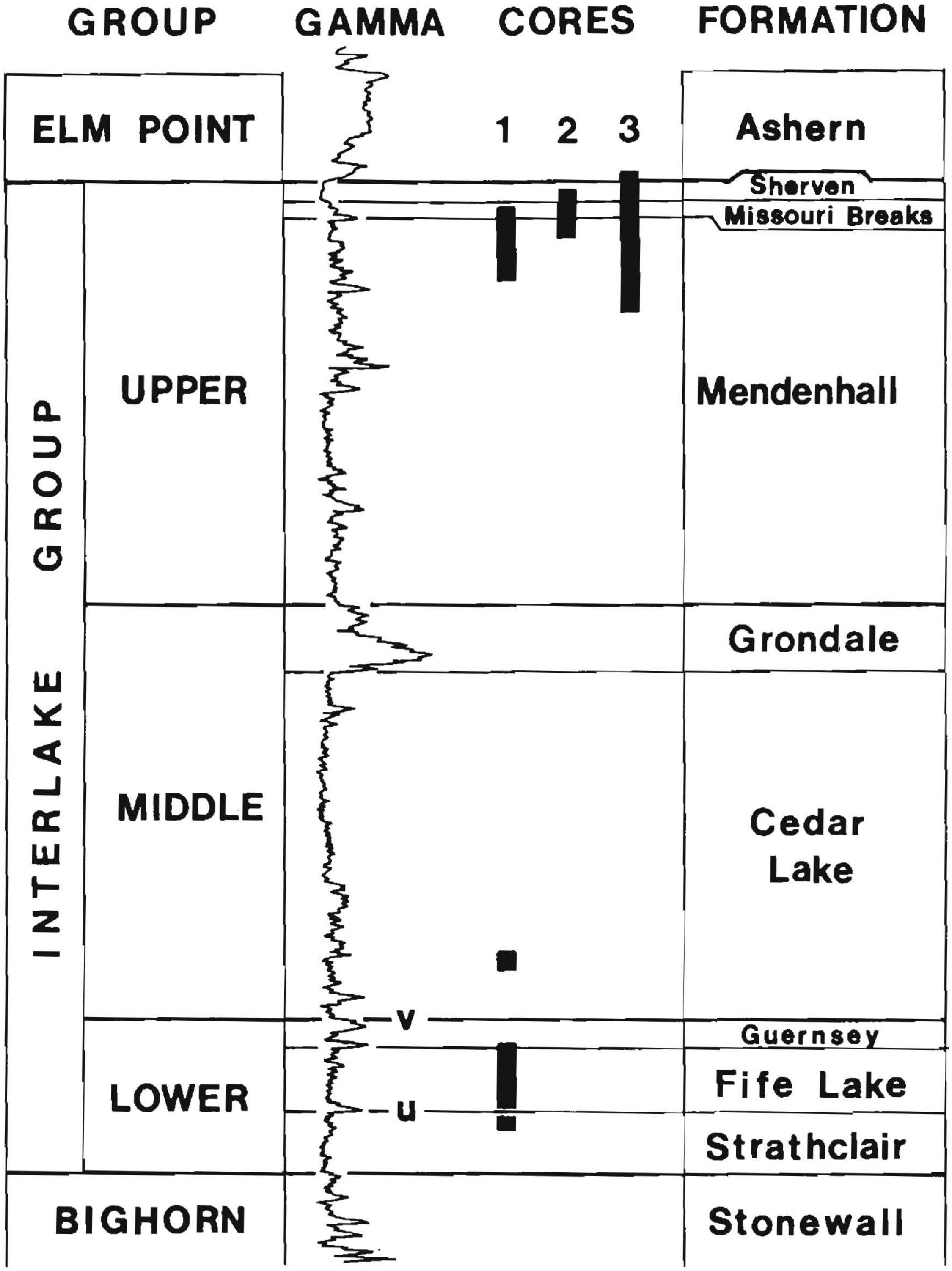

Figure 1. Stratigraphic position of cores

Vertical scale approximately 1" = 200'

uniform sequence of genetically similar facies, when in fact it is a non-uniform sequence of genetically disparate facies.

(b) referencing the Interlake as a formation leads explorationists to think of it as a single exploration target, rather than a complex sequence involving many different plays.

Geologists who are prepared to adopt the stratigraphic nomenclature proposed in this paper may gain an improved appreciation of the sedimentology and petroleum potential of this poorly understood sequence.

Stratigraphic Subdivision

Three Interlake subgroups can be distinguished on the basis of log characteristics originally identified by Porter and Fuller (1959), and eight separate formations have been recognized within these subgroups (Magathan, 1986). Formation nomenclature has been extended, where appropriate, from units previously described or referred to by Stearn (1956), King (1964), and Jamieson (1979). The historical evolution of this nomenclature is graphically illustrated by figure 2.

Major characteristics of the three subgroups are as follows:

1. The Lower Interlake Subgroup demonstrates a regional pattern of uniform 'layer-cake' stratigraphy, in which a series of 'clean' limestones and dolomites are punctuated by several gamma markers which persist across the entire basin. Three distinctive map units are recognized: the Strathclair, Fife Lake, and Guernsey Formations.

2. The Middle Interlake Subgroup is dominantly of clean dolomites. Regional cross sections suggest 'layer-cake' accumulation, but internal markers are not persistent and, except for defining the Grondale/Cedar Lake Formation boundary, do not facilitate further subdivision of the sequence.

3. The Upper Interlake Subgroup is characterized by a 'busy' radioactive signature with many striking, but laterally nonpersistent, markers. Three mappable formations were discriminated within this sequence: the Mendenhall, Missouri Breaks, and Sherven Formations.

Seven of the eight Interlake formations recognized in the central Williston Basin are represented in the cores selected for this workshop. They illustrate the facies sequence typical of the central part of the basin, but contrast in significant ways with facies identified in cores from Saskatchewan and Montana and Manitoba outcrops.

Lower Interlake Subgroup

The Lower Interlake Subgroup, which includes the Strathclair, Fife Lake, and Guernsey Formations, incorporates recurring cycles of turbidites, organic-rich basin laminites, anhydrites, and pebble-bearing 'event' markers, demonstrating cyclic shifts from normal marine to hypersaline deposition in the deep central part of the basin where these cores were cut. Each of these formations is represented in the core from the Texaco Inc. #1 Missouri Breaks well, and discussions of Lower Interlake units which follow are based on this core. Generally speaking, the basal marine turbidites in each cycle comprise limestones or dolomitic limestones, whereas overlying laminites tend to be entirely of dolomite. Bedded anhydrites or anhydritic dolomites cap each cycle, recording precipitation from hypersaline brines and suggesting that cycles were terminated by evaporative drawdown promoted by arid climatic conditions as modeled by Schmalz (1969).

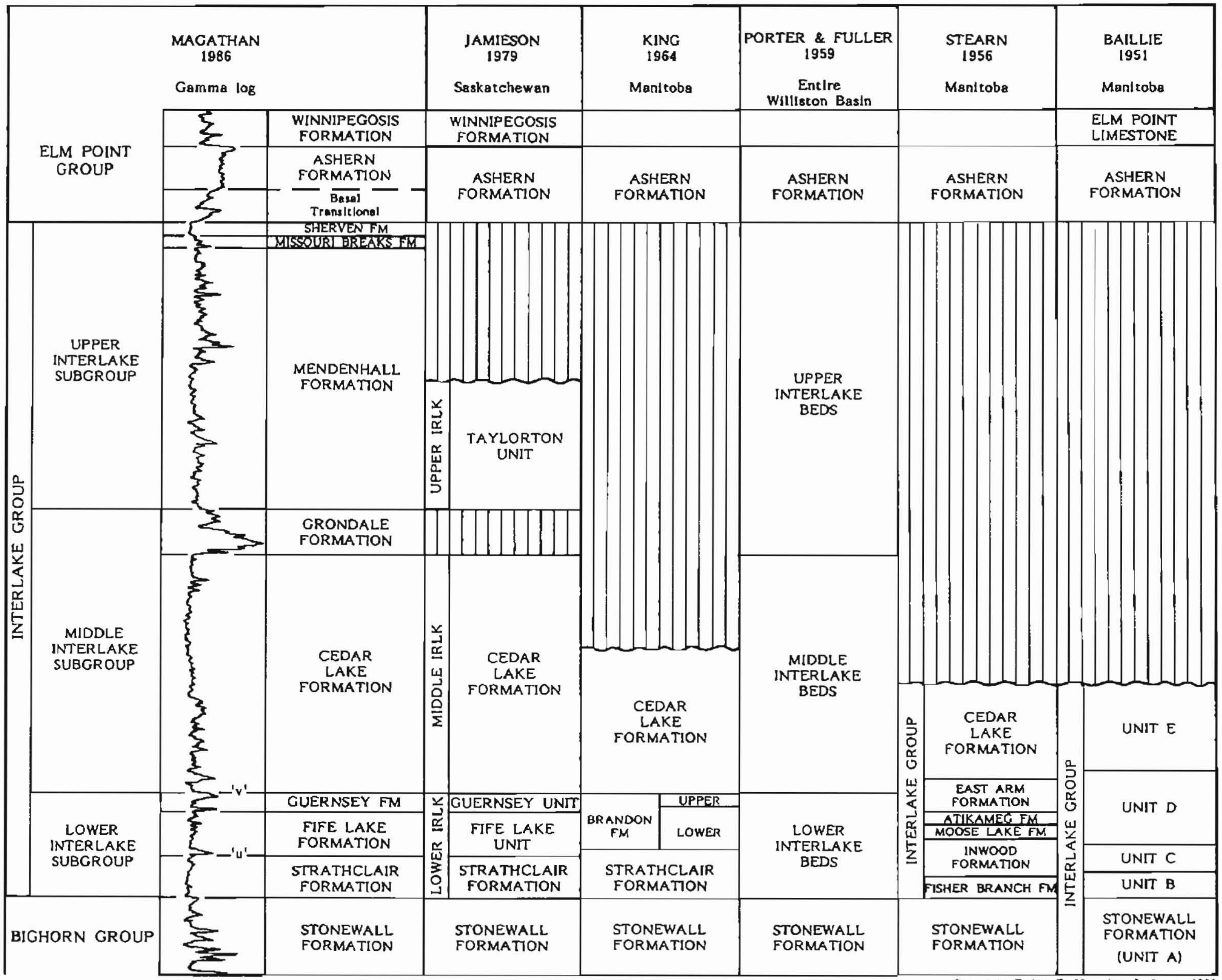

Figure 2. History of stratigraphic nomenclature of the Interlake Group.

Representative facies are illustrated in figure 3.

Strathclair Formation

The Strathclair Formation was proposed for the lowest unit of the Interlake Group by King (1964, p. 52), who designated as the type section the interval between 3118'-3157' in the Dome Strathclair well (8-34-16N-21W1) in southern Manitoba. This formation has been traced across Saskatchewan (Jamieson, 1979) and south along the Nesson anticline using the base of Porter and Fuller's 'u' marker as its upper boundary, a contact which marks a more abrupt lithologic change than the top of the marker, which King used to designate the boundary.

Part of the Strathclair Formation has been cored in the Texaco Inc. #1 Missouri Breaks well (10-153N-96W) where it is represented by the interval labeled 12,850' - 12,855'; adjusted to log measurements the corrected depth (C.D.) is 12,858' - 12,868'. In this core, the Strathclair is comprised entirely of dusky-yellowish-brown (10YR2/2)* microcrystalline dolomite. Although dominantly homogeneous in texture, convoluted lamination can be seen near the base of the core, and felted anhydrite needles are apparent in laminae at 12,857.5' (C.D. 12,865.5'). An absence of fossils suggests abnormal salinities, and the dark colors suggest a high indigenous organic content. Porosity measurements from core plugs in this interval ranged from 0.4% to 1.2%, and measured permeability was invariably less than 0.01 md except in fractured specimens, where measurements ranged up to 0.42 md.

Fife Lake Formation

Fife Lake was first used by Jamieson (1979) to designate a Lower Interlake carbonate unit which had previously been referred to as the Lower Member of the Brandon Formation (King, 1964, p. 52-53). Significant lithologic differences between this and the Upper Member of King's Brandon Formation were apparent in Saskatchewan cores, justifying separate formational status for the two units. The name Fife Lake was derived from an area near which the most complete sections of this unit were cored in Saskatchewan, and the type section is designated as the interval between 8257'-8305' in the Imperial Constance well (8-36-3-29W2) as described by Jamieson (1979).

The Fife Lake Formation is represented in the Texaco Inc. #1 Missouri Breaks core by the interval 12,770' - 12,830' (C.D. 12,781' - 12,836'). Parts of three major marine-evaporite cycles are preserved in this core, and basal contacts of two are displayed: the lower of these contacts is at 12,823' (C.D. 12,829'), and the upper is at 12,792' (C.D. 12,803'). Both contacts are marked by an upward change from dolomite to limestone which can be identified on the CNL-FDC log by proximal tracking of the neutron and density signatures along the zero baseline.

Sequences immediately above the contacts consist of skeletal turbidites: repetitive upward-fining lime packstone-mudstone beds in which skeletal debris and angular to subrounded flat limestone pebbles are common (fig. 3G,H). Gastropods and ostracodes are the most abundant skeletal grains, but some pelecypod and crinoid fragments have been noted in the upper cycle. Bioturbation is common in the muddy parts of these beds, and Chondrites burrows are present at 12,791' (C.D. 12,802'). From their repetitiveness, poor sorting, and upward fining, they are interpreted as marine slope deposits whose coarse components were derived from adjacent shallow shelf areas and swept downslope as debris flows into a basin dominated by fallout deposition

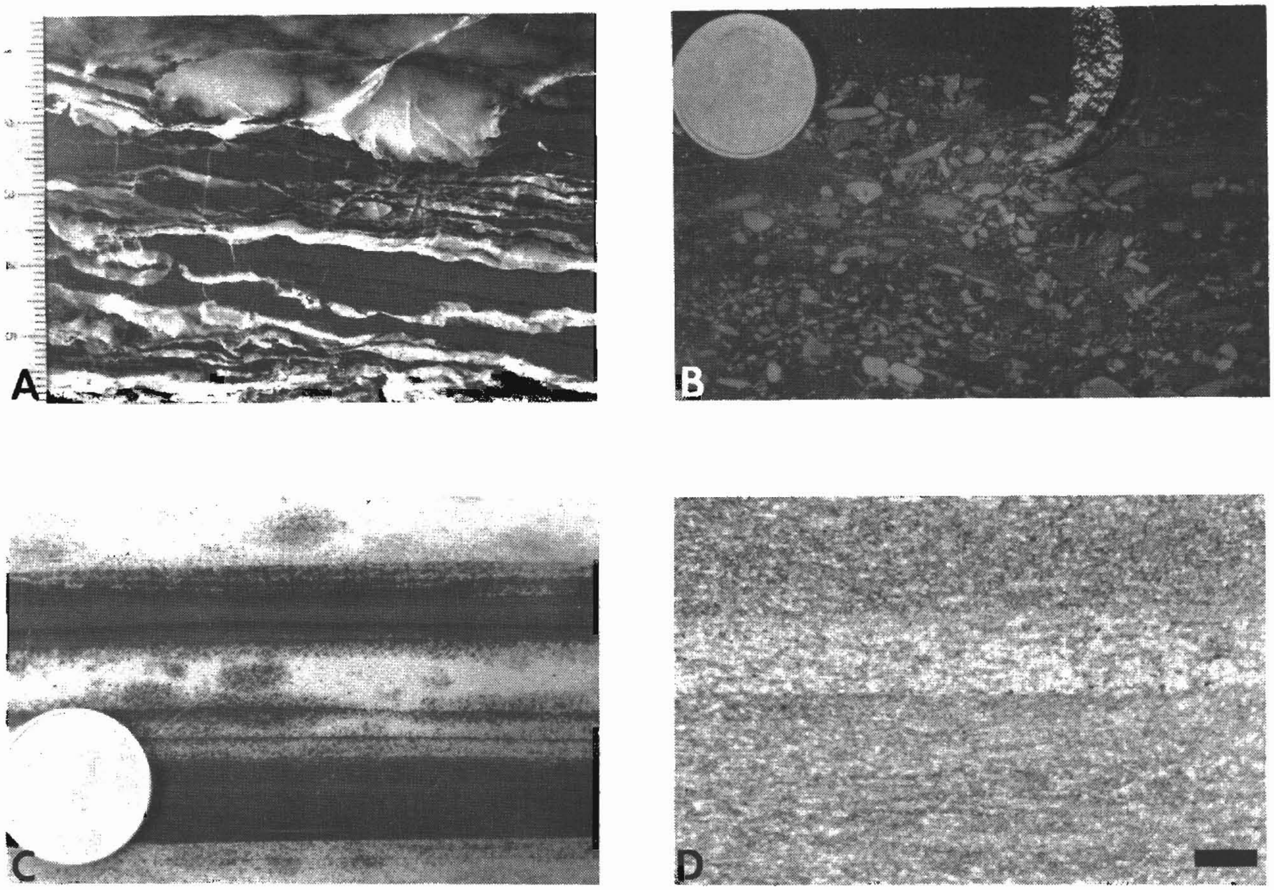

Figure 3. Lower Interlake facies cycles in the Central Williston Basin.*

Representative facies are illustrated by polished core surfaces selected from various wells and are displayed in normal order of succession, from bottom to top.

A. Bedded anhydrite. Lower Interlake cycles are capped by beds of nodular and contorted anhydrite, interlaminated with dark, organic-rich dolomite mudstone. Deformation of dolomite suggests displacive growth of anhydrite from an inferred gypsum precursor. Amerada #1 Iverson-Nelson: 12,365′. Strathclair Formation.

B. Fife Lake ′event′ marker. Anomalous bed of heterogeneous dolomite pebbles has interrupted the continuity of Lower Fife Lake laminites in the central part of the basin, preserving the result of a major marine transgression following a prolonged phase of evaporative drawdown. Texaco #1 Missouri Breaks: 12,792′.

C. Interlaminated anhydrite and dolomite. Pale microcrystalline dolomite, interlaminated with dark fine to medium crystalline anhydrite, records subaqueous accumulation of evaporites from hypersaline waters. Dark splotches are clusters of anhydrite crystals. Amerada #1 Iverson-Nelson: 12,323′. Fife Lake Formation.

D. Microscopic texture of interlaminated anhydrite and dolomite. Thin section shows intimate felting of microcrystalline dolomite rhombs (gray) and anhydrite crystals (white). Scale bar = 0.5 mm. Amerada #1 Iverson-Nelson: 12,323′, plane light. Fife Lake Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

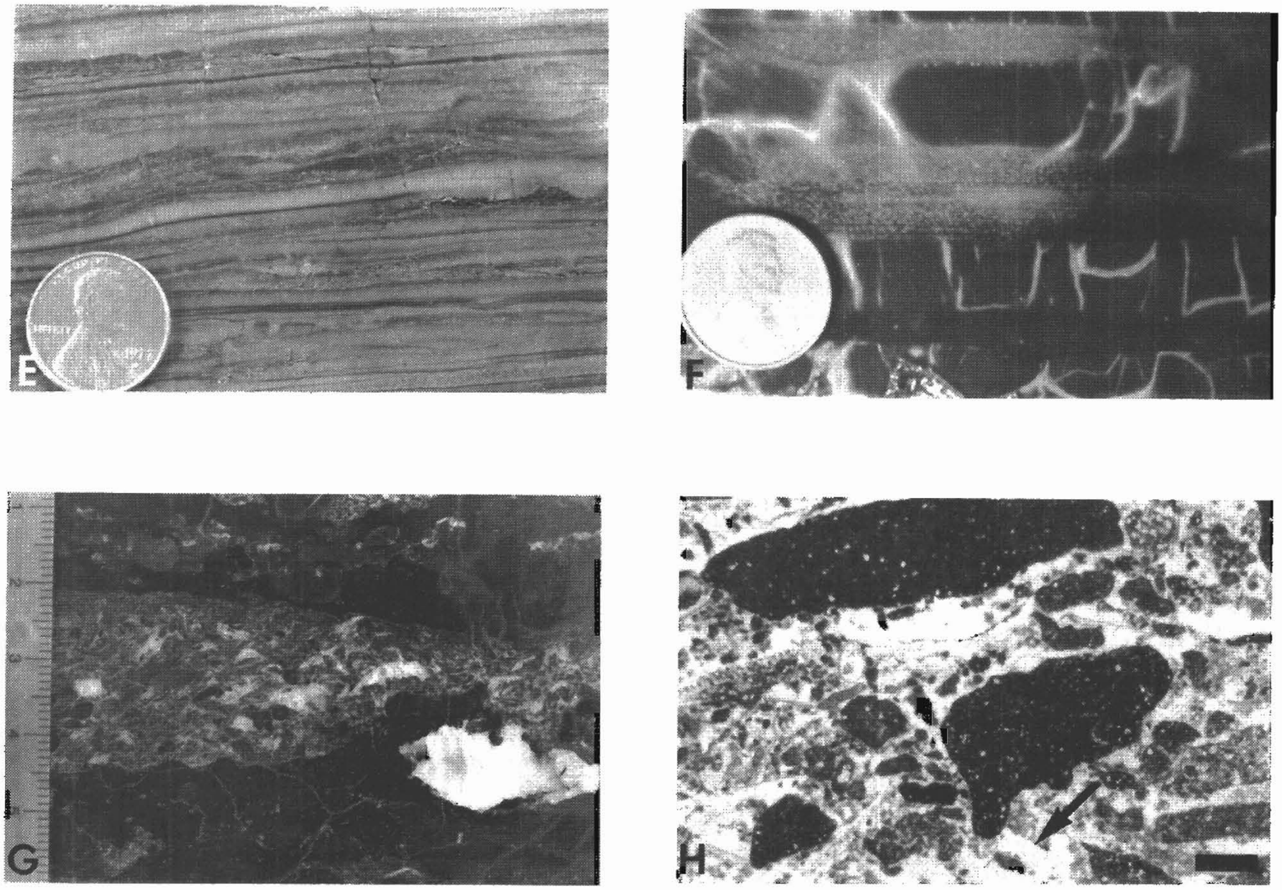

Figure 3*--Continued.

E. Basin laminite. Conspicuous ryhthmic laminations characterize basin deposits. Here, pellet packstones alternate with laminated mud. Dark laminae are of anhydrite crystals. Amerada #1 Iverson-Nelson: 12,350′. Fife Lake Formation.

F. Interbedded shelf-derived muds and basin laminites. Slurries of unfossiliferous homogeneous lime mud have interrupted background fallout of bituminous dolomite laminae from anoxic basin waters. Dark color and laminated fabric suggest source rock potential. Late diagenetic calcite spar has filled tension cracks that developed after muds had lithified. Texaco #1 Missouri Breaks: 12,780′. Fife Lake Formation.

G. Skeletal turbidites. Lenticular beds of skeletal and lithoclast packstone alternate with fine-grained burrowed lime mudstones at the base of Lower Interlake cycles, documenting episodic introduction of shelf-derived sediments onto the basin floor. Coarse white calcite has plugged all primary voids. Amerada #1 Iverson-Nelson: 12,316′. Fife Lake Formation.

H. Lithoclast-rich turbidite. Thin section shows grain-supported debris flow dominated by large imbricated lithoclasts, with accessory marine fossils and peloids. Recognizable skeletal grains include crinoid ossicles (arrow), mollusk fragments, brachiopods, and ostracodes. Scale bar = 0.5 mm. Amerada #1 Iverson-Nelson: 12,318′, plane light. Fife Lake Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

of fine lime mud, clay, and organic material. Significantly, the limestone slope deposits are tight because both intergranular and intragranular pores are invariably filled with clear calcite cement. Porosity measurements from core plugs in these intervals average 0.3%, and range only as high as 0.9%, while permeability is negligible.

Skeletal-lithoclast debris flows grade upward into homogeneous (burrowed?) microcrystalline dolomite (12,801' = C.D. 12,809') in the lower cycle, and into laminated (current-bedded?) unfossiliferous lime mudstones (12,780' = C.D. 12,783.5') in the upper cycle (fig. 3F). The homogeneous dolomite of the lower cycle is very porous, as is apparent from the CNL-FDC log, but permeability is low. Porosity measurements from core plugs in this interval range between 10% and 16.1%, averaging 13.2%, while measured permeability ranges between 0.01 and 0.05 md. By contrast, the undolomitized laminated lime mudstones of the upper cycle are invariably tight, and porosity does not exceed 0.3%.

Lamination becomes increasingly well-preserved in the upper part of each cycle (fig. 3F), and may be somewhat discontinuous, or so uniform and planar as to appear varve-like, as between 12,793' and 12,795' (C.D. 12,804-06'). Finely disseminated pyrite is common in the laminated zones, and rock colors are typically dusky yellowish brown (10YR 2/2). Anhydrite may be present as finely crystalline needles which are felted within, but masked by, the host carbonate. Such occurrences may be detected more readily by strong negative density log responses (as occurs between 12,804' and 12,811') than from the cores themselves (fig. 3C,D). Alternatively, anhydrite is interbedded with the laminites as contorted bands or beds which range from a few centimeters to more than 15 cm. in thickness (fig. 3A). Both laminites and anhydrites are attributed to precipitation in deep water from density-stratified hypersaline brines, as has been proposed for comparable Messinian facies in Sicily (Bellanca and Neri, 1986). The anhydrites and anhydritic laminites may form excellent barriers to hydrocarbon migration within Lower Interlake strata.

An anomalous pebble band demarcates the boundary between cycles in the Fife Lake Formation at 12,792-93' (C.D. 12,803-04'), serving as an 'event' marker which marks a change from passive fallout deposition of evaporitic mud to active deposition of shelly, shelf-derived lime muds (fig. 3B). Contortion and disruption of underlying muds suggests that this change occurred prior to cementation and was dramatic in nature. The heterogeneous, rounded dolomite pebbles were probably derived from pre-existing carbonate muds exposed and desiccated around the basin margins during periods of evaporitive drawdown. They were transported across the basin by the massive flood event which reintroduced marine waters into the basin for the final cycle of Fife Lake deposition.

Guernsey Formation

'Guernsey' was introduced by Jamieson (1979) to designate the uppermost map unit of the Lower Interlake Subgroup with type section in the Imperial Guernsey well, the first locality in Saskatchewan (13-34-33N-23W2) in which the interval was completely cored. In this well, the formation is defined as the interval between depths of 4,160' and 4,184'. Bracketed by strong radioactive spikes, the formation has a distinctive gamma signature which makes it the easiest Interlake formation to trace in the subsurface.

The Guernsey is a nondescript sequence of interbedded dolomite, argillaceous dolomite, and anhydrite in the central part of the basin. In this area, Guernsey lithologies cannot be easily distinguished from uppermost beds of the underlying Fife Lake Formation because all Lower Interlake lithologies are very dark in color. However, in distal shelf sequences, where Lower Interlake beds tend to be very pale dolomites, the Guernsey radioactive beds contrast strongly with adjacent lithologies because of their dark color and high content of clay, quartz silt, and floating grains of large, well-rounded quartz sand. Except for occasional burrows, fossils have not been identified from this formation.

Guernsey beds are invariably non-porous, but anhydrite beds developed within the formation may serve as seals for underlying Fife Lake reservoirs.

Middle Interlake Subgroup

Cedar Lake Formation

The Cedar Lake Formation is a thick sequence of dolomitized carbonates characterized on gamma logs by a relatively monotonous signature of low intensity. The formation was first named by Stearn (1956, p. 37) for a series of "fine-grained, thin-bedded, greyish yellow dolomites" that crop out in the Cedar Lake region of central Manitoba, and was later extended to subsurface nomenclature by King (1964, p. 52-53), who convincingly correlated it with strata assigned to the Middle Interlake in the subsurface by Porter and Fuller (1959, p. 164).

Lowermost Cedar Lake strata appear to be transitional from Lower Interlake units in the central part of the basin, where log signatures indicate the presence of anhydrite beds as well as several radioactive spikes. The character of Cedar Lake facies above the basal transitional beds is the least understood part of the Interlake Group, due to a paucity of core, pervasive dolomitization, a relatively characterless gamma signature, and the absence of regional marker horizons. Available cores are of dolomite sequences alternately rich in, and barren of, skeletal marine fossils. We infer from the barren dolomites that salinities must have periodically been elevated enough to eliminate invertebrate life, for they typically retain primary bedding lamination (which is stromatolitic in many places) but contain no evidence of skeletal remains, nor of bioturbation (fig. 4G).

In fossil-rich sequences, a broad range of marine forms has been recognized, including: massive, tabular, branching, and bulbous stromatoporoids, solitary and colonial rugose corals as well as tabulate forms, crinoids, bryozoans, brachiopods, and mollusks (fig. 4A-F). Dolomitization has so masked the structure of many of these fossils that they are just barely recognizable under binocular microscopes as 'ghosts' on rock surfaces. Because fossils and other primary constitutents can seldom be identified in thin sections, interpretation of Cedar Lake facies is more satisfactorily achieved by examining polished core surfaces and well cuttings than by conventional thin section petrography.

Sedimentary style can be inferred from bedding features unaffected by dolomitization, and from the textures of replacement dolomites. Bedding features indicate that subaqueous processes dominated throughout Middle Interlake time, for facies contacts tend to be conformable, demonstrating that sedimentation was uninterrupted across major facies changes. Common bedding features include lamination, contortion, bioturbation, current bedding, and accretionary reef fabric.

Dolomite textures appear to have been inherited from the original sediments. Fossiliferous beds tend to

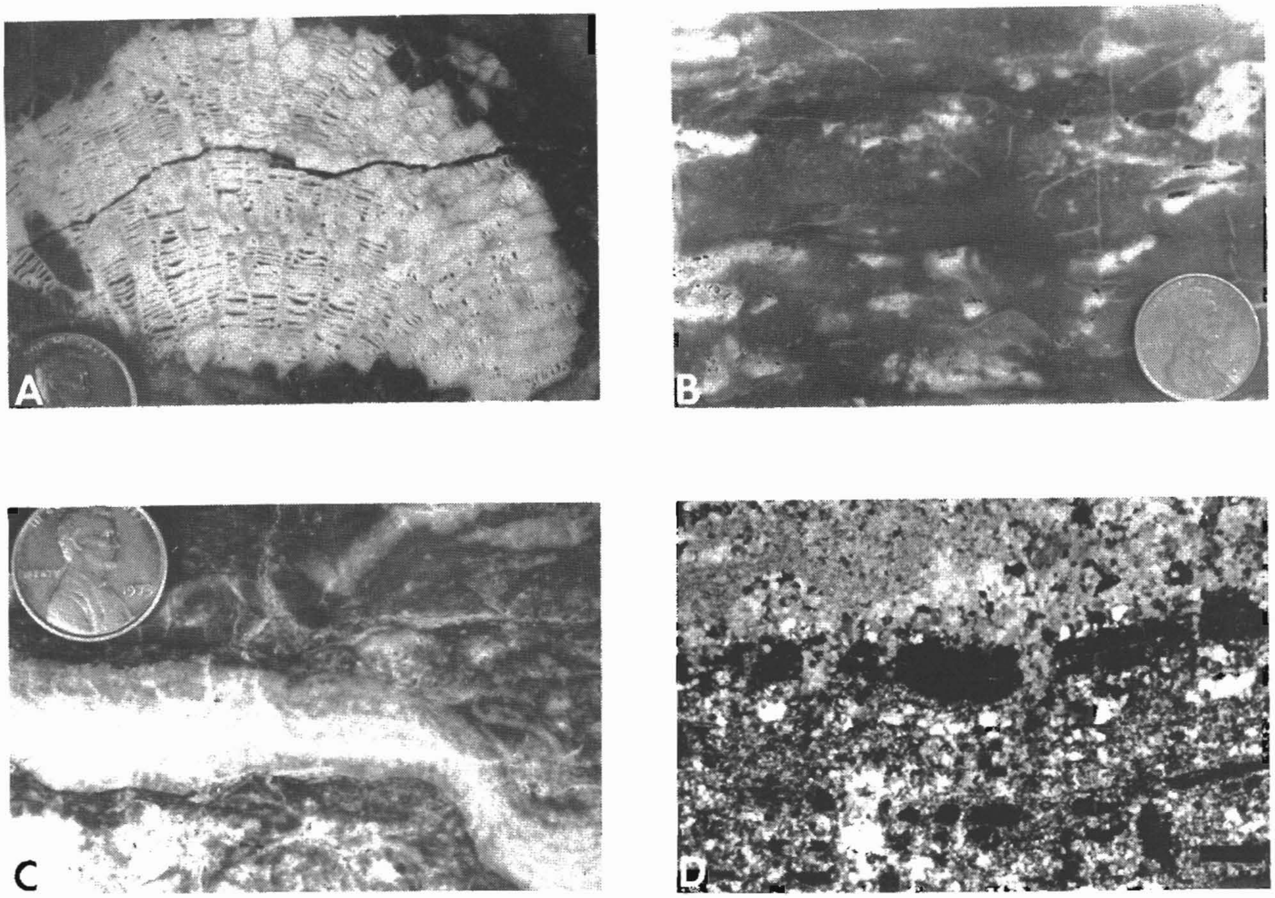

Figure 4. Typical Middle Interlake facies and porosity types.*

Porous, skeletal-rich facies alternate with tight barren dolomites throughout the Cedar Lake Formation, suggesting fluctuating salinities.

A. Reef-associated coral. Paleofavosites, found near the base of the Cedar Lake Formation, is a colonial tabulate coral common in Silurian reef facies. Primary intraskeletal pores have survived complete dolomitization of the coral. Texaco #1 Missouri Breaks: 12,662´.

B. Coral-bearing wackestone. Color mottling and textural inhomogeneity characterize skeletal-rich deposits, but identification of skeletal material is difficult due to replacement by medium crystalline dolomite. Moldic porosity is characteristic. Amerada #1 H. H. Shelvik: 13,275.5´. Cedar Lake Formation.

C. Stromatoporoid boundstone. Stromatoporoids are common in skeletal-rich sequences, documenting recurring phases of reef growth. Because their spreading growth forms welded them to the sea floor, they were the most important Interlake reef-builders. Texaco #1 Missouri Breaks: 12,663´. Cedar Lake Formation.

D. Porosity in stromatoporoid boundstone. Polarized view of thin section emphasizes original pores (black spaces) that may be preserved in stromatoporoid galleries and dissepiments despite dolomitization and partial silicification of the skeleton. Scale bar = 0.5 mm. Amerada #1 H. H. Shelvik: 13,203´, x-nicols. Cedar Lake Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

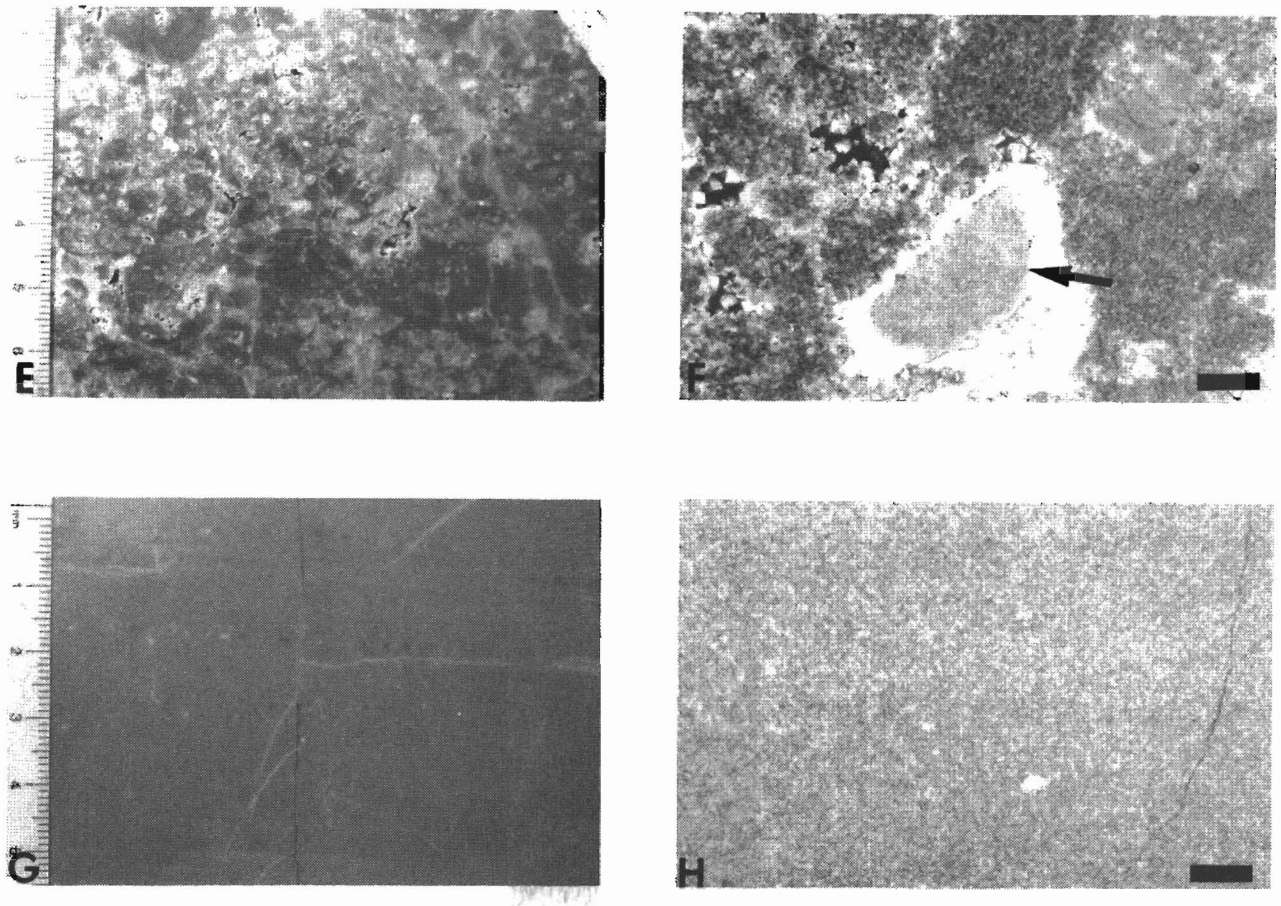

Figure 4*--Continued.

E. Burrowed crinoidal mudstone. Extensive bioturbation and differential crystallization of fossils and matrix has caused color mottling. Fossils were replaced by coarse white dolomite, and pelleted (?) mud matrix by brown microcrystalline dolomite. Scale in cm. Amerada #1 H. H. Shelvik: 13,290′. Cedar Lake Formation.

F. Porosity in burrowed crinoidal mudstone. Intercrystalline porosity in skeletal facies appears to be related to incomplete fill of skeletal molds by coarse calcite during dolomitization. Dolomitization has obscured the identity of all primary grains except crinoids (arrow), which are recognizable by their shape and speckled granular microtexture. Scale bar = 0.5 mm. Amerada #1 H. H. Shelvik: 13,290′, plane light. Cedar Lake Formation.

G. Barren mudstone and pellet packstone. Barren Cedar Lake dolomites generally have a translucent appearance, so primary textural features, such as current lamination, are only vaguely apparent. Granular appearance of ′speckled′ laminae suggests a pellet packstone precursor. Scale in cm. Amerada #1 H. H. Shelvik: 13,249.5′. Cedar Lake Formation.

H. Tight barren dolomitized mudstone. Thin section of barren mudstone reveals only a cryptic mass of uniform, non-porous, granular medium crystalline dolomite. Scale bar = 0.5 mm. Amerada #1 H. H. Shelvik: 13,249.5′, plane light. Cedar Lake Formation.

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* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

be replaced by porous dolomite of bimodal crystal size (figs. 4D,F), whereas unfossiliferous mudstones tend to be replaced by tight, very finely crystalline dolomite (fig. 4H). Medium crystalline dolomites with unimodal textures are interpreted as replacements of homogeneous pellet pack/grainstones. Collectively, Cedar Lake textural features record alternating deposition of skeletal-rich burrowed muds, current-bedded sands, reefs and non-skeletal, homogeneous or laminated muds and stromatolites.

Cedar Lake cements are invariably of dolomite (in contrast to Upper Interlake rocks which include much calcite cement), but anhydrite is common as a late diagenetic pore-plugging cement. Pervasive dolomitization of Cedar Lake carbonates was probably promoted by repetitive salinity changes in surface and near-surface phreatic waters which promoted ideal conditions for 'mixing zone' dolomitization as proposed by Badiozamani (1973), and Folk and Land (1975).

A representative marine cycle is well preserved in the Missouri Breaks core between 12,656' and 12,674' by alternating current-bedded skeletal pack/grainstones and stromatoporoid-coral boundstones. This sequence is decidedly more porous than the underlying barren dolomites due to preservation of intraskeletal pores in corals (fig. 4A), selective leaching of fossils, and intercrystalline voids in the sucrosic dolomite matrix. Partial infill by coarse, clear cavity-lining dolomite and later void-filling anhydrite has reduced porosity somewhat. Measured porosity averages about 5% through this interval, ranging from 1.2% to 7.1%, but would be considerably greater had the pores not been partially filled by the late diagenetic dolomite and anhydrite. Permeability ranges from 0.07 to 9.9 md.

Generally speaking, reef and reef-associated facies in the Cedar Lake Formation tend to be porous and represent a widespread and viable, but largely overlooked, exploration target in the Interlake Group.

Typical barren dolomites are represented by the interval 12,674' -12,680' in the Texaco #1 Missouri Breaks core. The primary constituents of these rocks have been masked by very finely crystalline dolomite whose uniformity suggests an original sediment of silt or fine sand. Textural ghosts preserve sediment lamination with some convolution, suggesting deposition by fallout or by currents, punctuated by occasional sediment loading. Fissure systems, brecciation, mottling, and geopetal sediment in solution features together suggest surficial exposure within the upper part of this sequence. Porosity in barren cycles is typically low (fig. 4H), and here range from 0.3% to 1.6%.

Grondale Formation

The upper part of the Middle Interlake is characterized in the central part of the basin by a distinctive quartz sand-bearing unit with a strong radioactive signature previously referred to as a 'ferruginous dolostone' by LoBue (1983). Although uncored in the Nesson anticline area, sample examinations indicate that it is a variegated red/green sequence of argillaceous, silty carbonate interbedded with quartz sandstones and siltstones. We propose to name this unit the Grondale Formation and designate the type-section in the Kissinger 1-9 Grondale well (sec9, T155N, R94W) between depths of 12,840' and 12,952'.

The Grondale Formation is easy to identify on gamma logs because of its pronounced radioactive response. Its basal contact may be abrupt or may 'feather' up from underlying Cedar Lake carbonates. Its upper contact is usually marked by a radioactive deflection and frequently coincides with a strong caliper break which records a pronounced caving of basal beds of the Mendenhall Formation.

The appearance of this thick quartz-bearing unit above Cedar Lake dolomites documents a major turning point in Williston Basin history. Interlake beds beneath the Grondale Formation record an essentially unbroken history of carbonate sedimentation in normal marine and hypersaline waters. By contrast, overlying Interlake strata document exclusively freshwater and subaerial deposition. We conclude that a major sea level fall, accompanied by a significant climate change, led to deposition of the sandy Grondale Formation. The arid climates that had promoted high evaporation during Lower and Middle Interlake times were replaced by humid conditions, and this change promoted a flourishing plant life during Upper Interlake times. The anomalous appearance of quartz sands across a basin which had been exclusively one of carbonate generation since the Middle Ordovician indicates that the change coincided with accessing of a newly exposed sandstone source. We suggest that Cambro-Ordovician sands may have been exposed at this time along distal margins of the basin, and were reworked into the basin by streams and/or winds.

Upper Interlake Subgroup

The Upper Interlake Mendenhall, Missouri Breaks, and Sherven Formations are variably dolomitized limestone sequences whose fossil content of charophytes, ostracodes, gastropods, fish remains, pelecypods, spongiostromate algal nodules, burrows, carbonaceous fragments suggestive of plants, and rhizomorphs record sedimentation exclusively in freshwater systems (fig. 5A-F). Furthermore, primary cements which have been preserved in these formations indicate vadose and phreatic precipitation from fresh water (fig. 5G,H). Collectively, these formations document the filling of a terrestrial inland basin by karst, stream, lake, and marsh sediments which were mechanically and chemically cannibalized from pre-existing carbonate rocks exposed around the basin margin, as proposed by Jamieson (1973). Abundant evidence of plant life and the absence of primary evaporites suggest that Upper Interlake climates must have been humid.

Mendenhall Formation

The basal Upper Interlake unit is herein named the Mendenhall Formation; it is the thickest and most widespread Upper Interlake unit recognized in the central Williston Basin. The type section is designated at the Amerada #1 Mendenhall Unit well (9-154N-95W) as the interval between 11,785' and 12,220'. Good sample cuttings are available from the type well, and a long core from the nearby Amerada-Hess 9-34X Mendenhall well serves as an excellent supplementary reference.

The lower Mendenhall contact with the Grondale Formation is recognized in samples by the appearance of rounded quartz sand grains and red and green color mottling, and on gamma logs by a pronounced increase in radioactivity. Where the formation directly overlies the Cedar Lake Formation, the contact is subtle in well logs, and can only be identified with confidence from lithologic changes seen in cores or well cuttings. Mendenhall lithologies differ from those of the Cedar Lake in that they are less pervasively dolomitized, lack marine fossils, contain argillaceous and quartzose

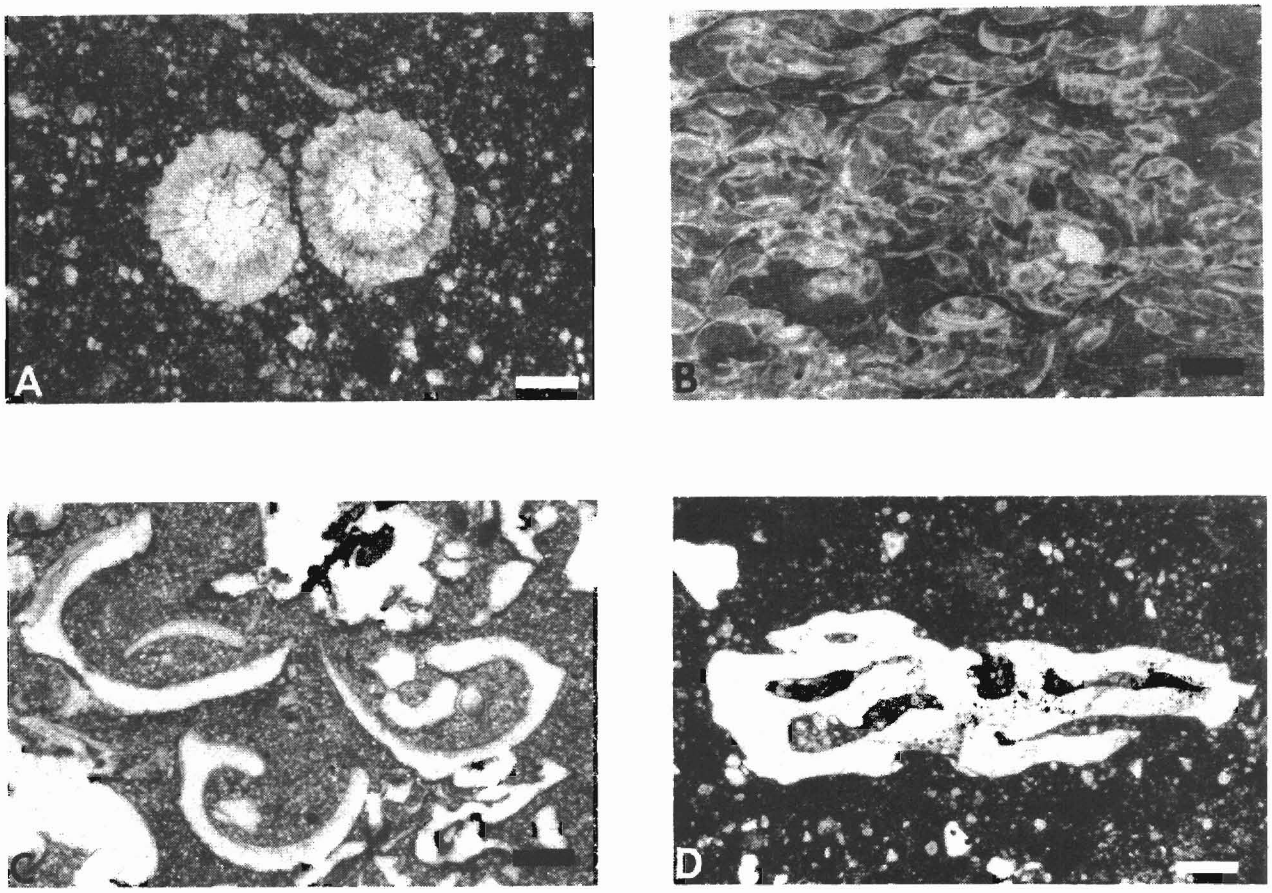

Figure 5. Upper Interlake fresh water indicators.*

Fossils and early diagenetic cements common in Upper Interlake sequences are diagnostic of fresh water environments and, since no fossils diagnostic of normal marine salinities have been recognized in these formations, they are inferred to be exclusively fresh water deposits.

A. Charophytes. Gyrogonites display thick wall structure and fluted outer cortex diagnostic of calcified oogonia of charophytes, fresh water algae which flourish best in shallow, well-oxygenated alkaline ponds and lakes. Scale bar is 0.13 mm. Texaco 5-A Garland: 11,650.5', plane light. Mendenhall Formation.

B. Ostracodes. Abundant thin-shelled ostracodes, in the absence of other invertebrate fossils, suggest a fresh water origin. Good preservation of skeletal structure is attributed to low-Mg calcite mineralogy. Scale bar is 0.5 mm. Amerada #1 Iverson-Nelson: 11,772', plane light. Mendenhall Formation.

C. Gastropods. Very small size of gastropods suggests fresh water forms. Scale bar is 0.5 mm. Amerada 15-33 Sivertson: 12,515', plane light. Mendenhall Formation.

D. Fish fragment. Thin section shows fragment of porous collophane diagnostic of bone tissue. Fragment is probably from an agnathid fish, whose distinctive ornamented plates are common in anoxic lacustrine facies. Scale bar is 0.13 mm. Texaco #1 Oscar Johnsrud: 12,273', plane light. Missouri Breaks Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

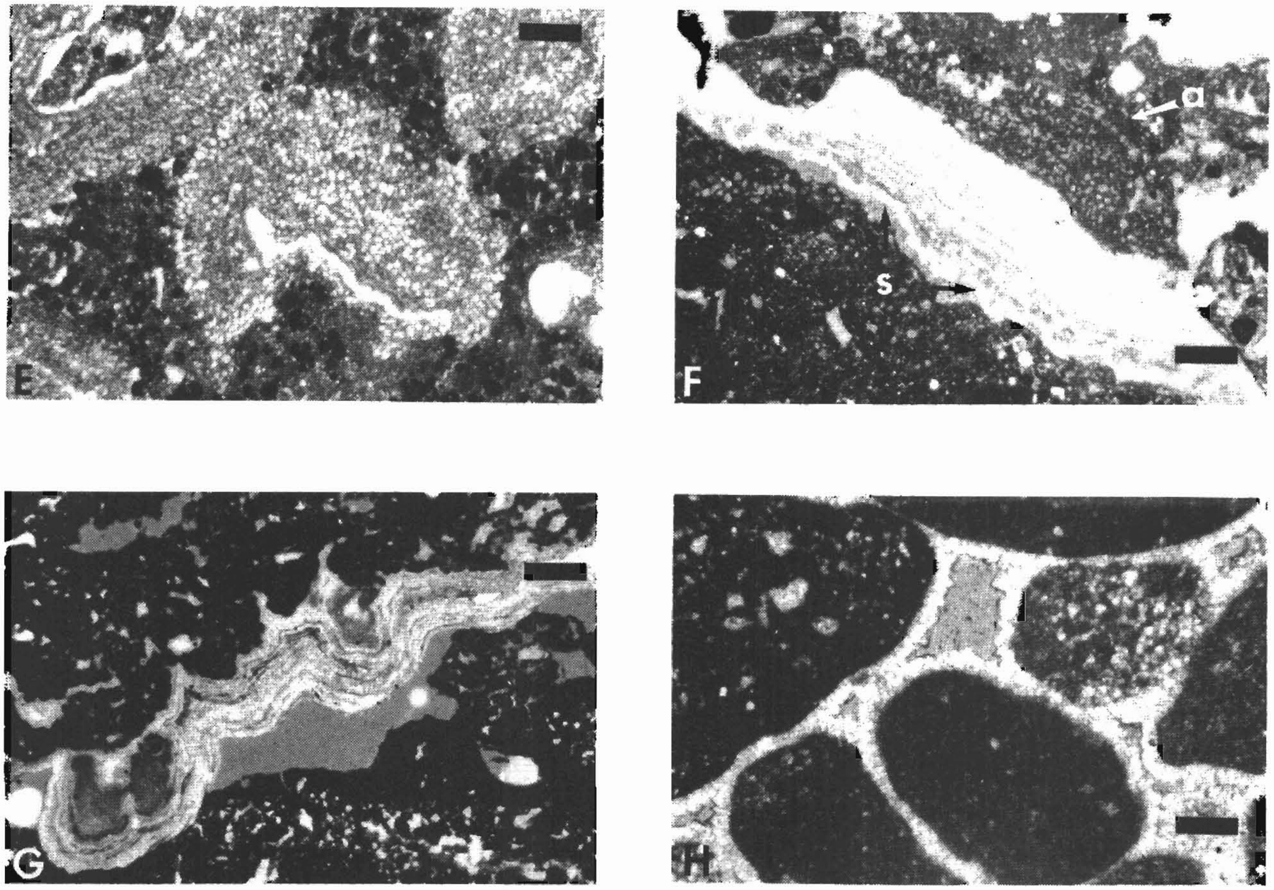

Figure 5*--Continued.

E. Algal nodules. Oncoids visible here encrust skeletal nuclei, such as the ostracode at upper left. Cellular, spongiostromate structure is diagnostic of algal nodules which form in fresh water systems (Peryt, 1983). Scale bar is 0.5 mm. Tiger 11-25 Siguardson Trust: 12,166.5', plane light. Mendenhall Formation.

F. Pelecypod. Although uncommon in Upper Interlake beds, pelecypods are recognized on core slabs by their characteristic shell shapes. Thin section shows original shell layers preserved as dark 'ghost' laminations. Upper layer has been selectively dissolved and the resultant mold filled with coarse calcite spar, while inner laminae have been partially replaced by white patches of silica (s). Porous encrustations on the shell are of spongiostromate algae (a). Scale bar is 0.5 mm. Tiger 12-23 Dinwoodie: 12,118', plane light. Missouri Breaks Formation.

G. Vadose cement. Dolomite "dripstones" are ubiquitous throughout the entire Upper Interlake sequence, most commonly occurring in solution fissures and vugs. They obviously precipitated from fresh meteoric waters percolating down through the rock, so record lowered water tables. Scale bar is 0.5 mm. Amerada 9-34X Mendenhall: 11,802', plane light. Mendenhall Formation.

H. Phreatic cement. Isopachous dolomite documents cementation below water table in the phreatic zone, and the columnar to blocky crystal habit of the dolomite suggests a fresh water origin. Cementing groundwaters probably had high Mg/Ca ratios which promoted dolomite precipitation in preference to calcite. Scale bar is 0.13 mm. Home #1 Sherven: 12,124', plane light. Mendenhall Formation.

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* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

contaminants, and are characterized throughout by current-bedded sequences of lithoclast sandstone which usually have a distinctive 'salt-and-pepper' appearance.

The upper contact with the Missouri Breaks Formation is an abrupt one, recorded on gamma logs by a very strong radioactive spike, and in cores by quartzites or quartz-bearing limestones. In some wells (including the Texaco Inc. #1 Missouri Breaks core) uppermost Mendenhall beds are collapse breccias, and they are generally represented by low gamma signatures.

The Mendenhall Formation is a texturally variable sequence of carbonates dominated by mud, pellets, lumps, lithoclasts and skeletal grains, with minor admixtures of non-calcareous sand, silt, and clay. The variability in composition results in a gamma log signature that is best described as 'busy'. Rock types range texturally from mudstones to grainstones, reflecting varying depositional energy levels, and current bedding, upward fining cycles, and well-preserved lamination indicate that most deposition was subaqueous. Most facies can be readily interpreted using analogs from modern fresh water deposits (fig. 6).

The upper part of the formation is best understood because its lithologies are reservoirs for most Interlake production on the Nesson anticline and have been extensively cored. Generally speaking, gamma spikes record dark laminated muds interpreted as lake-bottom deposits, or pale argillaceous laminites interpreted as lacustrine delta-fill, whereas 'clean' gamma signatures record pure carbonates attributable to shoreface, fluviatile, or collapse breccia origin. The Mendenhall Formation encompasses the 'B' to 'G' porosity zones of Bates (1986).

Secondary features are the most pronounced aspects of Mendenhall facies. Primary depositional fabrics are commonly interrupted by fenestrae, root tubules, fissure systems, or solution channels, suggesting that subaqueous deposition was repeatedly interrupted by periods of subaerial exposure (fig. 7A-E). Erosional breaks punctuate the formation throughout, and facies beneath these breaks frequently display signs of diagenetic or chemical modification (fig. 7G,H). Most common are chalky textures resulting from solution of dolomite, and 'melanization' - a pervasive color alteration of rock surfaces to dark brown (fig. 7F). The melanization may have one of several explanations: modern analogs suggest soil processes (James, 1972) or algal-bacterial mats (Ward, Folk, and Wilson, 1970, p. 554); alternatively, we suggest that the discoloration and corrosion of the melanized surface may have been chemically induced by standing swamp waters with a high tannic acid content.

The Mendenhall Formation is interpreted as a freshwater deposit of fluviatile, marsh, and lacustrine origin. Sedimentary textures and structures are identical to Recent (35,000-10,000 yrs. B.P.) non-calcareous freshwater deposits of the Atchafalaya basin illustrated by Coleman (1966), and appear similar to the calcareous freshwater Miocene-Pliocene Verde Formation of central Arizona (Nations and others, 1981). Explaining the provenance of the volumetrically abundant 'salt-and-pepper' lithoclast sands which typify the formation necessitates active erosion of an extensive carbonate terrain, and the most obvious source would be from older Silurian and Ordovician carbonates which were being exposed and weathered around the basin margins at that time. Cyclically

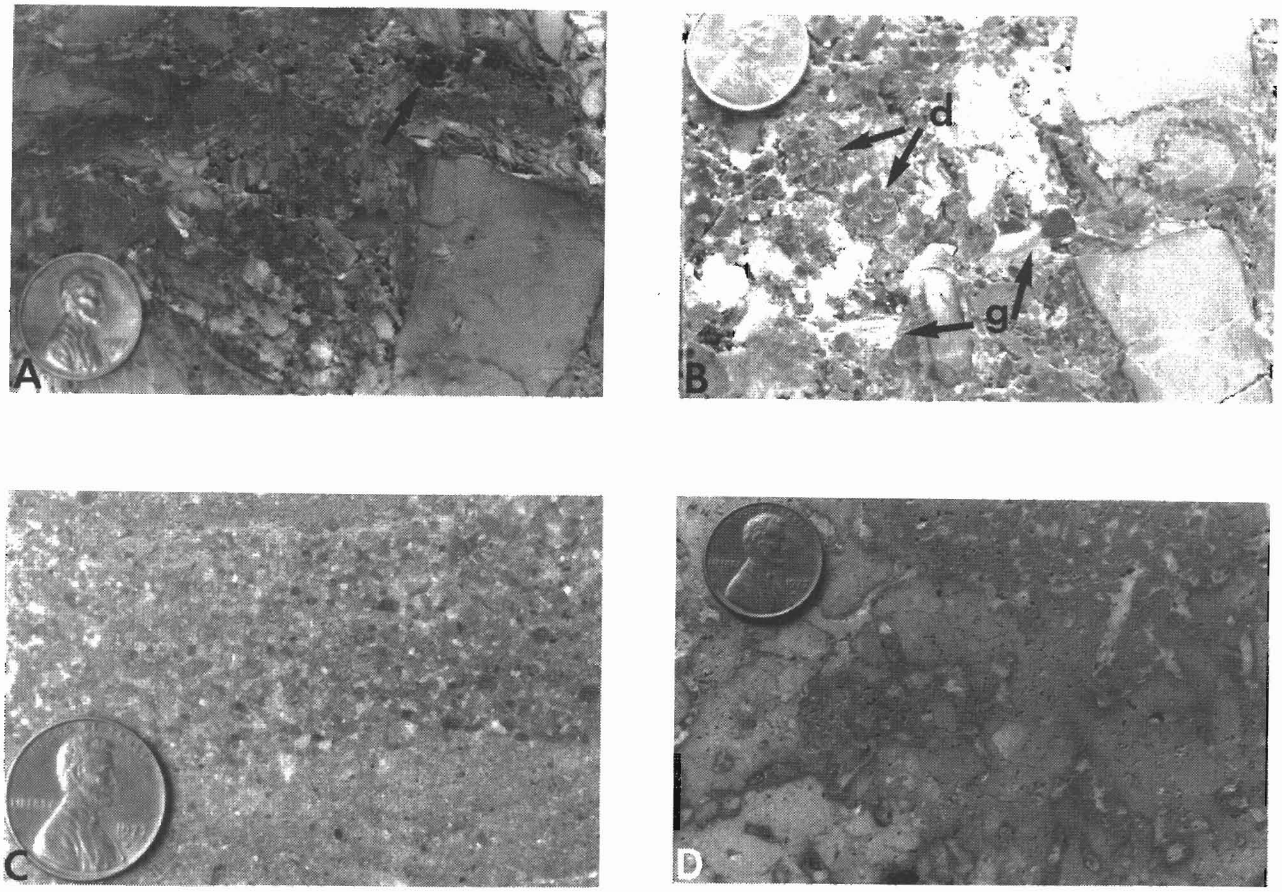

Figure 6. Representative Upper Interlake facies.*

Upper Interlake facies from various cores are arranged to display, from top to bottom, an idealized upward-shallowing progression.

A. Collapse breccia. Chaotic angular limestone clasts record collapse of cavernous host rock, and dark dripstone pendants (arrow) demonstrate subsequent percolation of vadose fluids through the deposit. Intergranular porosity, once good, has been plugged here by late diagenetic halite. Amerada 9-34X Mendenhall: 11,772´. Sherven Formation.

B. Collapse breccia. Multiple features of cave deposits are apparent on core slab, including thick dripstone pendants (d), and geopetal sediments (g) introduced by muddy waters trickling down through the sediment. Late diagenetic salt has plugged once-effective pore space. Tiger 12-23 Dinwoodie: 12,100´. Sherven Formation.

C. Fluvial lithoclast grainstone. Inferred stream deposits, these 'salt and pepper' sands are unique to Upper Interlake formations. Provenance from precursor dolomites is indicated by heterogeneity of the lithoclasts, and current deposition is suggested by excellent sorting, roundness of grains, and well-preserved current bedding. Tiger 12-23 Dinwoodie: 12,126´. Mendenhall Formation.

D. Root-bound marsh deposit. Rhizomorphs of varying diameters are pervasive through Upper Interlake beds, preserved by sparry calcite or dolomite, chalky dolomite, or by open pore systems. Similarities with deposits of the Pliocene-Miocene Verde Formation in Arizona suggest that most root systems were created by marsh plants. Tiger 1-25 Siguardson: 12,151´. Mendenhall Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

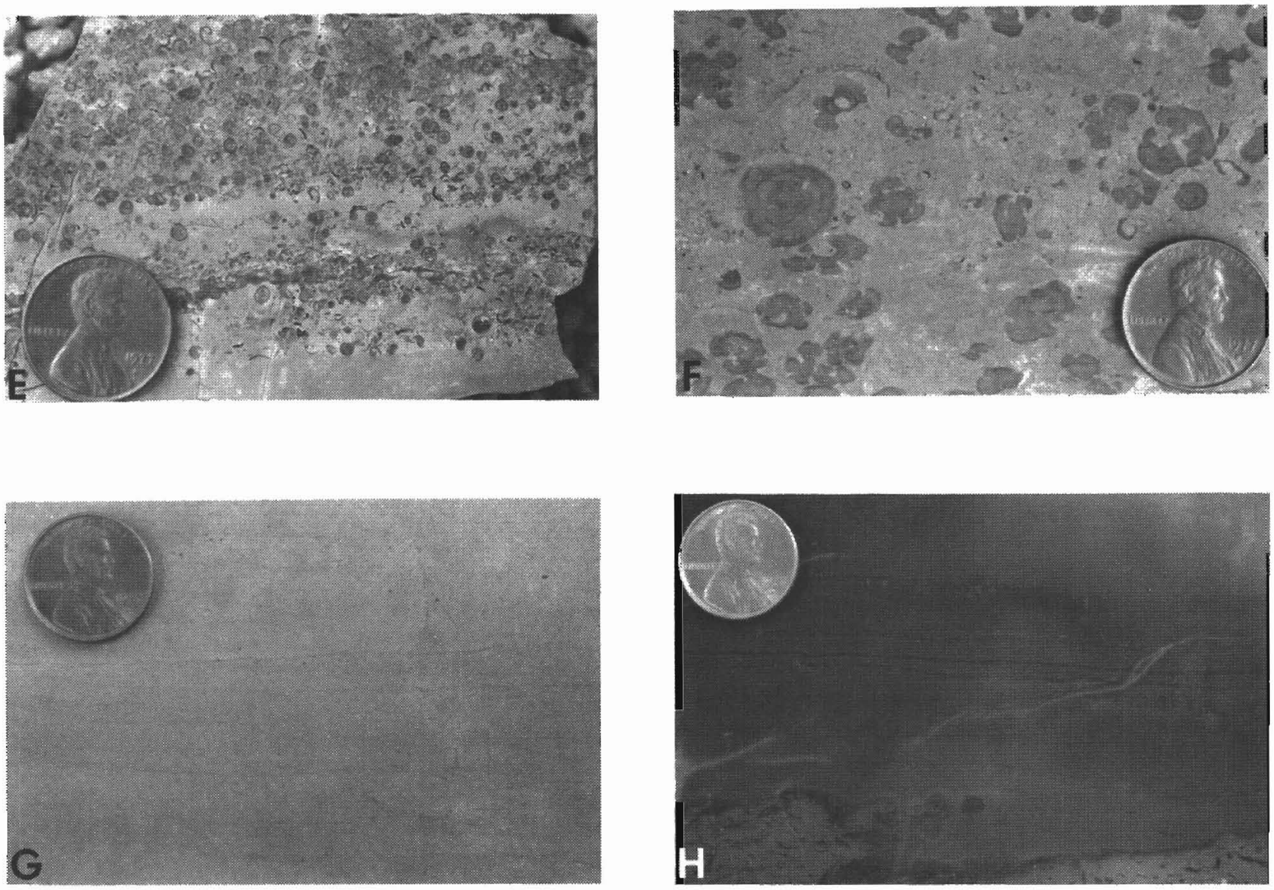

Figure 6*--Continued.

E. Gastropod-rich stream or shoreline deposit. Packstone dominated by tiny gastropods, with ostracodes and pelecypods, is comparable to shell sands known to be accumulating in a stream draining a sinkhole lake in the Verde Valley of central Arizona. Tiger 11-25 Siguardson Trust: 12,140′. Mendenhall Formation.

F. Oncoid-rich stream or shoreline deposit. Freshwater algal nodules suggest accumulation in shallow, agitated waters in nearshore lacustrine environment or in stream. Amerada #1-B Antelope: 11,929.5′. Mendenhall Formation.

G. Wispy laminated argillaceous mudstone. Fine grain size, pale colors, discontinuous microlamination, and content of clay and quartz silt suggest comparison with Recent lacustrine delta fill of the Atchafalaya Basin. Amerada 9-34X Mendenhall: 11,866′. Mendenhall Formation.

H. Anoxic lake bottom mudstone. Limestones, characterized by dark colors, uniform lamination, fish fragments, occasional ostracode-rich laminae, abundant disseminated pyrite, and non-calcareous sand, silt, and clay are interpreted as lake-bottom gyttja deposits with source rock potential. Irregular contact at base defines boundary of Missouri Breaks Formation with underlying Mendenhall Formation. Tiger 12-23 Dinwoodie: 12,115.5′.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

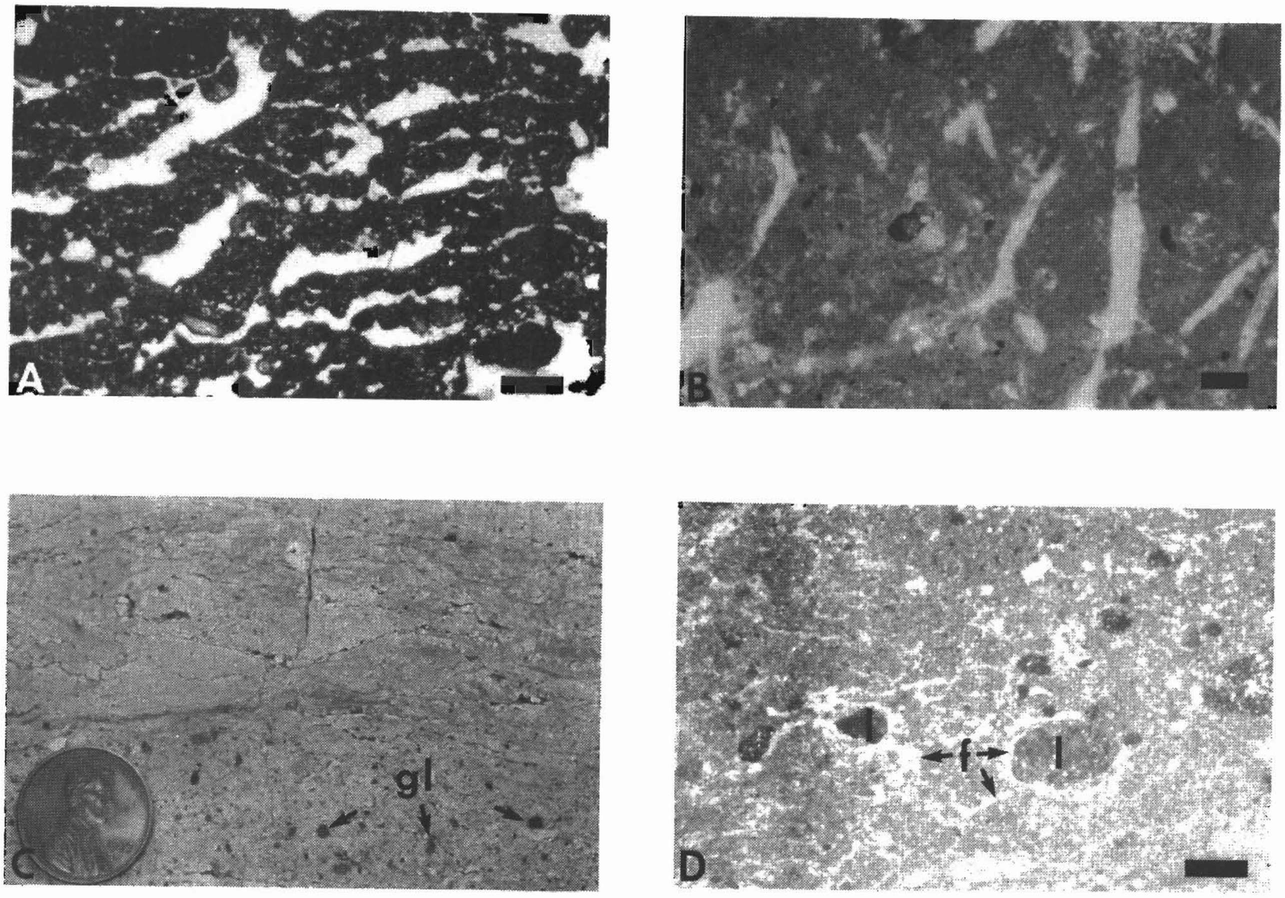

Figure 7. Upper Interlake indicators of water table shifts.*

Secondary fabrics and facies contacts indicative of rising and falling water tables recur throughout Upper Interlake formations.

A. Fenestrae. Fenestral fabrics record early sediment dewatering and a falling water table. Excellent primary porosity has been plugged by sparry calcite cement. Scale bar = 0.5 mm. Tiger 11-25 Siguardson Trust: 12,132.5′, plane light. Mendenhall Formation.

B. Root molds. Subvertical tubules with convergent-upward branching, sharply-defined walls, and spar filling diagnose molds of plant roots, whose penetration of the substrate suggests a falling water table. Scale bar = 5 mm. Texaco #1 Exchange: 12,481′. Mendenhall Formation.

C. Fissure systems. Extensive fissure systems, brecciation, and glaebules (gl) document incipient soil development in uppermost Interlake strata, recording prolonged subaerial exposure. Universal Resources 1-29 Olson: 11,940′. Sherven Formation.

D. Soil fissure systems. Circumgranular nature of soil fissure systems is apparent in thin section, which shows sinuous spar-filled fissures (f) converging on, and surrounding, large dolomite lithoclasts (l). Scale bar = 0.5 mm. Tiger 32-22 Westdahl: 12,133′, plane light. Mendenhall Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

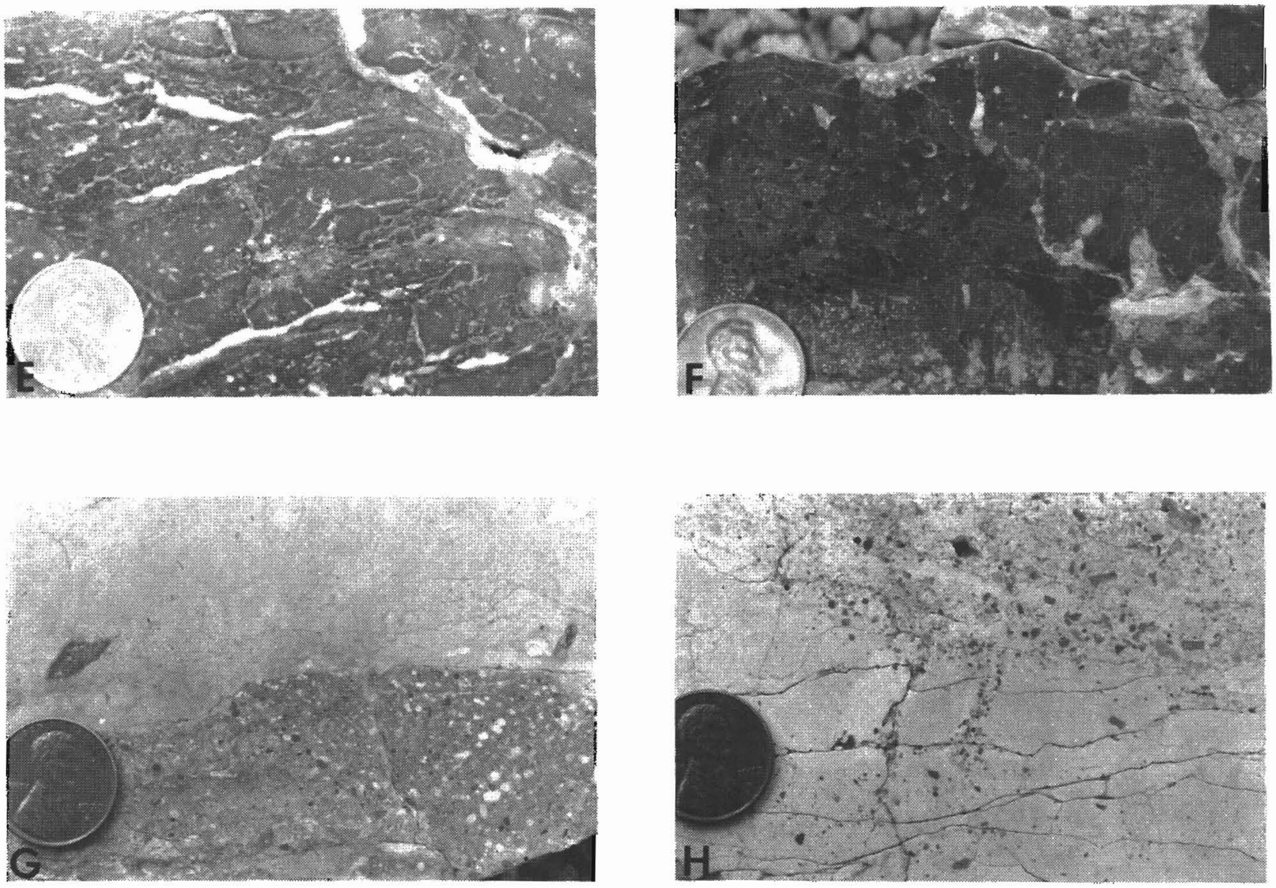

Figure 7*--Continued.

E. Solution channels. Subhorizontal channels chart lateral migration of aggressive undersaturated meteoric waters through host limestone above, or at, the water table surface. Spar filling of channels was effected later by phreatic groundwaters. Home #1 Sherven: 12,104'. Sherven Formation.

F. Melanized surface. Pronounced darkening characterizes many exposure surfaces in Upper Interlake rocks, suggesting chemically-induced discoloration and corrosion, possibly by standing swamp waters with high tannic acid content. Texaco #1A L. J. Grantier: 12,407'. Missouri Breaks Formation.

G. Contact preserves water level rise. Typical Upper Interlake facies contact records flooding across a corroded and highly altered bedrock surface which had been pervaded by plant rootlets (chalky vermiform patches), and partially melanized. Tiger Oil Siguardson 11-25: 12,167'. Mendenhall Formation.

H. Mudcracked contact. Evidence of subaerial desiccation and subsequent flooding has been preserved by fluvial lithoclast sands that have trickled down into mudcracks. Tiger Oil Siguardson 11-25: 12,098'. Sherven Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

repeating facies and recurring zones of dripstone cement together demonstrate that water tables constantly rose and fell throughout deposition of the formation.

Porosity in excess of 20% is not uncommon in the Mendenhall Formation, and occurs as variable and discontinuous zones within gross pay intervals. Porosity types vary and appear to be somewhat independent of facies types (fig. 8), except that argillaceous facies are invariably tight and impermeable. There is much evidence that porosity has been enhanced considerably by solution (fig. 8D, F, and H), and proprietary maps and cross sections demonstrate that gross porosity in the formation is geographically controlled. We conclude that retention of high porosity in the Mendenhall is largely a result of prolonged regional flushing by waters of meteoric origin which were undersaturated with respect to calcium carbonate.

Intergranular pores in current-bedded lithoclast sandstones, root tubules, and fenestrae display some of the best porosities, but molds, fissures, vugs, and intercrystalline pores form much of the void space in this formation. Open fractures may be present, but are of secondary importance. Porosity varies considerably: in the Texaco Inc. #1 Missouri Breaks core, it averages 8% and ranges up to 16.2%; in the producing interval of the the Prosper Energy 27-1 Sherven well, it exceeds 10%, and ranges from 5% to more than 18% through the rest of the cored interval. In some producing wells along the Nesson anticline, porosity values measured for cores exceeds 25%.

Missouri Breaks Formation

The Missouri Breaks Formation is introduced for an Upper Interlake lacustrine unit with a distinctive log signature. The formation name is derived from the Texaco Inc. #1 Missouri Breaks well (SWSEsec 10, T153N, R96W) from which a well-preserved and representative core has been retrieved; the type-section is designated as the interval between 11,778' and 11,805'. In logs, the formation is characterized by a strong basal radioactive spike and pronounced caliper break, and at the top by a sharp cornice which demarcates contact with clean carbonates (usually collapse breccias) of the overlying Sherven Formation. It is equivalent to the top of the 'B' zone defined by Bates (1986) from Charlson Field cores.

Lithologically, the Missouri Breaks Formation is usually characterized at the base by a tight, silica-cemented quartz sandstone, or series of sandstone stringers, which interlaminate with, and grade up into dark, almost black, laminated limestones. This quartzite zone is well displayed in the Home #1 Sherven core at 12,123' (C.D. 12,128'), and in the Prosper Energy #1 Sherven between 12,075' and 12,080' (C.D. 12,069' - 12,074'). In the Texaco Inc. #1 Missouri Breaks core, basal quartzites are not present, but rounded quartz sand grains have worked down into the matrix of the underlying collapse breccia. The laminated limestones usually contain much terrestrial sand and silt and are characterized by conspicuous laminae of thin-shelled ostracodes. Fish fragments are common, particularly in basal beds where quartz sand is abundant and can be seen in the Prosper Energy 27-1 core at 12,079' (C.D. 12,073'). Pyrite is disseminated through the black limestones and also occurs in nodular masses replacing fossils. Typically, the dark colors of the basal limestones grade upward in the formation to pale red (10YR 4/2). The upper part of the Missouri Breaks Formation may

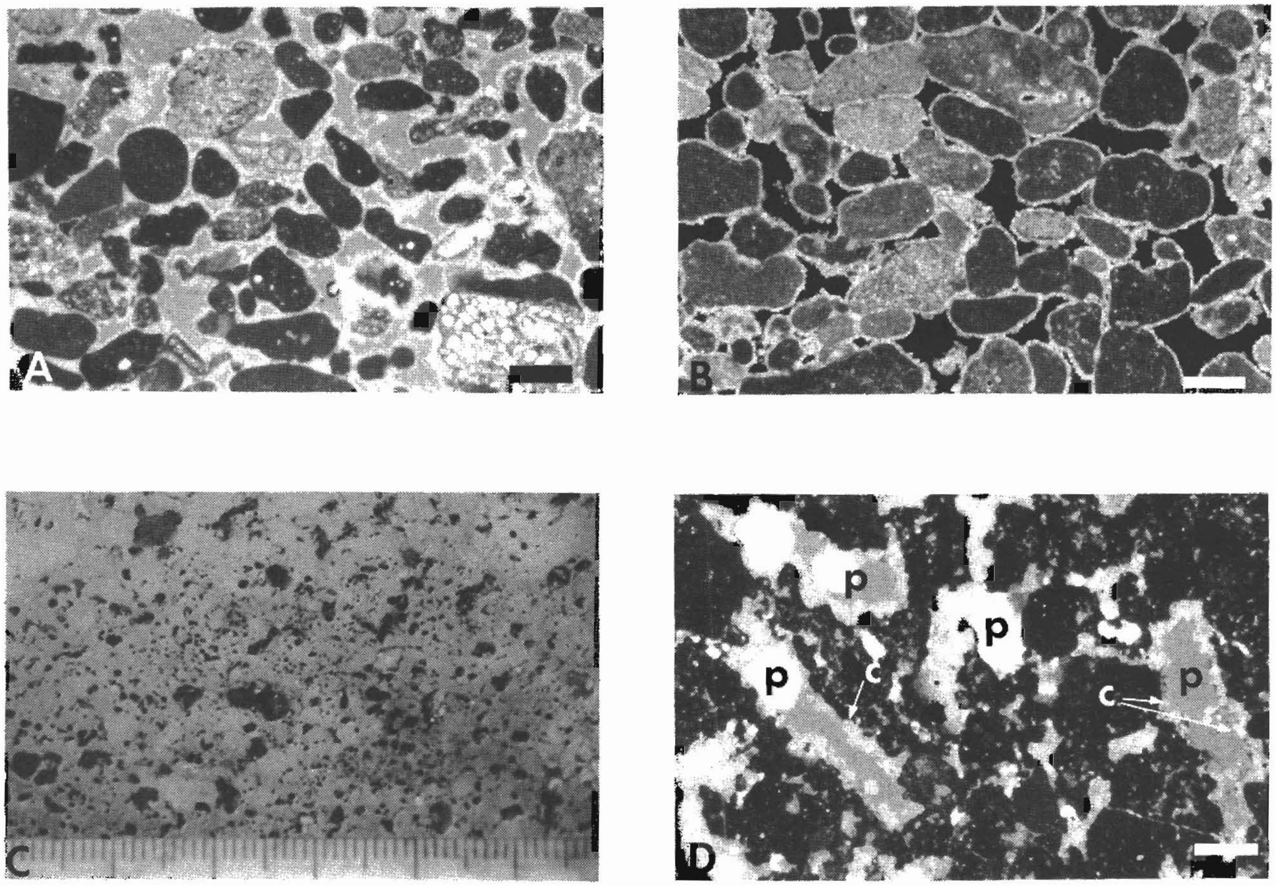

Figure 8. Representative Upper Interlake Reservoir facies.*

High porosities in productive Upper Interlake facies are due partially to retention of primary pore spaces but, more significantly, to early diagenetic enlargement of these spaces by aggressive undersaturated groundwaters.

A. Intergranular porosity. Thin section of lithoclast grainstone shows that much original pore space (gray areas) has been retained in this because minimal penecontemporaneous cementation by isopachous calcite inhibited compaction. Scale bar is 0.5 mm. Home #1 Sherven: 12,124′, plane light. Mendenhall Formation.

B. Intergranular porosity. X-nicols view of lithoclast grainstone emphasizes porosity, which is estimated to be approximately 20%. Scale bar is 0.5 mm. Home #1 Sherven: 12,124′, x-nicols. Mendenhall Formation.

C. Tubule porosity. Much effective porosity in Upper Interlake facies is due to the presence of anastomosing root systems which create tubular cavity networks of varying diameters. Scale in cm. Amerada 16-14 State: 12,035′. Mendenhall Formation.

D. Solution-enhanced tubule porosity. Thin section shows effective porosity (p) in root molds (gray areas with white bubbles due to epoxy stain) that has been enhanced by solution of sparry calcite infill (c). Deeply embayed and corroded surfaces of the spar document this solution. Scale bar is 0.5 mm. Tiger 32-22 Bernard Westdahl: 12,159′, plane light. Mendenhall Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

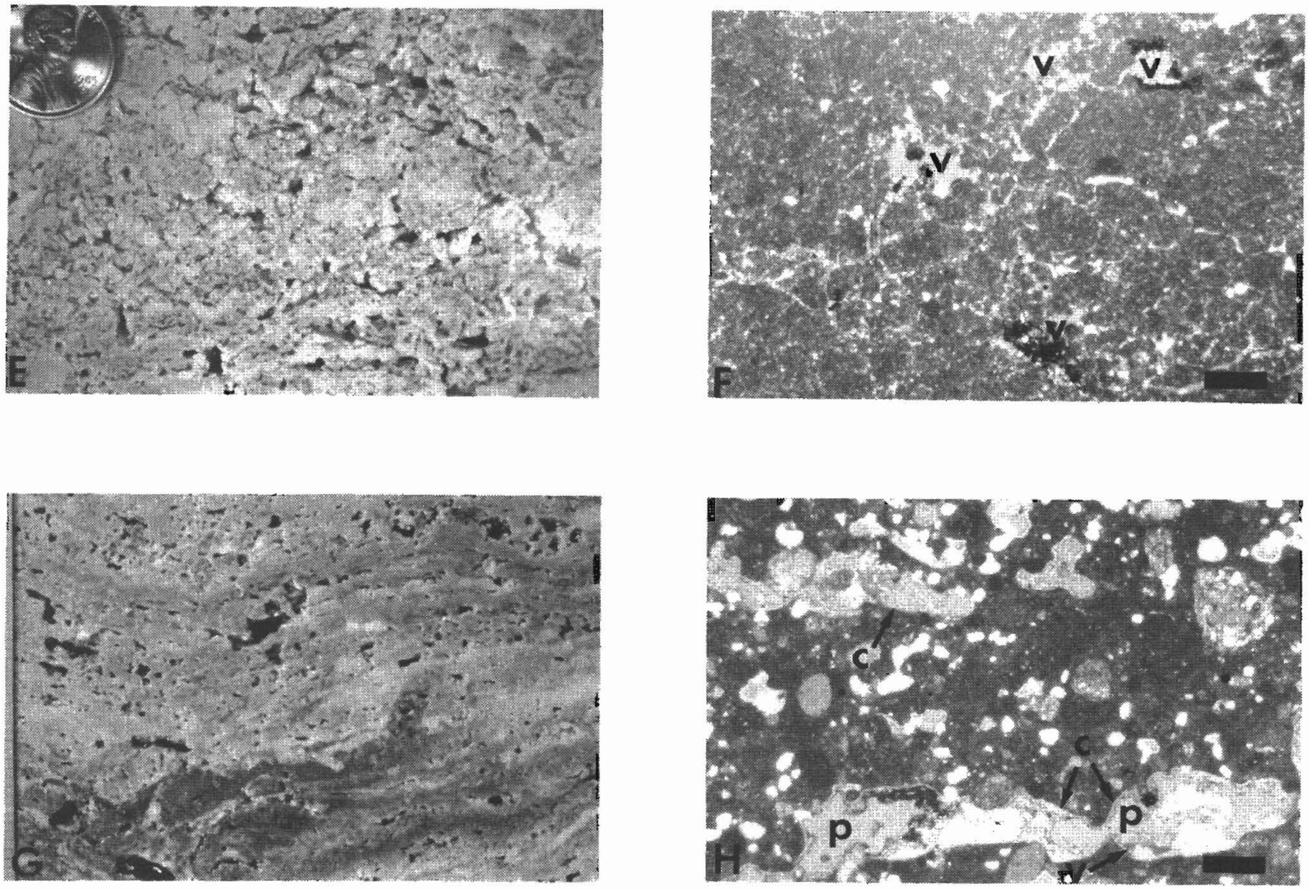

Figure 8*--Continued.

E. Fissure porosity. Excellent permeabilities are associated with interconnected fissure networks in Upper Interlake facies, but have locally facilitated late diagenetic plugging by halite, as has occurred here. Amerada 9-34X Mendenhall: 11,824′. Mendenhall Formation.

F. Solution-enhanced fissure porosity. Thin section demonstrates enlargement of fissure systems by solution, which has created vugs (v) at intersections of the delicate fissures. Note black hydrocarbon residue lining pores. Scale bar is 0.5 mm. Hunt 1-30 Knight: 11,943.5′, plane light. Sherven Formation.

G. Fenestral porosity. Well developed fenestral porosity is apparent in algal laminite. Core Lab analysis yielded a porosity value of 23.2% from a plug cut from this rock. Scale is in cm. Texaco #1 Exchange: 12,359′. Mendenhall Formation.

H. Solution-enhanced fenestrae. Thin section shows fenestral pores (p) that were partially filled with isopachous dolomite cement (c) and vadose silt (v), but have been enlarged by later solution. Host rock is a lithoclast packstone with many quartz grains (white). Note hydrocarbon staining at lower left (arrow). Scale bar is 0.5 mm. Hunt 1-30 Knight: 11,942′, plane light. Sherven Formation.

* Depths noted for cores illustrated in figures 3-8 have not been corrected to logs and are listed as originally reported and labeled on cores.

include argillaceous soil, marsh, and fluviatile facies similar to those of the Mendenhall Formation.

The Missouri Breaks Formation is interpreted as an anoxic lake deposit which accumulated during the last major flooding of the Williston Basin in Silurian time. Its basal contact with the underlying Mendenhall Formation is that of an emergent terrain that had been exposed to a prolonged period of surficial weathering and karsting (fig. 6H), and was finally covered by a thin veneer of quartz sand. Its lithologic profile defines passive, deep lacustrine sedimentation at the base, with upward shallowing into terrestrial facies.

The Missouri Breaks Formation is essentially non-porous, so it has no reservoir potential, but it is an important aquiclude which has historically separated hydrodynamic flow between the Mendenhall and Sherven Formations. Where it has confined connate halite-precipitating brines to the overlying Sherven Formation, underlying Mendenhall reservoirs have been protected from destructive salt plugging. Production from Mendenhall reservoirs in both the Home #1 Sherven and Prosper Energy 27-1 Sherven wells may be attributed to protection from salt plugging by the Missouri Breaks Formation.

Sherven Formation

The uppermost Interlake Formation recognized along the Nesson anticline is distinguished by a series of well-preserved collapse breccia units. The type section is designated as the interval between 12,028' and 12,058' in the Prosper Hunt 27-1 Sherven well where a complete section of the formation was cored. The Sherven Formation encompasses the 'A' porosity zone of Bates (1986).

The Sherven Formation is characterized by collapse breccia sequences, lithoclast sandstones, and solution zones in which multiple generations of vadose dripstone and isopachous dolomite cement are pervasive, and red coloration common. The solution zones are particularly well displayed in the Home #1 Sherven core (fig. 7E). Collapse breccia zones are generally of pure lime mudstone, so they have clean radioactive signatures which make them easy to identify on gamma logs. They typically contain large cavity networks which are partially lined by dripstone cements and are often plugged by halite (fig. 6A,B).

The boundary of the clean Sherven carbonates with the underlying argillaceous Missouri Breaks Formation is a sharp cornice on gamma logs. The upper contact with the overlying Ashern Formation is demarcated by a sharp re-entrant on gamma logs, recording a pronounced increase in argillaceous content.

Carbonates of the Sherven Formation record an initial period of fluvio-lacustrine sedimentation, followed by a prolonged period of subaerial weathering and extensive subaerial karsting. Fossil water tables can be identified from vertical changes in cement fabrics, and one is particularly well-defined in the Home #1 Sherven well at 12,113' (C.D. 12,118') where brown dolomite cements change from isopachous (implying formation in the phreatic zone <u>below</u> water table) to pendant (indicating formation in the vadose zone <u>above</u> water table). Interconnected cavity systems in collapse breccias and lithoclast sandstones give the Sherven Formation excellent primary reservoir characteristics, and it is locally productive along the Nesson anticline. However, salt plugging of Sherven reservoirs is common and is apparent in each of the three cores displayed. Paragenetic relationships consistently demonstrate that halite was the last cement to form in Interlake rocks and precipitated during deep burial diagenesis. Its formation is attributed to precipitation from connate brines which remobilized salts from younger rock formations.

Interlake - Ashern Boundary

The cessation of Interlake deposition is marked by an unconformity of considerable ambiguity. Regional cross sections suggest significant erosion of Interlake strata prior to deposition of the overlying Ashern Formation, but onlap of the Interlake surface by Ashern beds toward the basin margins clearly demonstrates diachronous formation of the contact, as originally proposed by the author (as Jamieson, 1973). Hence, erosion of Interlake beds was occurring around the basin margins as lowermost Ashern beds began to accumulate in the basin center. Not surprisingly, therefore, facies similarities between Upper Interlake and lowermost Ashern strata make precise identification of the contact difficult in some cores despite the generally strong radioactive contrast between the formations, as is apparent in the Prosper Energy #27-1 Sherven core.

Elm Point Group

Ashern Formation

The Ashern Formation was first named by Baillie (1950, p. 10) for 'brick-red to greyish orange argillaceous dolostone strata that lie between the overlying Elm Point (Winnipegosis) limestone and the underlying dolostone of known Silurian age' in outcrops near the village of Ashern, Manitoba. Subsequently, the formation was correlated with a subsurface interval previously referred to in Canada as the 'third red beds', and the new name became extended throughout the Williston Basin. The Ashern Formation has a distinctive blocky gamma signature which makes it easy to recognize in logs.

Its lower boundary is usually a very pronounced gamma inflection which sets it clearly apart from the underlying clean Interlake carbonates. However, the presence of a transitional zone of deeply weathered Interlake facies makes this contact ambiguous in many wells, and is designated as the 'basal transitional zone' of the Ashern to differentiate it from the upper, highly radioactive part of the formation. Frequently the transitional unit contains quartz sand and, in some places, it is a pure quartzite. Elsewhere, it may be characterized by bands of reworked anhydrite nodules.

The Ashern's upper contact with the Winnipegosis Formation is invariably abrupt both in logs and cores. In the Winnipegosis, gamma logs show a sharp decrease in radioactivity, and cores display a pronounced change from unfossiliferous to extensively bioturbated facies.

The Ashern Formation is mainly of very fine-grained silty and argillaceous dolomite or dolomitic limestone and, except for rare calcispheres of unknown affinity (Lobdell, 1984), is essentially barren of fossils. Typically, basal Ashern beds are red in the central part of the basin, but are replaced upwards and laterally by darker greenish-gray beds. Grain size generally ranges from mud to silt grade and, while textural monotony is the rule, intraformational dolomite pebbles are common, and black clay lenticles or streaks are occasionally incorporated into the matrix. Fine components are assumed to be insolubles derived from weathering of the immediately surrounding carbonate terrain as well as from external, eolian-derived sources. Coarse components near the base of the formation consistently indicate derivation from immediately underlying Interlake beds: large dolomite clasts are common where the unit succeeds collapse breccias of the Sherven Formation along the Nesson anticline, whereas quartz sand is abundant where it overlies basal quartz sandstones of the Missouri Breaks Formation along its subcrop boundary in western North Dakota.

Ashern depositional textures are cryptic: wispy, discontinuous laminations are most common, but deformation features, pebble bands, and occasional scour features have been recognized. Collectively, these features suggest that deposition was dominantly subaqueous.

Locally the formation is very anhydritic and, around the flanks of the Nesson anticline, it includes salt beds that have recently been described and partially mapped by Fischer and Anderson (1984). The anhydrite occurs as detrital nodules in basal beds (see Prosper Energy 27-1 Sherven at 12,025': C.D. 12,019') and as a microcrystalline 'felt' in upper beds; distorted fabrics associated with the microcrystalline anhydrite indicate that growth predated lithification of the host sediment. The presence of these evaporite beds, together with the absence of fossils, suggests that the Ashern was deposited by a body of hypersaline water, and Alan C. Kendall (personal commun.) has suggested that alternate precipitation and solution of evaporite minerals in a large hypersaline sea or lake may explain the textural discontinuities and contortions which characterize the formation.

The Ashern Formation is interpreted as a subaqueously reworked karst residue. It was probably originally red throughout, but has been differentially altered to gray-green by surficial reduction during the earliest part of the Winnipegosis transgression. Subaqueous deposition is suggested by fabrics which reflect primary bedding, and a saline body of water is indicated by component anhydrite and halite.

The Ashern is inferred to be a diachronous unit which accumulated between Late Silurian and early Middle Devonian time. Available fossil evidence is insufficient to date it accurately, but regional stratigraphic relationships show that it post-dated Middle Silurian beds and was succeeded by Devonian rocks containing Eifelian fossils (Lobdell, 1984, p. 6). Because our observations indicate that the basal beds are transitional with Interlake facies, we conclude that the Ashern Formation accumulated between Late Silurian and Early to Middle Devonian time, when the earliest Winnipegosis seas transgressed across the basin.

The change from fresh to hypersaline waters defined by the Interlake/Ashern contact is compared to the change that resulted in the replacement of fresh water Lake Bonneville by the hypersaline Great Salt Lake, and is attributed to a major climate change. Regional onlap of the underlying surface indicates that the saline Ashern Sea initially occupied a small depression in the central part of the basin, but gradually expanded outwards across the entire basin, encroaching over the weathered Lower Paleozoic surface.

Because the Ashern Formation is regionally persistent and impermeable, it is important as a seal facies for Interlake reservoirs throughout the Williston Basin.

HYDROCARBON POTENTIAL

The variabilities of climate and salinity that accompanied Interlake and Ashern deposition resulted in the development of many excellent source, reservoir, and seal facies, endowing the succession with excellent hydrocarbon potential.

Organic-rich facies with source rock potential accumulated as anoxic basin deposits during several Lower

Interlake deposition cycles, and intermittently as lake deposits during Upper Interlake time.

Porous reservoirs occur in dolomitized turbidites in Lower Interlake formations, in reefs and associated skeletal deposits in Middle Interlake formations, and in marsh, stream, and karst deposits in Upper Interlake formations in the central basin. However, away from this area, porosity distribution changes considerably in each formation due to significant lateral changes in facies and diagenetic features.

Excellent reservoir seals are products both of facies and diagenesis: anhydrite beds confine some Lower Interlake reservoirs, impermeable dolomites appear to confine certain Middle Interlake reservoirs, and Upper Interlake reservoirs are confined both by tightly cemented quartzites and by halite remobilized during late burial diagenesis. Regionally, all Interlake beds are confined by impermeable facies of the overlying Ashern Formation.

CONCLUSIONS

The Interlake Group is a highly productive, but underplayed oil-producer in the Williston Basin. Several Interlake formations have now been established as attractive exploration targets in different parts of the basin, yet wildcatting has been restricted by a lack of coherent regional exploration models. Core studies offer the only sound basis for developing these models because log signatures convey only limited facies-diagnostic information about these formations. Extensive core and sample studies in northeastern Montana and northwestern North Dakota have enabled us to map and project facies and porosity trends for Interlake units with known production, and to outline several promising unexploited trends.

Our regional analyses have proven that three major long-held exploration concepts concerning 'the Interlake play' are inappropriate:

1. It is clear that the Interlake is not a single play, but a number of plays controlled by stratigraphy, facies, and diagenetic factors;
2. It is probable that much of the petroleum produced from Interlake reservoirs was not derived from Ordovician rocks as originally suggested by Dow (1974), but was sourced by Interlake rocks;
3. Productive Interlake reservoirs are not all confined as simple unconformity traps beneath the Ashern Formation; on the contrary, considerable oil and gas has been trapped in reservoirs within the Interlake Group, confined by internal seals of primary and diagenetic origin.

An understanding of the stratigraphic, facies, and diagenetic factors which affected the distribution of source rock, porosity, and salt plugging should considerably enhance future exploration of the Interlake Group.

ACKNOWLEDGMENTS

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COTEAU AND DALE INTERVALS OF THE MISSISSIPPIAN MISSION CANYON FORMATION; FLAXTON FIELD, BURKE COUNTY, NORTH DAKOTA

by
Nels E. Voldseth
BHP Petroleum
(Americas) Inc., Englewood, CO 80111

ABSTRACT

Considerable data have become available from additional drilling in the Flaxton Field area, Burke County, North Dakota, and it is now possible to distinguish two additional intervals which lie at the top of the Mission Canyon: the Coteau and the Dale. These intervals were previously miscorrelated as Bluell.

Flaxton Field produces oil from a structural-stratigraphic trap in the Mississippian Mission Canyon and Charles Formations. The field was discovered in 1956 with completion of the Texota 1 Sorum. This and other early wells in the field were completed in the Midale and Nesson intervals of the Charles. The field was rediscovered in 1981 with completion of the Monsanto 1 Bird in the Coteau interval of the Mission Canyon. Until recently the Coteau as well as the Dale intervals have commonly been lumped together, and miscorrelated to the Bluell interval of the Mission Canyon.

The Mission Canyon Formation in the more recently developed part of the field is a limestone with variable, but generally low porosity and permeability (usually less than 15 percent and 1 md). Most of the reservoir rocks were deposited in shallow-marine shoals which were sometimes exposed subaerially. Diagenetic changes, especially cementation, have had an important effect on the reservoir.

INTRODUCTION

Most of the oil production on the east flank of the Williston Basin is from the Mississippian Mission Canyon Formation. This formation is the main reservoir in the recently developed part of Flaxton Field.

Flaxton Field produces oil from a structural-stratigraphic trap in the Mississippian Mission Canyon and Charles Formations. The field is located in Burke County, North Dakota, on the northeast flank of the Williston Basin (fig. 1).

Flaxton Field was discovered in 1956 with completion of the Texota Oil Company 1 Sorum (SESEsec 23, T163N, R92W) pumping 80 bbl of oil per day (12.7 m^3/d) from the Nesson interval of the Charles Formation. Within a few years, two distinct pools have been developed. All the early completions were in the Midale and/or Nesson intervals of the Charles (fig. 2).

Flaxton Field was rediscovered in 1981 with completion of the Monsanto 1 Bird (SENEsec 13, T163N, R91W) flowing 90 bbl of oil per day from the Coteau interval of the Mission Canyon (fig. 3).

STRATIGRAPHY

In the study area, the Mission Canyon is a marine limestone and is con-

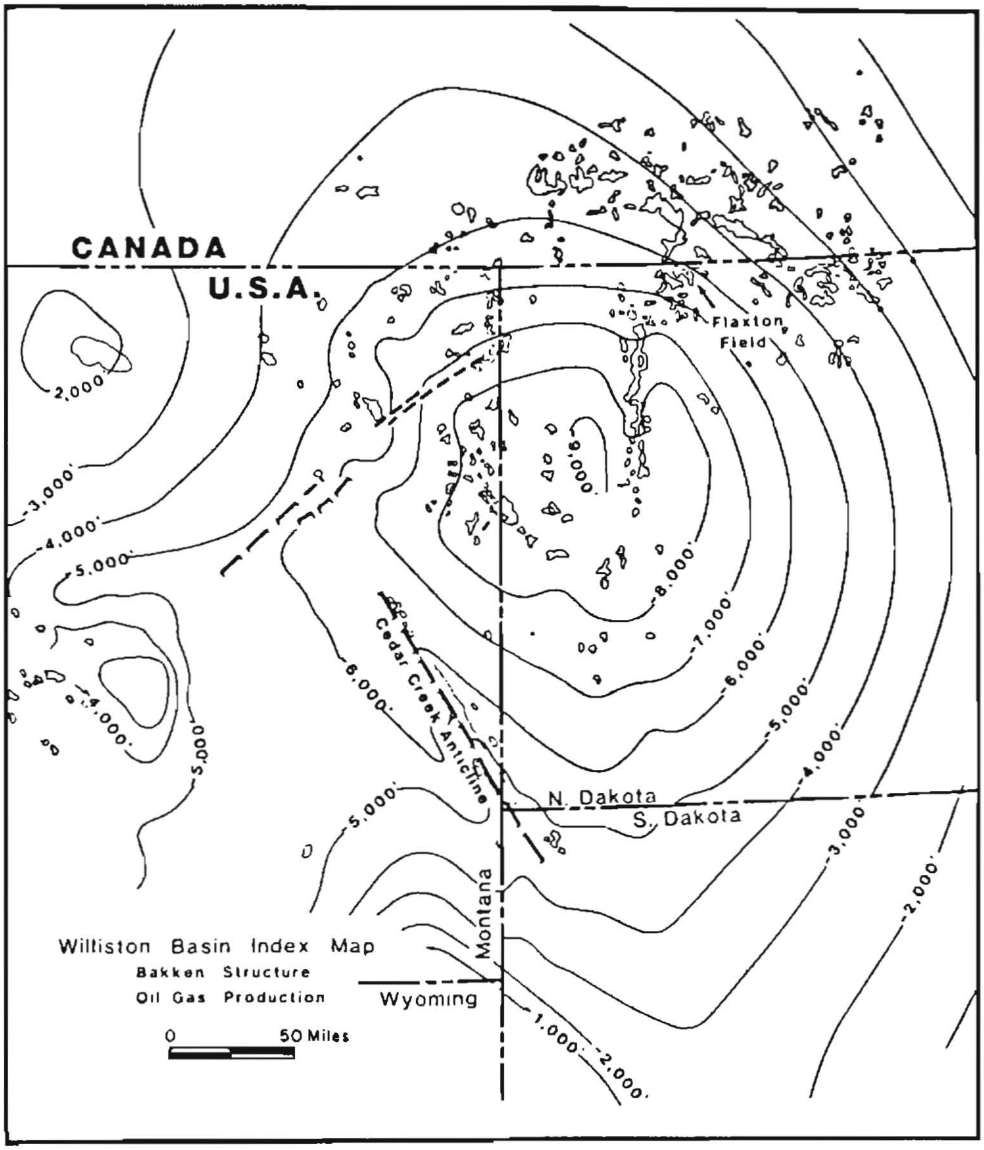


Figure 1. Index map of Williston Basin, showing location of Flaxton field.

formably overlain by the Charles Formation, which is largely evaporite. It is convenient to treat the Charles and Mission Canyon as diachronous, rock-stratigraphic units (Bluemle and others, 1981). On this basis, the top of the Mission Canyon in Flaxton Field is picked at the top of the limestone below the lowest Mississippian anhydrite (fig. 4). The entire Mission Canyon Formation was drilled in two wells in the Flaxton Field (NWSEsec12, T163N, R91W and SENWsec13, T163N, R91W). These wells bottomed in the underlying Lodgepole Limestone and are the deepest tests in the field.

The cyclic character of sedimentation in the upper Mission Canyon was illustrated by Harris and others (1966). Since their paper was published, considerable data have become available from additional drilling and improved well logs, and it now is possible to distinguish two additional units which

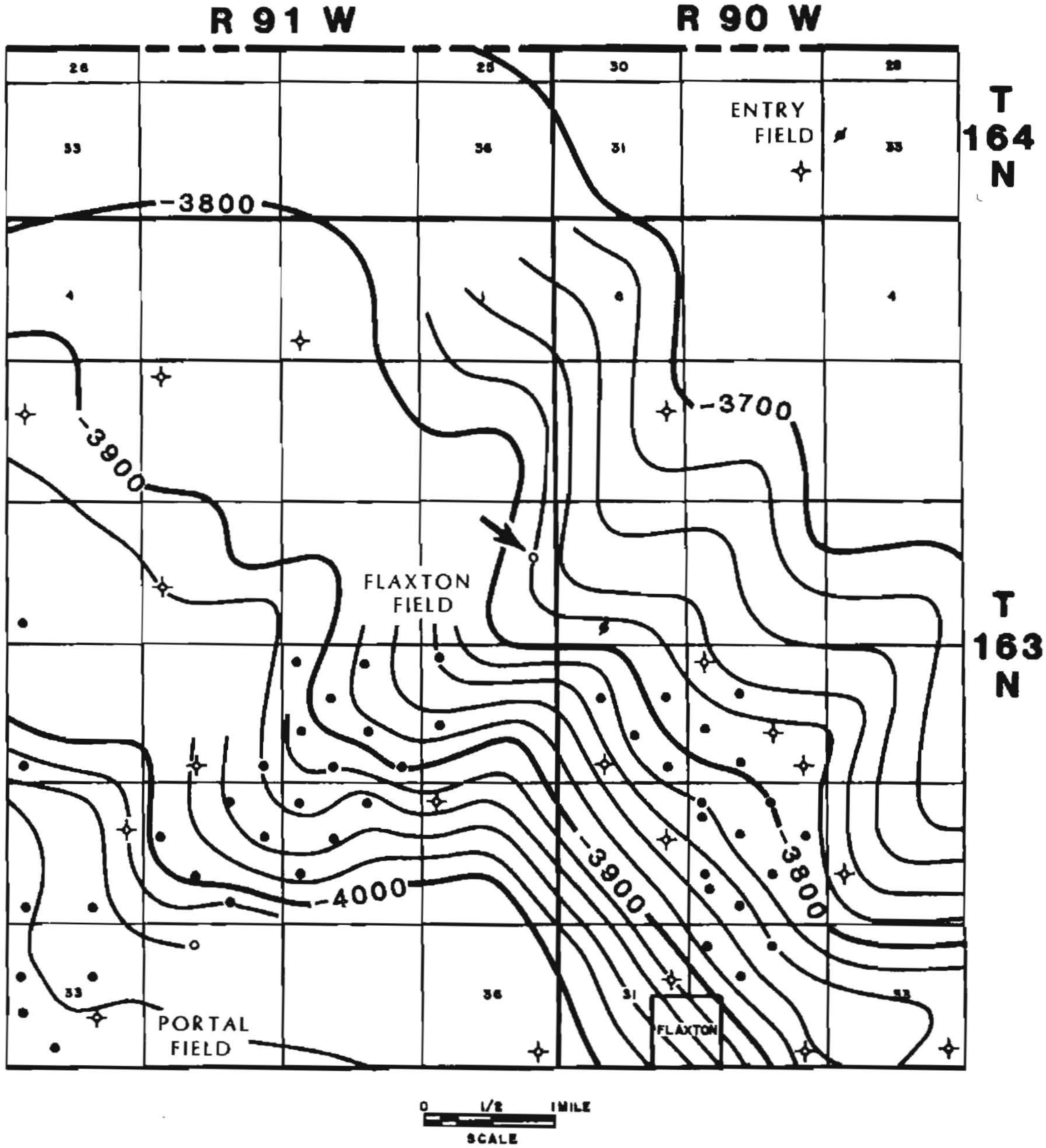


Figure 2. Flaxton field area, Burke County, North Dakota, 1981 interpretation of Nesson structure. Arrow shows location of Monsanto 1 Bird. 20 ft (6m) contours.

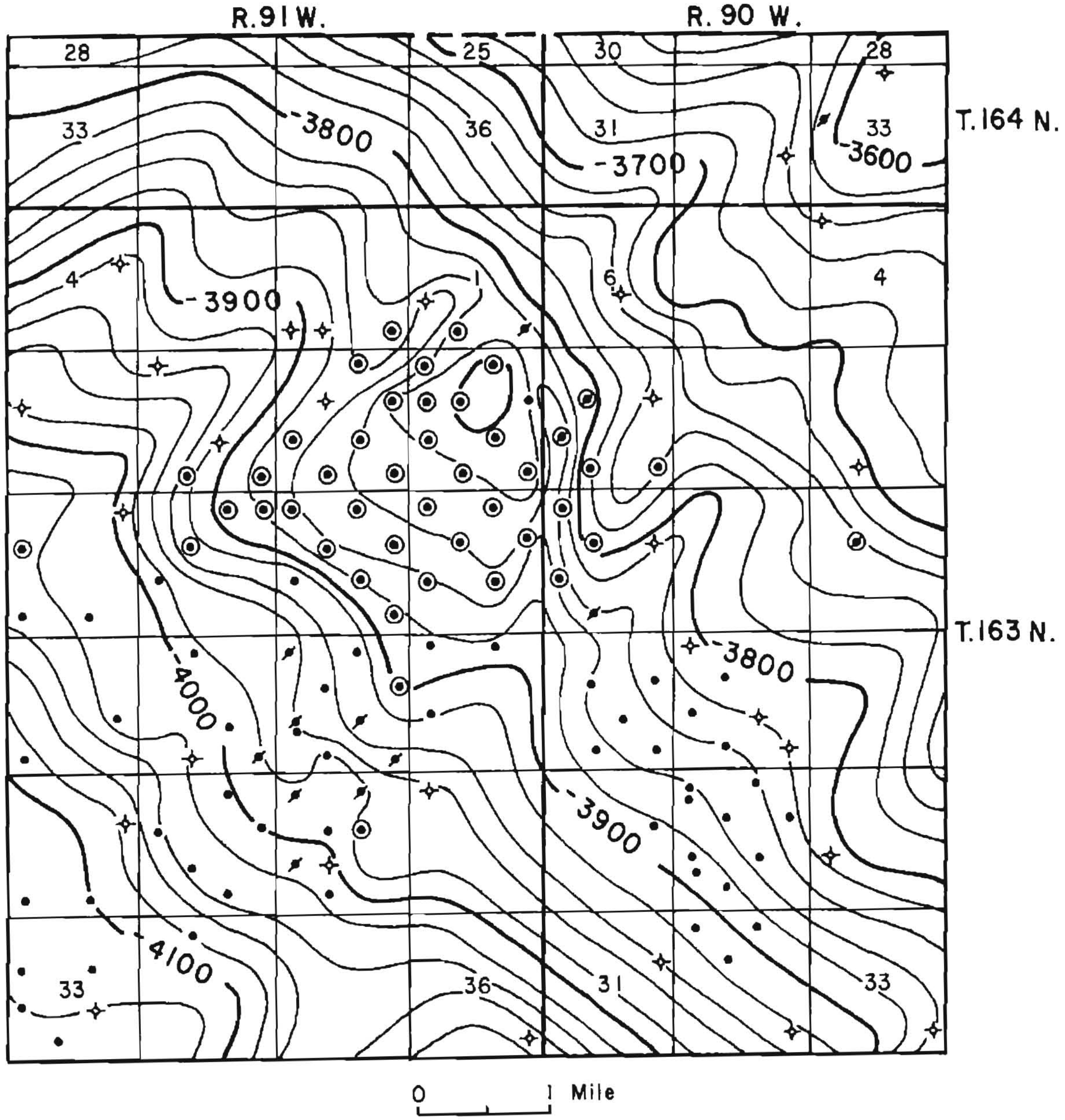


Figure 3. Flaxton field area, Burke County, North Dakota, current interpretation of Mission Canyon structure. 20 ft (6m) contours. Mission Canyon producers are circled; other wells are Midale and/or Nesson completions.

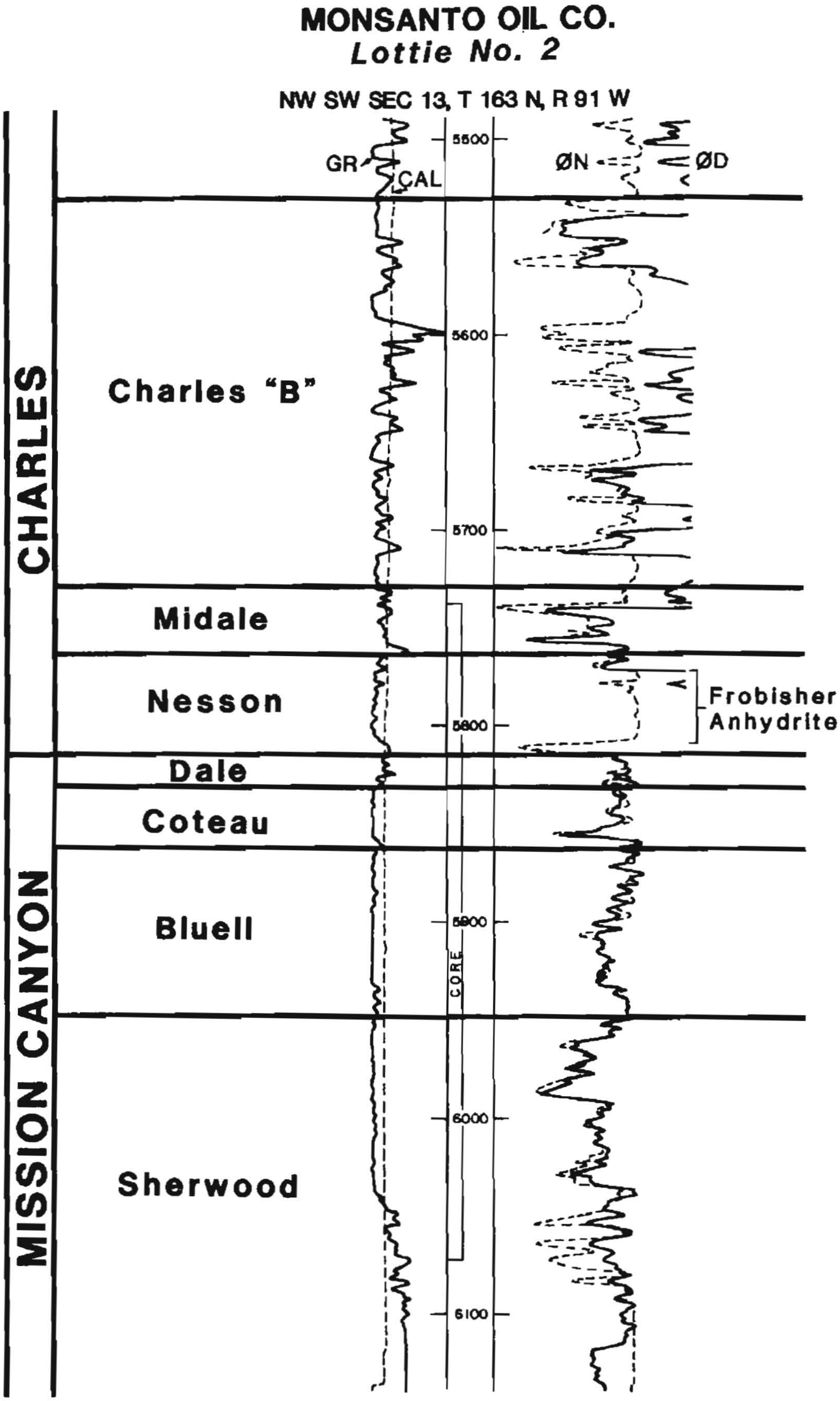


Figure 4. Gamma ray-compensated neutron-formation density log of Monsanto 2 Lottie, NWSWsec13, T163N, R91W.

lie at the top of the Mission Canyon in Burke County: the Coteau and the Dale. The Coteau overlies the Bluell and constitutes the interval from 5830-60 feet in the Monsanto 2 Lottie (NWSWsec13, T163N, R91W) (see fig. 4). It is named for the abandoned Coteau Field (sec28, T161N, R90W) which was the first to produce in Burke County and which was completed in this interval. The Dale overlies the Coteau and constitutes the interval 5815-30 feet in the 2 Lottie. Its name is taken from the Dale Field (sec33, T162N, R90W) where this interval is productive. The Coteau and Dale have commonly been lumped together and miscorrelated to the Bluell interval of Harris and others (1966). The interval from 5860-5947 feet in the 2 Lottie is herein correlated to the type Bluell; this interval has more generally been called Sherwood. Figure 5A shows the Mission Canyon facies relations and subdivisions of Harris and others (1966); figure 5B shows the modifications proposed in this paper.

The Charles Formation in the Flaxton Field consists of anhydrite, limestone, and dolomite. Basin-center salts that are typical of the Charles in deeper parts of the Williston Basin are absent. Just southwest of the field, the Charles is conformably overlain by the Kibbey, but in the field, the Kibbey and upper beds of the Charles have been eroded and the Charles is overlain by the Triassic Spearfish Formation in a pronounced angular unconformity.

The lower part of the Charles and upper part of the Mission Canyon were cut in six consecutive cores in the Monsanto 2 Lottie (figs. 4, 6-9). These cores provide a good illustration of a typical section of these strata in the Flaxton Field area. Photographs of the core from 5790.5-5862 feet and from 5906-5917 feet are shown here. Depths marked on the cores are within a foot of log depths. For a discussion of the Midale and Nesson intervals, which are not shown here, the reader is referred to articles by Anderson and others (1960) and Mitchell and Petter (1958).

Typical Frobisher Anhydrite is from 5790.5-5808 feet (fig. 6a, 6b). There are thin layers of finely laminated dolomite at 5790.9 feet and 5794 feet. Chicken-wire texture at 5795 feet and enterolithic structure at 5801 feet are commonly cited as evidence of a coastal sabkha environment of deposition.

A dolomite unit from 5808-5815 feet is at the base of the Charles in the Flaxton Field. The downward sequence of lithology and sedimentary structures within the dolomite unit as noted in core is:

(1) Anhydrite, often massive and featureless (5807 feet);

(2) Anhydrite and dolomite with contorted lamination;

(3) Dolomite with parallel, nearly horizontal lamination;

(4) Mottled dolomite (5810 feet);

(5) Featureless dolomite (5813 feet);

(6) Limestone, usually tightly cemented with anhydrite and calcite (5815 feet).

The dolomite is micro-to-cryptocrystalline and commonly has as much as 25 percent porosity and 5-10 md permeability. It is seldom productive, apparently the small pore size results in practically no relative permeability to oil. The darker mottling and lamination owes its color to finely disseminated pyrite. The dolomite is often cribed as silty or argillaceous. Analyses from the Flaxton Field indicate that about three-quarters of the rock is dolomite, the rest being primarily calcite with 1-2 percent each of anhydrite, pyrite, quartz, feldspar, and clay (Powell and Thomas, 1983). This dolomite is often correlated to the State "A," but the writer believes that it is younger.

The Dale interval (5815-30 feet) shows common Mission Canyon rock types. The lighter-colored intervals are

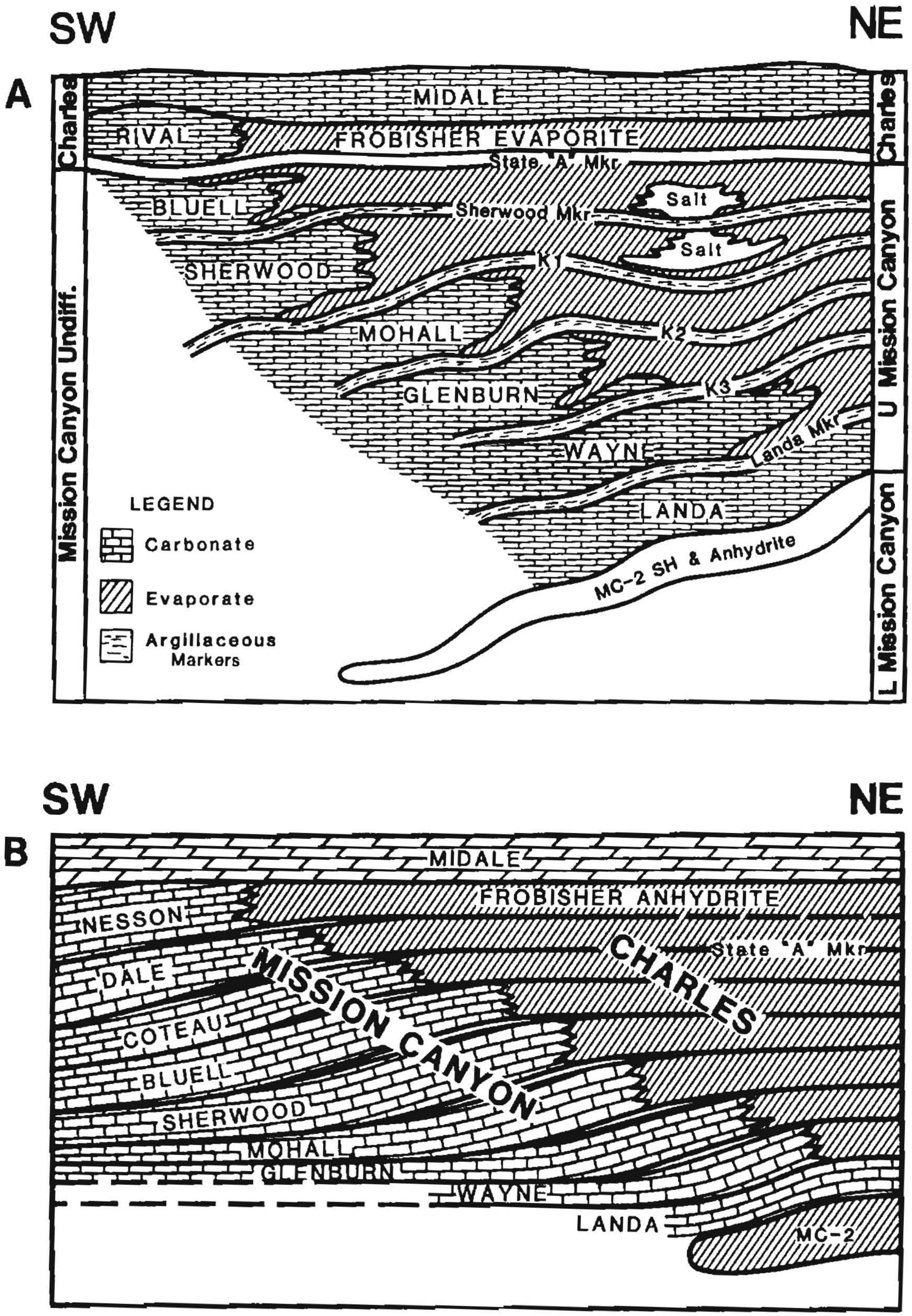


Figure 5. (A) Mission Canyon facies relations diagram of Harris and others (1966); (B) Modification of 5A used in this paper.

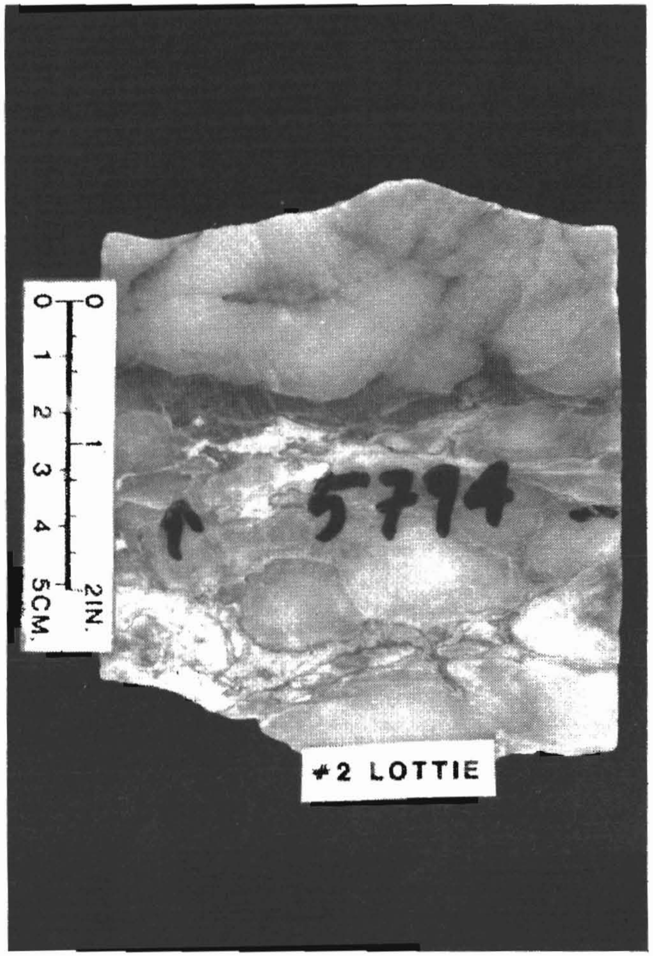


Figure 6. (A) 5794´ Nodular Frobisher Anhydrite.

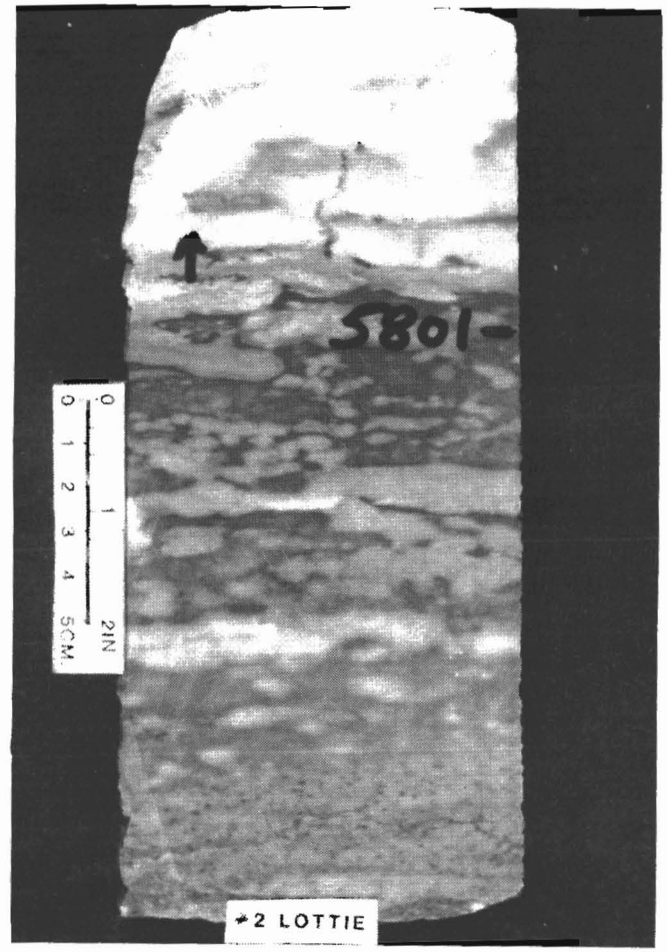


Figure 6. (B) 5801´ Frobisher Anhydrite. Note similarity of form to mottled dolomite at 5824´.

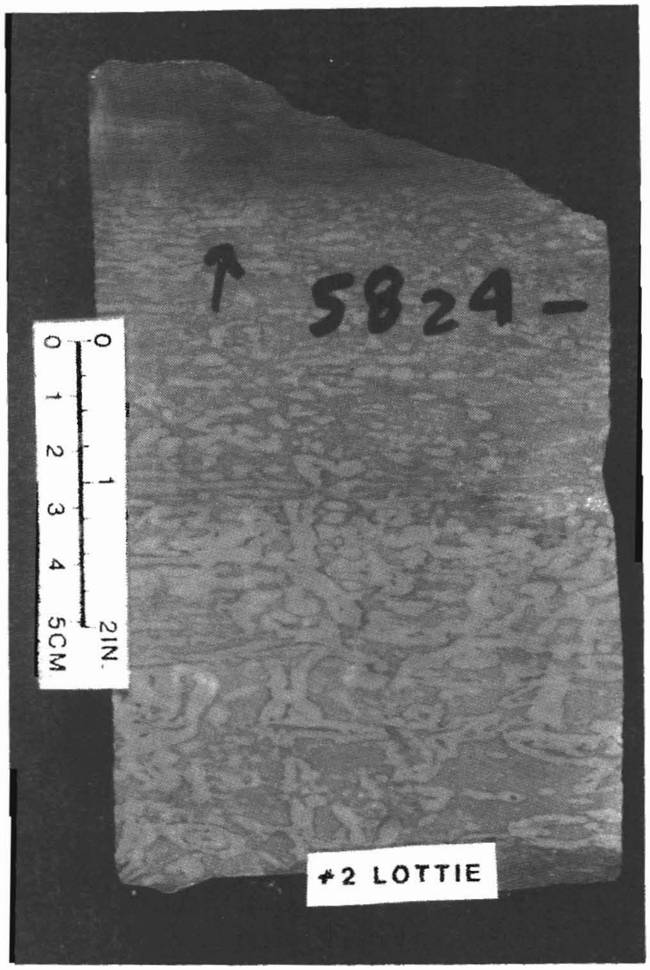


Figure 7. 5824'. Mottled (pattern) dolomite in State A marker

largely oolith-pisolith-pellet grainstone with fenestral pores. This facies is one of the most common in Mission Canyon reservoir rocks, but it is tightly cemented here. A thin-section view of similar rocks is shown in figure 10A. Micritic and possibly algal crusts are common in this facies (fig. 11B). Fossils are rare, but ostracodes, gastropods, and foraminifera are occasionally recognizable. These grainstones were deposited in a series of shallow-marine shoals. Periodic exposure is indicated by crusts, shrinkage cracks, and interval sediment (fig. 11A, B, C).

The darker-colored rocks toward the base of the Dale are correlated by the writer to the type State "A" dolomite (fig. 7). These rocks are much muddier than the overlying grainstones and are partially dolomitized. Darker color is associated with increased radioactivity throughout the Mission Canyon.

The Coteau interval (5830-61 feet) is similar to the Dale, but in this well has more porosity (fig 8A, B, C). Porosities in the Mission Canyon at Flaxton range up to 25 percent but are more typically 5-8 percent. Permeabilities measured from cores are usually

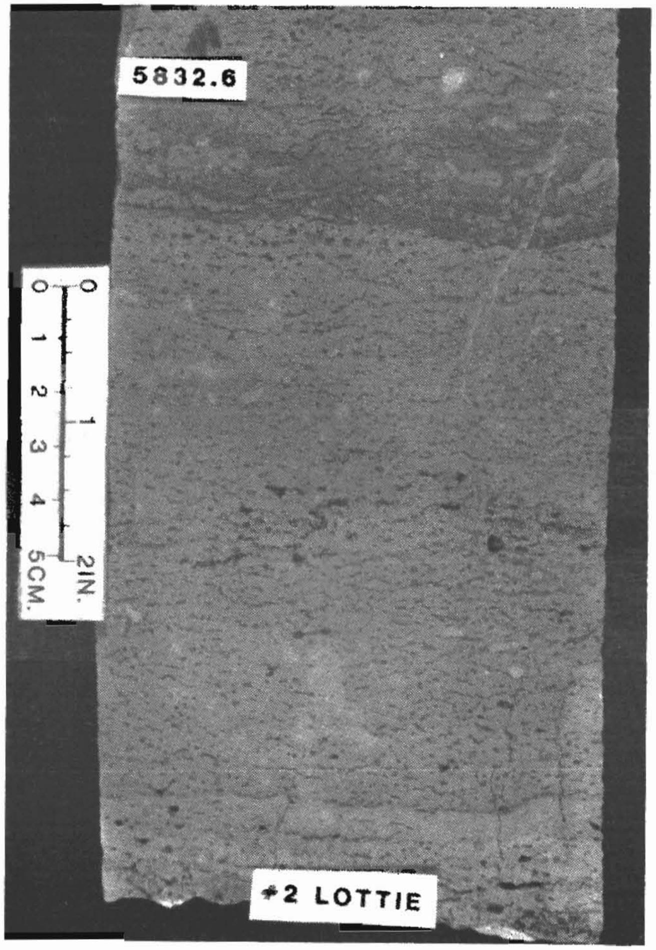


Figure 8. (A) 5832´ Fenestral porosity almost completely infilled with blocky calcite cement. Coteau interval.

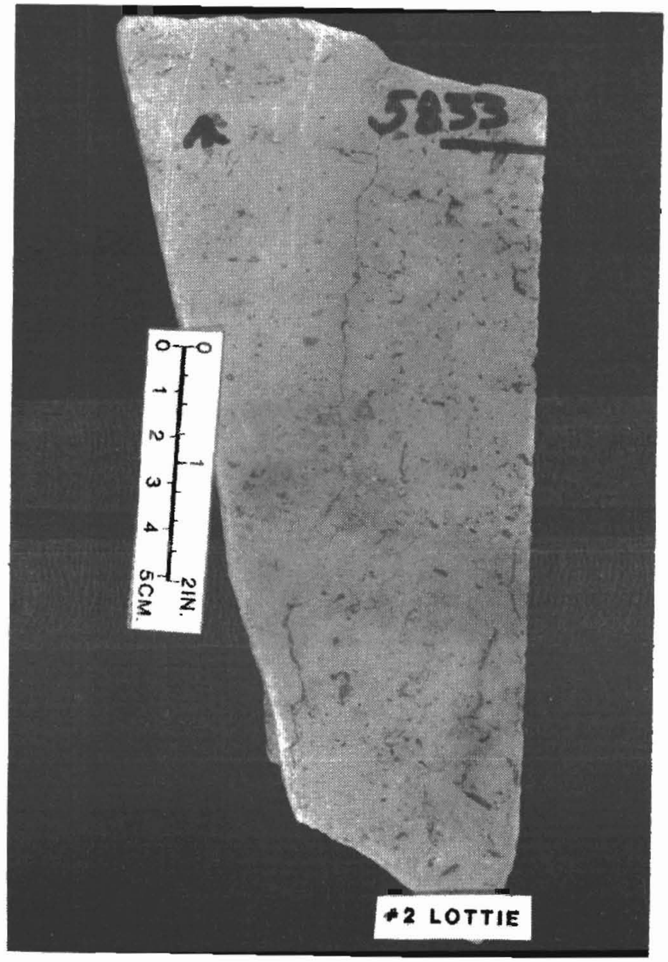


Figure 8. (B) 5833´ Mudstone. Coteau interval. Vertical fractures, now mostly cemented, are important contributors to permeability when open.

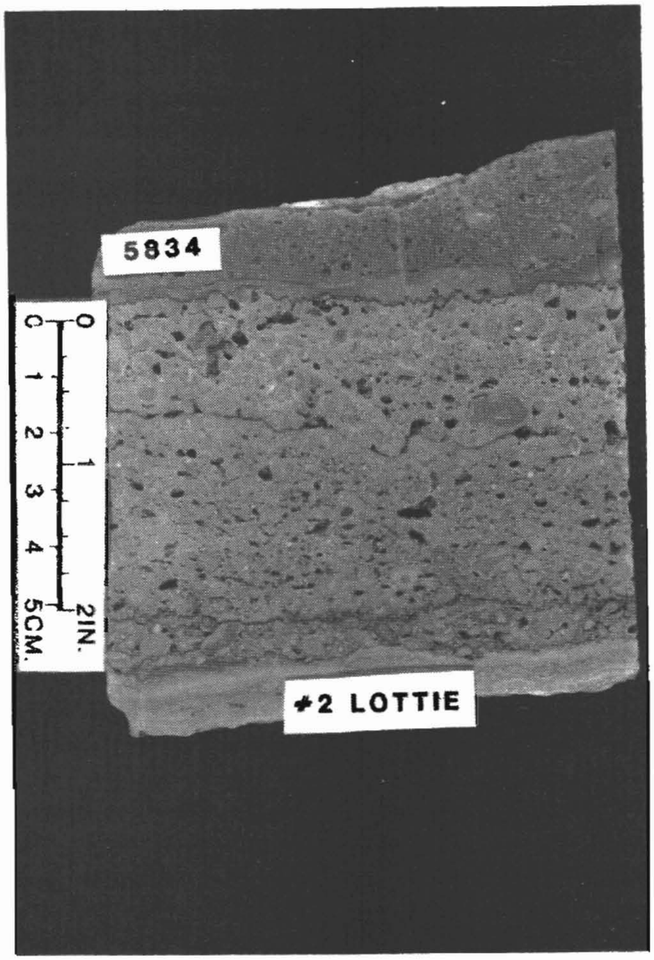


Figure 8. (C) 5834′ Oolite-pisolite grainstone, Coteau interval. Some open fenestral pores, several stylolites, crust at base.

less than 1 md. The low permeabilities result from many of the pores being isolated, as can be seen on the core slabs. The porous interval at the base of the Coteau (5850-57 feet) is generally present throughout the field and is the most important individual productive zone (fig. 9). In the 2 Lottie, it is a pelleted mudstone with minor wackestone. The pores are intercrystalline rather than fenestral, and are too small to be readily seen without magnification. A natural fracturing of this interval greatly enhances its permeability.

The dark-gray limestone at the base of the Coteau (5857-62 feet) has the typical high gamma-ray character of a marker bed within the Mission Canyon. Microstylolites are common in the marker beds and often coalesce into stylolite seams (5860.1 feet). Although stylolites are ubiquitous throughout the upper Mission Canyon, they are less common in grainier rocks. The marker beds can be correlated over wide areas of the Williston Basin, although the lithology of these beds varies in a systematic way. As this marker is traced east (toward the

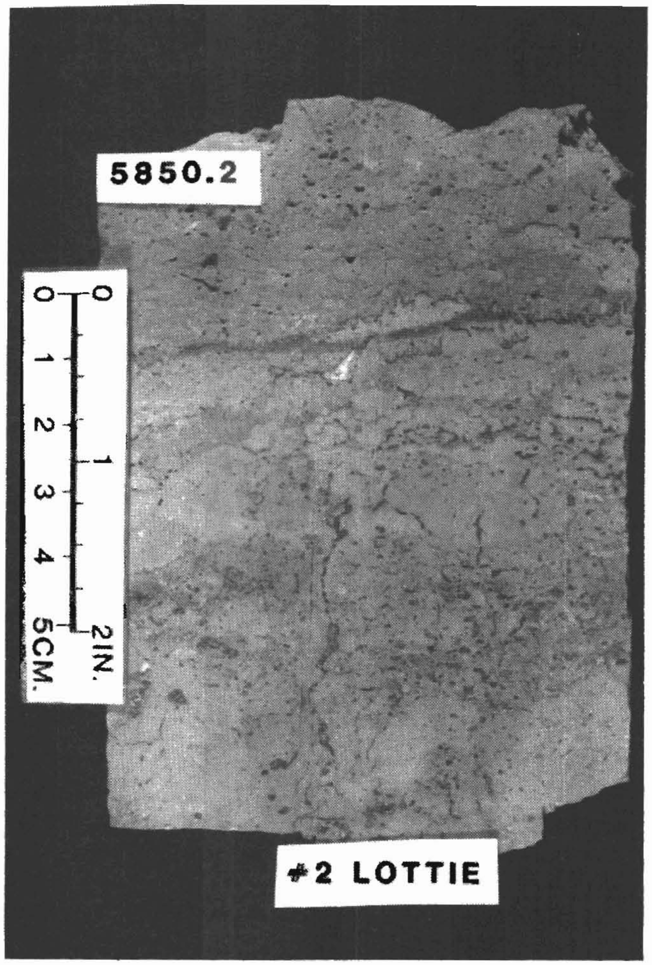


Figure 9. 5850′ Ostracod calcisphere wackestone, Coteau interval. Top of main porosity streak in Coteau.

edge of the basin) it becomes more dolomitic and resembles in turn the lighter-colored intervals such as 5819-30 feet and 5808-15 feet in the 2 Lottie. The darker (unoxidized) color and muddier textures of the marker beds within the Mission Canyon suggest periodic transgressions within a general regression as noted by Harris and others (1966). At the northern edge of the Flaxton Field, the marker beds are difficult to follow due to an overall increase in mud content within the productive intervals (fig. 12).

Other rock types not well illustrated in the 2 Lottie are noted elsewhere at Flaxton. Fossiliferous wackestone is common. Ostracodes, foraminifera, and mollusks are the most abundant fossils but crinoid pieces, brachiopods, and corals are also seen. In the 2 Galvin (NWNW sec12, T163N, R91W) good porosity is developed in a bioclastic packstone or grainstone (fig. 10B). This facies is unusual, but makes good reservoir rock. The more fossiliferous rocks were deposited in slightly deeper-water marine environments than the oolith-pisolith grainstones. The fossils present indicate that none of this sediment was deposited in water more

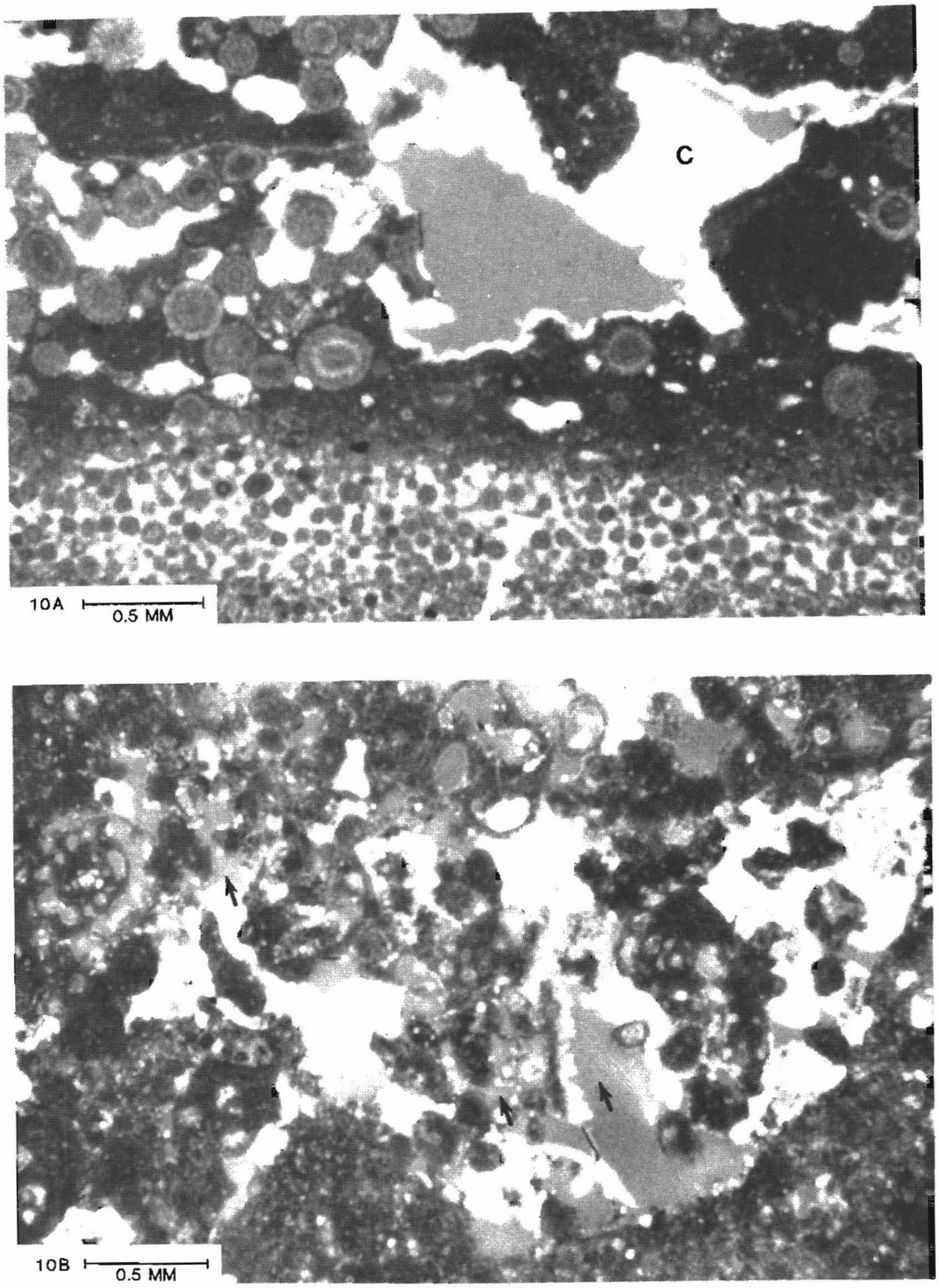


Figure 10. (A) Oolith-pisolith grainstone, 1 Marvin well, SESWsec 12, T163N, R91W, 5777.5 ft. Note drusy calcite lining fenestral pores which are partially to completely infilled with blocky calcite (labelled "C" on photo). (B) Bioclastic packstone and grainstone, 2 Galvin well, NWNWsec 12, T163N, R91W, 5318.5 ft. Note good interparticle porosity.

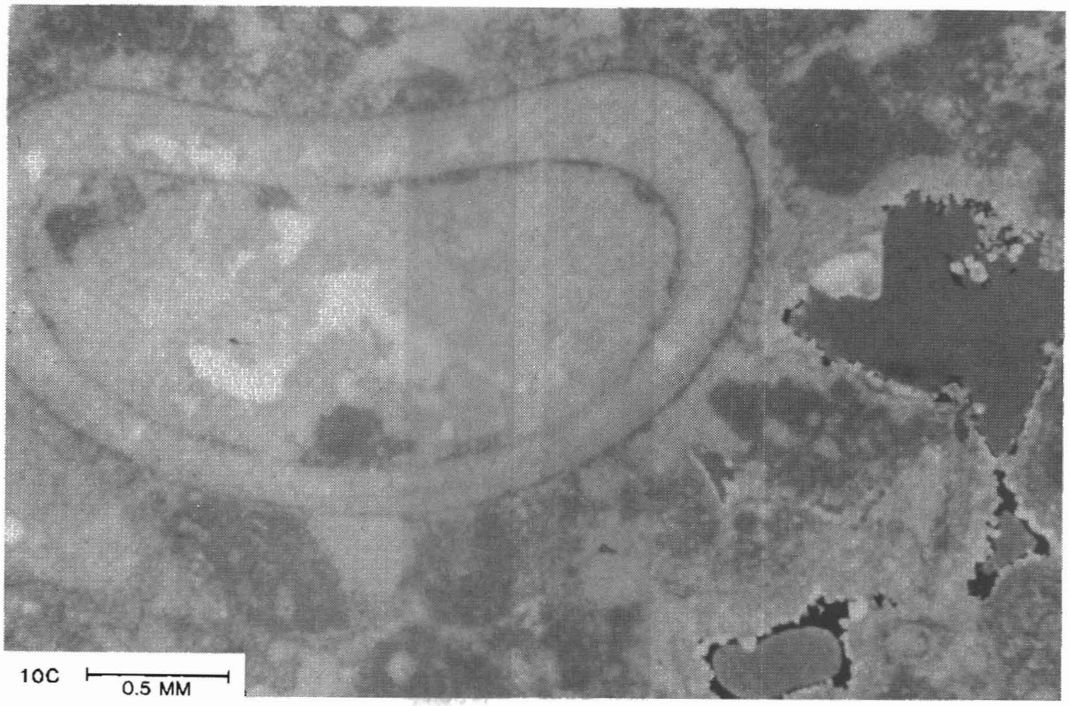


Figure 10. (C) Ostracod-gastropod-calcisphere wackestone, 16-10 Gregory well, SESEsec 10, T163N, R91W, 5857 ft. Note fenestral pore with drusy calcite cement and oil stain and rectilinear outline of pore. Photographs courtesy of Hendricks and Associates.

than a few feet deep. The entire upper Mission Canyon and lower Charles section ranges from shallow subtidal to marginal-marine supratidal.

DIAGENENIS OF MISSION CANYON RESERVOIR

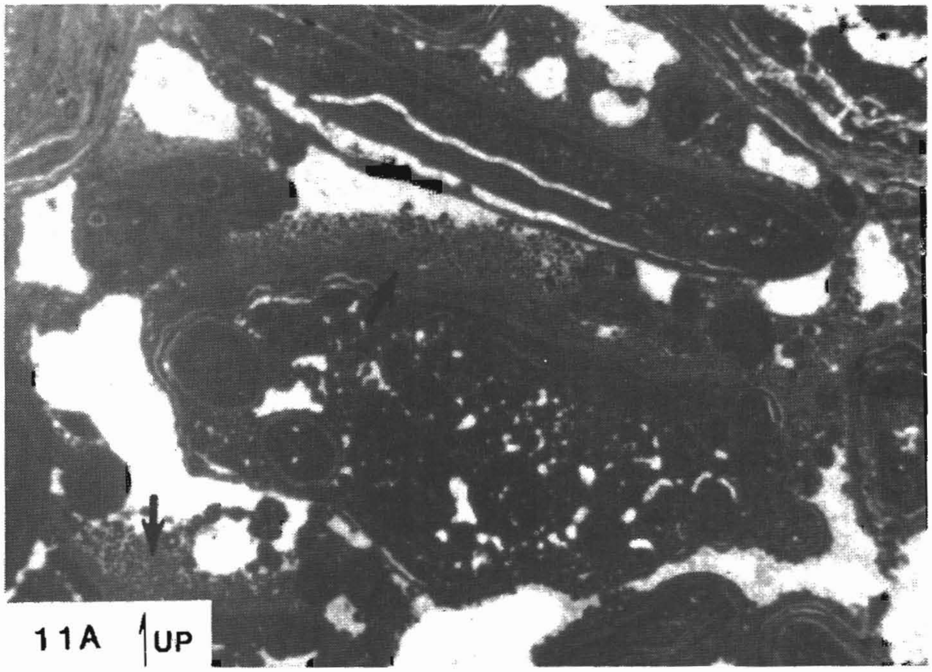
Diagenetic alterations are a significant factor in controlling porosity and permeability development in the Mission Canyon reservoir in Flaxton Field. Observations from cores suggest this general diagenetic sequence.

(1) Deposition of Mission Canyon sediments with contemporaneous for mation of fenestral pores in grainier facies by gas bubbles or internal shrinkage. This was accompanied by very early cementation of the matrix (Shinn, 1983) in the form of isopachous drusy calcite cement (Lee and others, 1983; Hendricks and others, 1983).

(2) As the sediments were buried, compaction proceeded (Shinn and Robbin, 1983). This process was more effective in muddier or uncemented sediments (Beach and Schumacher, 1982). Compaction would destroy fenestrae unless the matrix were cemented or the pores were filled (Shinn, 1983).

(3) As the Charles sabkha prograded over the Mission Canyon there was some alteration of lime mudstone to dolomite. There is very little dolomite observed in grainier rocks.

(4) Also during progradation of the Charles sabkha, many of the pores were filled with anhydrite. Lee and others (1983) have observed that this pore-filling anhydrite often replaced part of the limestone matrix. The anhydrite has a distinctive rectilinear outline.



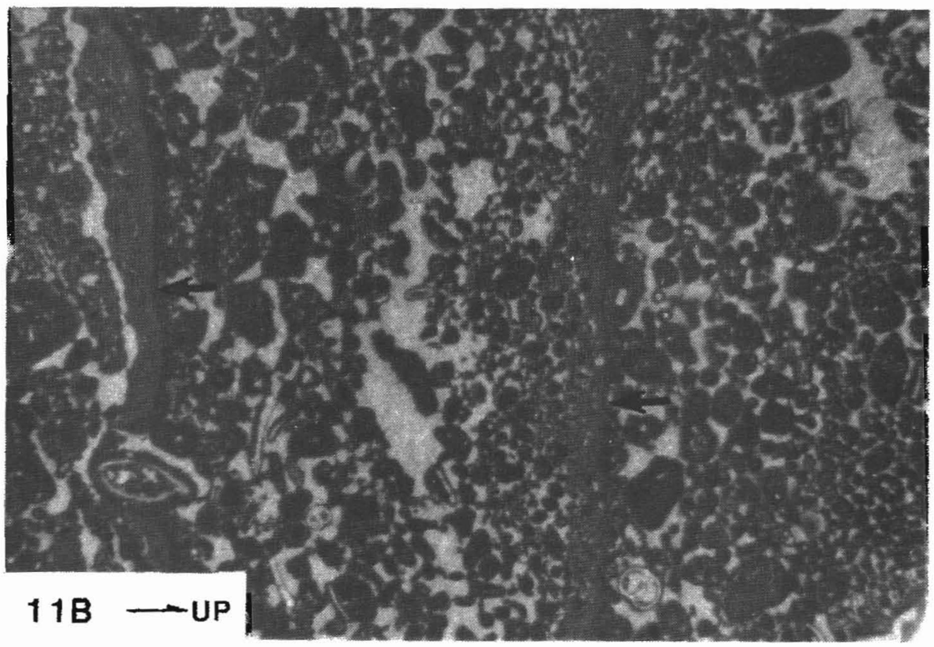


Figure 11. (A) Internal sediment with reverse-graded bedding, 1 Jensen well, SESWsec 18, T163N, R90W, 5814 ft.
(B) Algal? crusts in oolith-pisolith grainstone, 1 Jensen well, SESEsec 18, T163N, R90W, 5771 ft.

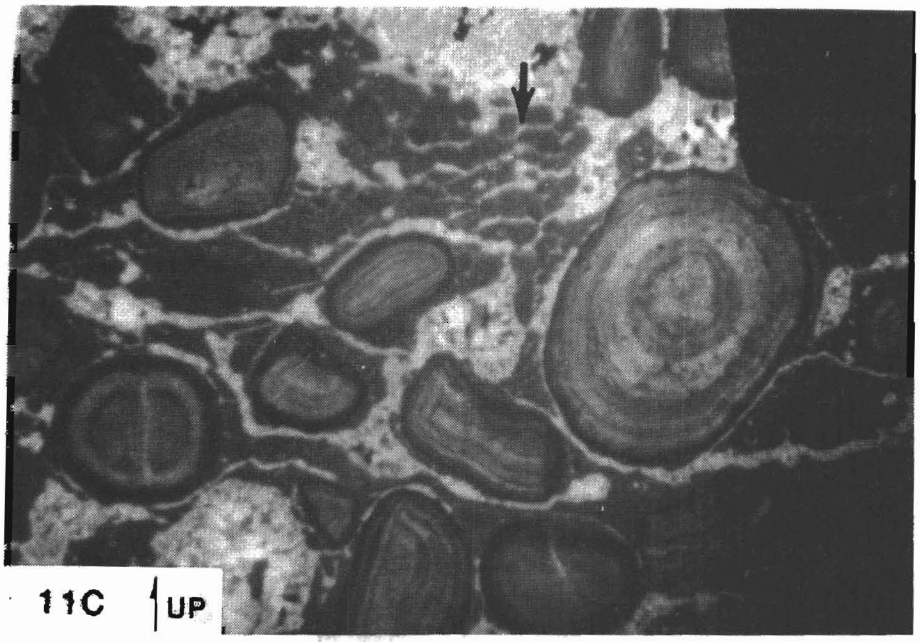


Figure 11. (C) Desiccation cracks subsequently infilled with drusy and blocky calcite cement, 2 Lottie well, 5946 ft. Photographs courtesy of Sue T. Reid.

(5) Prior to deposition of the Triassic Spearfish Formation, the Paleozoic section was beveled to the northeast. As the Charles and Mission Canyon were eroded, meteoric waters percolated downdip into the rocks and the more soluble minerals such as halite and anhydrite were leached. The rectilinear outlines of many pores indicate that pore-filling anhydrite has been dissolved (Lee and others, 1983) (fig. 13C).

(6) Blocky calcite and less frequently dolomite have been precipitated in many pores.

(7) The rocks have been fractured. There is evidence outside the field to suggest fracturing as early as the Jurassic. Fracturing facilitates other diagenetic processes by allowing greater movement of formation fluids.

(8) Using Meissner's (1978) range of 6200-8200 feet (1900-2500 m) for depth of burial of the lower Mississippian Bakken (generally thought to be the source for Mission Canyon oil), hydrocarbon generation and migration would have begun in the Late Cretaceous.

STRUCTURE

The structure in the Flaxton Field at the top of the Mission Canyon is shown in figure 3. Regional dip is southwest and average less than 1°. At a datum within the Mission Canyon, there is much less structural relief--a phenomenon similar to that described in the Stanley Field by Beach and Schumacher (1982). Evidently the process of differential compaction has worked in both places. A 'Charles-B to Nesson' isopach shows the thickening of this interval over the areas where compaction has occurred (fig. 13). This is an especially useful map for prospecting in Burke County because virtually all the wells there have been drilled to the Nesson, but only about half have penetrated more than a few

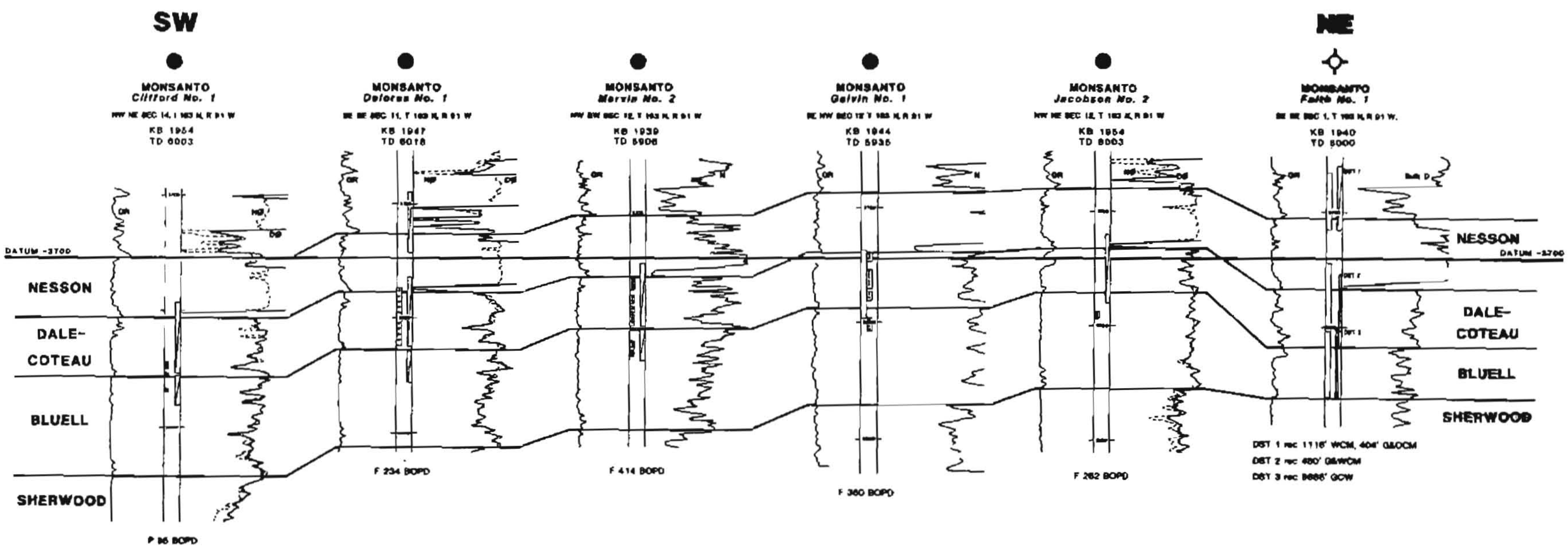


Figure 12. Dip section through Flaxton field. Datum is -3700 ft. Line of section is shown on figure 3.

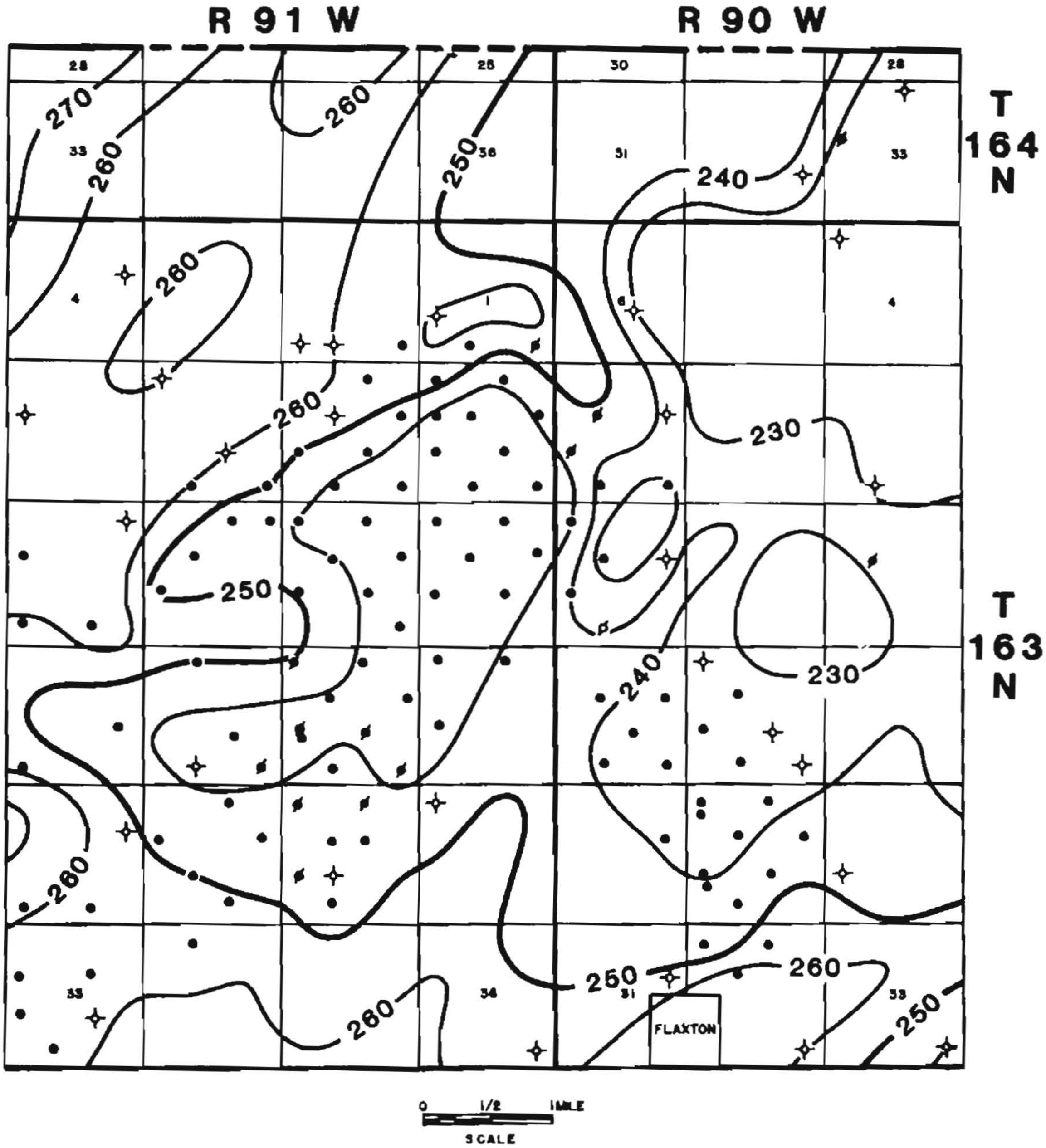


Figure 13. Charles B to Nesson isopach, Flaxton field. Burke County. North Dakota. 10 ft (3 m) contours.

Figure 14. Landsat view of Flaxton area. Field outline and Souris River fault are shown. Image processed by Aero Service.

feet of Mission Canyon. If the anhydrite in the Charles was originally deposited as gypsum, the isopach thick areas have been slightly accentuated by subsequent dehydration.

A west-northwest trending lineament lying along the north edge of the Flaxton Field is clearly visible on Landsat images and aerial photographs (fig. 14). This feature was named the Souris Valley fault by Kupsch (1956). No fault cuts were noted in any of the wells closest to this lineament, but there is a general loss of reservoir quality in these wells which causes the trap in the field. The writer adheres to a minority opinion that the trap isrelated to this lineament in an obscure fashion. The occurrence of a stray limestone in the Jurassic Swift Formation along the Souris Valley fault suggests activity along this feature at that time.

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