DEPOSITIONAL ENVIRONMENTS AND SANDSTONE DIAGENESIS IN THE TYLER FORMATION (PENNSYLVANIAN), SOUTHWESTERN NORTH DAKOTA

by

Stephen D. Sturm

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Don L. Halvorson, State Geologist

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ABSTRACT

The Tyler Formation, of Early Pennsylvanian age, in southwestern North Dakota can be divided into upper and lower units, reflecting changes in both lithology and depositional environments. The lower unit is dominated by varicolored, noncalcareous shales and mudstones, siltstones, thin coal beds, and medium-grained sandstones. The upper unit, in the areas of the Square Butte to Fryburg Fields, can be divided into a lower subunit, dominated by dark-gray to grayish-black, argillaceous limestones and calcareous shales, and an upper subunit dominated by grayish-red, anhydritic limestones, varicolored to reddish-brown, calcareous shales, and locally, thin anhydrite. In the area of the Dickinson Field, the upper unit is dominated by a variety of lithologies, which indicates rapid changes in depositional environments.

In the depositional model suggested for the Tyler Formation, the lower unit is interpreted to represent sedimentation on a progradational delta plain. Distribution of sandstones in the lower unit indicates the presence of two trends: an east-west trend (in Golden Valley to Stark Counties) of medium-grained, well-sorted quartz arenites, interpreted as a delta-front deposit, and to the south, a northwest-southeast trend of medium-grained, poor to fairly well-sorted quartz arenites, interpreted to be distributary channel-fill deposits.

The controlling influence affecting depositional environments in the upper unit was the formation of barrier islands in Billings and Stark Counties. Barrier-island development was followed by north-to-northwestward progradation of estuarine-lagoonal environments in the Dickinson area (Stark County) and transgression of a shallow, anoxic sea in Golden Valley and Billings Counties. Continued north-to-northwestward shoreline migration in the Dickinson area, and the withdrawal of the Tyler sea in the areas of the Square Butte to Fryburg Fields (Golden Valley and Billings Counties) created similar depositional environments throughout the region in the uppermost Tyler Formation. Depositional environments are characterized as tidal flats in the area of the Square Butte to Fryburg Fields, and marsh in the remaining areas bordering the Tyler sea.

Each sandstone depositional environment had its own effect on diagenesis and porosity development. Characteristically, channel sandstones have low original porosity and permeability due to the large percentage of detrital clay matrix. Porosity and permeability are reduced by the emplacement of authigenic kaolinite and late-stage ankerite cement. Delta-front sandstones are tightly cemented by anhydrite: as much as 30 percent of the original porosity has been eliminated by precipitation of calcium sulfate derived from local hypersaline lakes. Detrital clay coatings on quartz grains inhibited overgrowth and total cementation. Late-stage authigenic kaolinite has further reduced primary intergranular porosity and permeability.

ACKNOWLEDGMENTS

The North Dakota Geological Survey is gratefully acknowledged for its financial support, material assistance, and the use of its facilities for this study. I thank the following North Dakota Geological Survey people: Sidney B. Anderson, for helpful discussions and suggestions on the stratigraphic portion of this study; Julie LeFever, for assistance in handling computer work for data used in this study; and especially Randolph B. Burke for many helpful suggestions and discussions and his time and energy assisting in preparation of displays and papers presented at the annual meeting (June, 1982) of the American Association of Petroleum Geologists in Calgary and the 4th International Williston Basin Symposium (October, 1982) in Regina.

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A very special thanks goes to my parents, Stanley and Ellen, for their patience, understanding, and moral support. I dedicate this study to the memory of my beloved sister, Judith Susan.

INTRODUCTION

General Statement

Recent investigations of modern and ancient delta and barrier-island sequences have provided a better understanding of depositional processes and the resultant products. The economic importance of sandstone reservoirs associated with deltaic and barrier-island complexes has been established in many areas. Depositional patterns of sandstones and associated strata have been used to produce predictive, three-dimensional models that can be applied to coal exploration (Ferm, 1970; Ryer, 1981) and oil exploration (Curtis, 1970; Weimer, 1970; Edwards, 1981). Although a better understanding of depositional environments, lithofacies, and predictability of sandstone trends may be realized from depositional modeling, no such study has been done in the Tyler Formation in North Dakota.

The Tyler Formation, of Early Pennsylvanian age (Ziebarth, 1964; Grenda, 1977), is a varied sequence of quartz arenites, shales, mudstones, carbonates, and, locally, thin anhydrite and coal. Sandstones in the Tyler have been important sources of oil in southwestern North Dakota since the late 1950s. Grenda (1977, p. 38) inferred that sandstones in the Tyler are distributary channel deposits in an "overall deltaic complex of environments." Land (1976, 1979) stated that oil production in the Dickinson Field (Stark County) was from quartz sandstones deposited as barrier islands. However, detailed facies relationships and the relationship between sandstone bodies at different stratigraphic positions in the Tyler Formation have not been well understood.

The purpose of this report is to interpret the depositional environments of the Tyler Formation in southwestern North Dakota (fig. 1) and to produce a depositional model by relating the distribution and thickness of Tyler sandstones to the distribution of associated strata. Also of interest is the relationship between diagenesis in the Tyler sandstones and depositional setting. This study will provide additional information regarding the depositional history and facies relationships in the Tyler Formation and it may also be used as a model to be applied to other areas of Tyler deposition in North Dakota as an aid in interpreting depositional environments and reservoir potential of Tyler sandstones.

Geologic Setting

Regional Stratigraphy

The Tyler Formation underlies most of the western half of North Dakota. It is conformably overlain by the Amsden Formation (Pennsylvanian) and unconformably overlies the Mississippian Kibbey and Otter Formations and limestones of the Madison Group. The distribution of units below the Tyler Formation is illustrated in figure 2. The overlying Amsden Formation consists of pinkish-gray to pale-yellowish-brown dolostone interbedded with dark-reddish-brown shale, white to grayish-brown anhydrite, with gray to pale-red, fine-grained sandstone developed near the top of the formation (Bluemle et al., 1980). The Alaska Bench Limestone Member is developed at the base of the Amsden Formation and provides an excellent log marker in southwestern North Dakota. Below the Tyler, the Kibbey Formation consists of reddish-gray to light-gray, medium-grained sandstone, white to brown limestone, and reddish to variegated shale. The "Kibbey lime" is an excellent log marker in the Mississippian Big Snowy Group. The Otter Formation conformably overlies the Kibbey and consists of greenish-gray to reddish-gray shale and finely laminated oolitic limestone (Bluemle et al., 1980).

Regional Structure

The Williston Basin is a major structural and sedimentary basin that occupies part of southern Saskatchewan, eastern Montana, northwestern South Dakota, and most of North Dakota (fig. 1). In North Dakota, the Williston Basin contains rocks ranging in age from Precambrian through Quaternary.

The boundary of the Superior and Churchill Provinces in central North Dakota (fig. 3) has been identified as a hinge line for the eastern part of the Williston Basin by Ballard (1963, p. 30). Gerhard et al. (1982, p. 991) have stated that "stratigraphic and gravity studies suggest that this boundary is an important factor in Phanerozoic basin development."

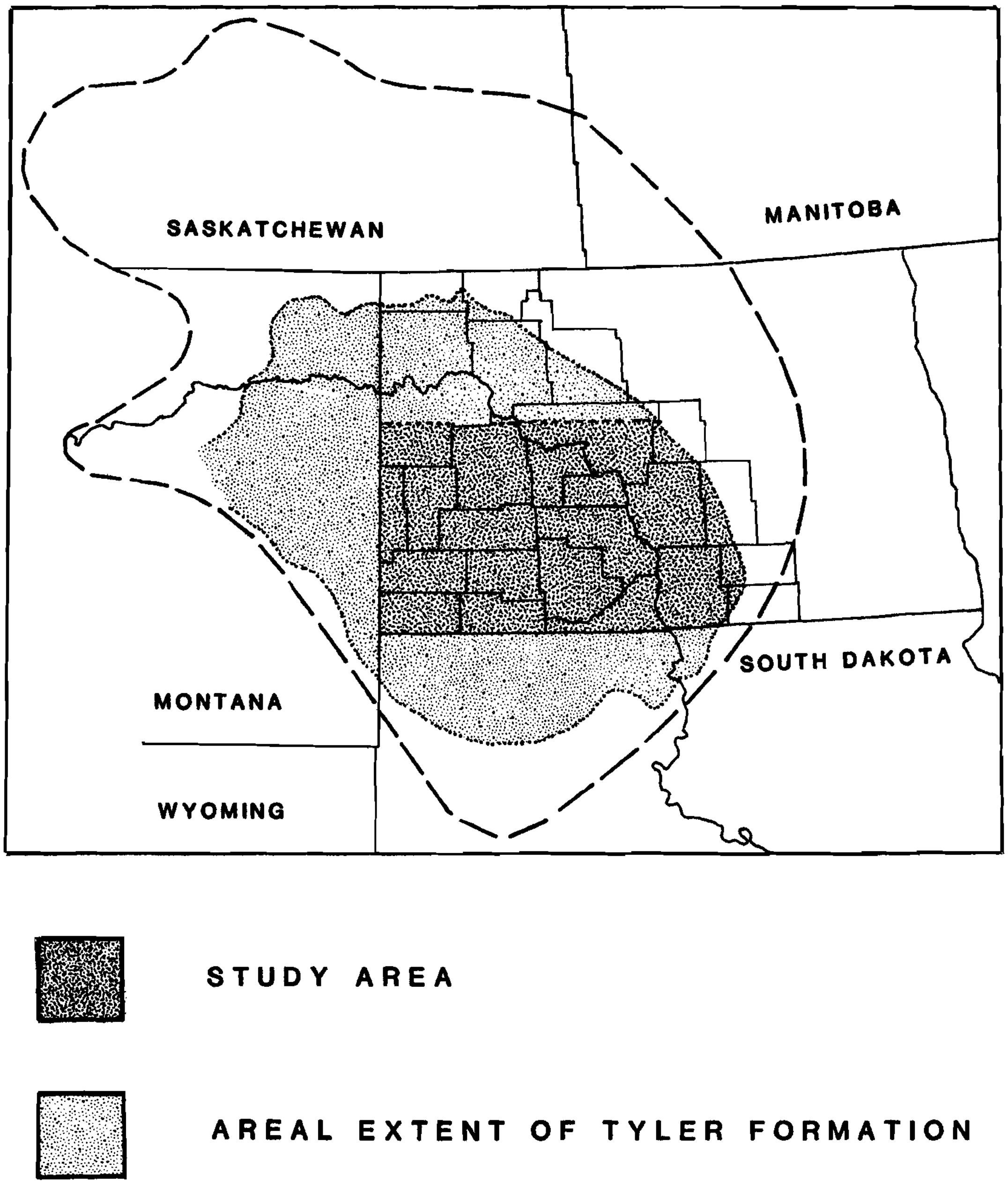

Figure 1. Location of study area and areal extent of the Tyler Formation in the Williston Basin (dashed line). Solid lines represent county lines and state boundaries.

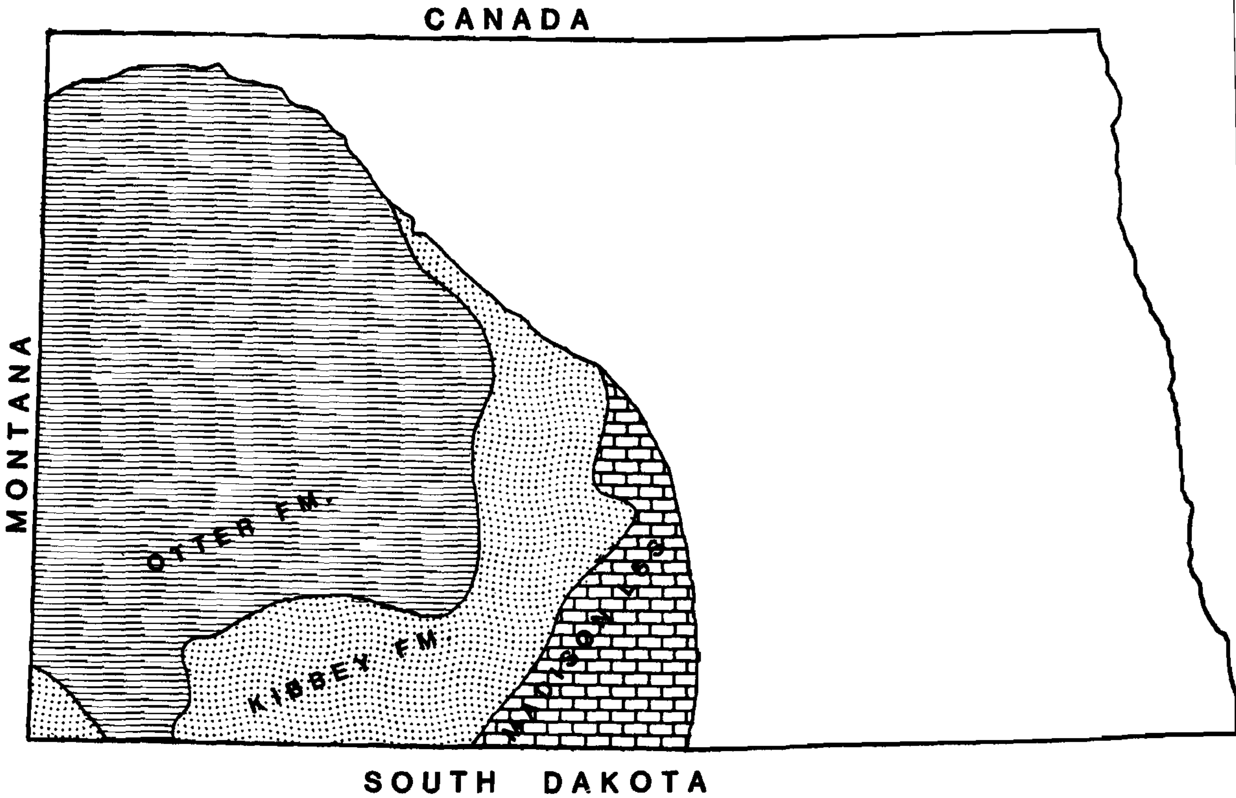

Figure 2. Lateral extent and contacts of formations underlying the Tyler Formation in North Dakota. Redrafted and modified from Grenda (1977).

Structural features trending north-south and northwest-southeast within the North Dakota part of the Williston Basin are the Nesson, Cedar Creek, Little Knife, Antelope, and Billings Anticlines. Northwest-southeast trending lineaments include the Bismarck-Williston lineament and the Red Bank-Alexander trend (fig. 3). Thomas (1974) and Gerhard et al. (1982) have suggested that northwest-southeast and northeast-southwest trending structural lineaments may be an expression of basement-weakness zones that have undergone regional compressive stress and lateral adjustment creating drag-folds (Nesson, Cedar Creek, and Little Knife Anticlines), vertical (epeirogenic) uplift of basement blocks, step faults, and crossfold tensional faults.

At the beginning of Pennsylvanian time (fig. 4) the Williston Basin became connected to the Cordilleran miogeosyncline by the elongate Big Snowy trough (Smith and Gilmour, 1979, p. 9). Uplift of both the Wyoming and Alberta shelves during the late Mississippian provided a source area for terrigenous material during Tyler time in the Big Snowy trough (Maughan and Roberts, 1966; Smith and Gilmour, 1979). In North Dakota, clastic sediment was probably derived from erosion of the underlying Kibbey Formation, as suggested by Ziebarth (1964, p. 124), or from uplift and erosion of the Canadian Shield, to the north and east, and the Sioux Ridge (Transcontinental Arch), to the southeast of the Basin.

Thickness of the Tyler Formation

In the study area, the Tyler Formation ranges in thickness from a maximum of 270 feet (82.3 m) in northwestern Golden Valley County to a zero along its erosional limit (pl. 1). The thickness of the Tyler Formation is highly variable, probably as a result of lateral migration of one or more depocenters, paleotopography, major changes in depositional environments in part of the study area during Tyler time, differential compaction, local subsidence, or a combination of several of these factors. Variation in thickness, however, does not indicate that known Williston Basin structures such as the Billings Nose, Cedar

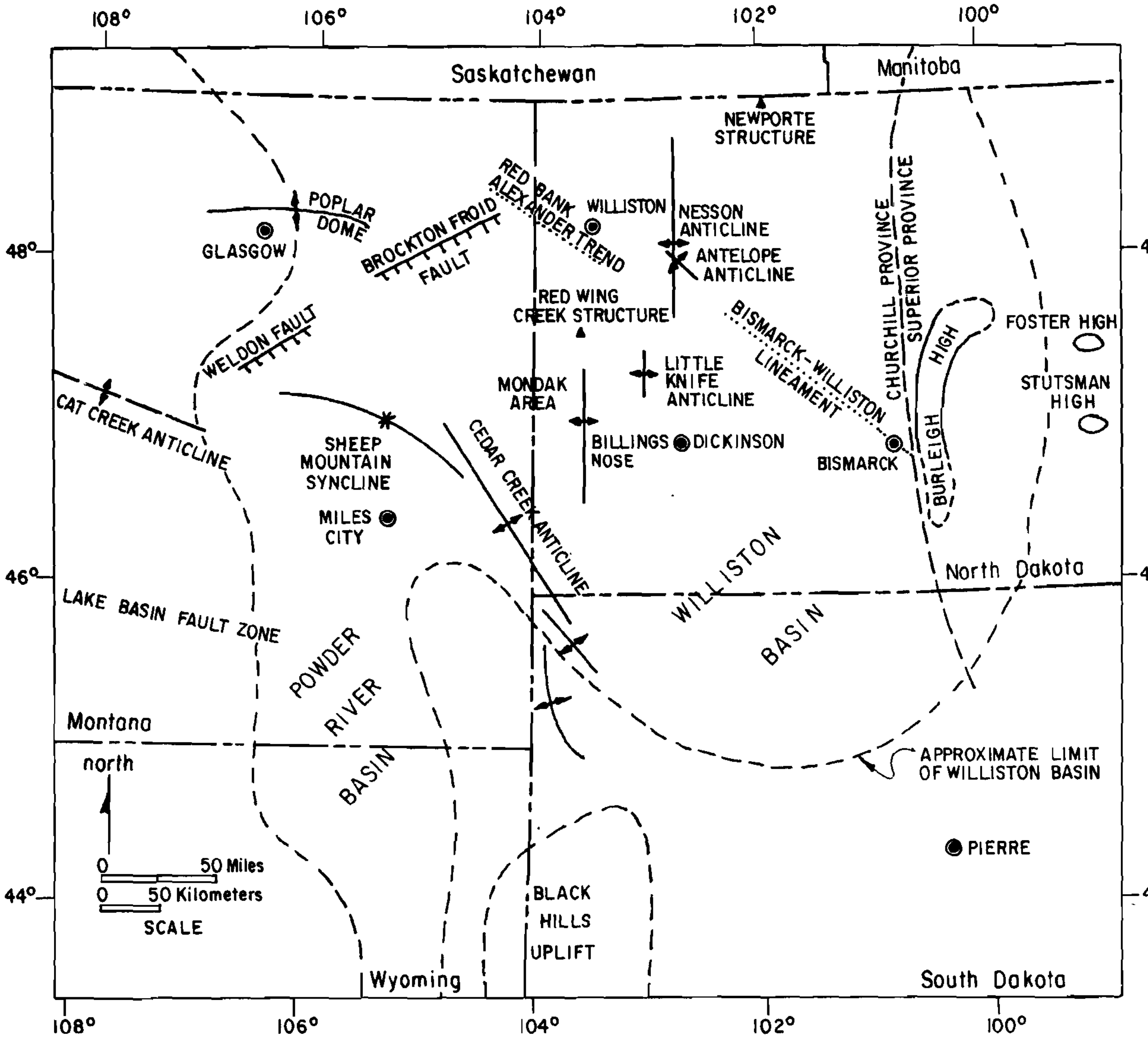

Figure 3. Major structures of the Williston Basin based on current subsurface structural mapping and geophysical interpretations (Anderson and Bluemle, 1982).

Creek, Little Knife, and Nesson Anticlines were positive areas during Tyler time.

If Williston Basin structures did influence the thickness of the Tyler Formation, it is best seen on the isopach map of the lower unit (pl. 2). Three distinct linear trends of greater thickness are present in the area studied: one trend is oriented approximately N 70° W, extending from Burleigh County to Dunn County; one trend lies east-west, extending from Burleigh County to Stark County; and one trend runs approximately N 25° W, extending from southeast Billings County through Adams County, but bifurcating in Hettinger County with one arm extending into Grant County. These linear trends of greater thickness are interpreted to be the result of local subsidence during deposition of Tyler sediments overlying structural lineaments identified by Thomas (1974). Similarly, Cooper (1956, p. 82-85) suggested that faulting of basement rocks is responsible for locally thick accumulations of Tyler and Heath sediments in part of Montana. This hypothesis is further supported by Brown (1978) and Slack (1981), who demonstrated that Paleozoic sedimentation patterns correspond to regional lineaments in the Williston Basin and Black Hills area.

Sturm (1982) reported that the upper unit of the Tyler Formation thickens from a zero, in eastern Hettinger and Adams Counties, to 60 feet (18.3 m) with local thickening up to 80 feet (24.4 m) toward the northwestern part of the study area. This

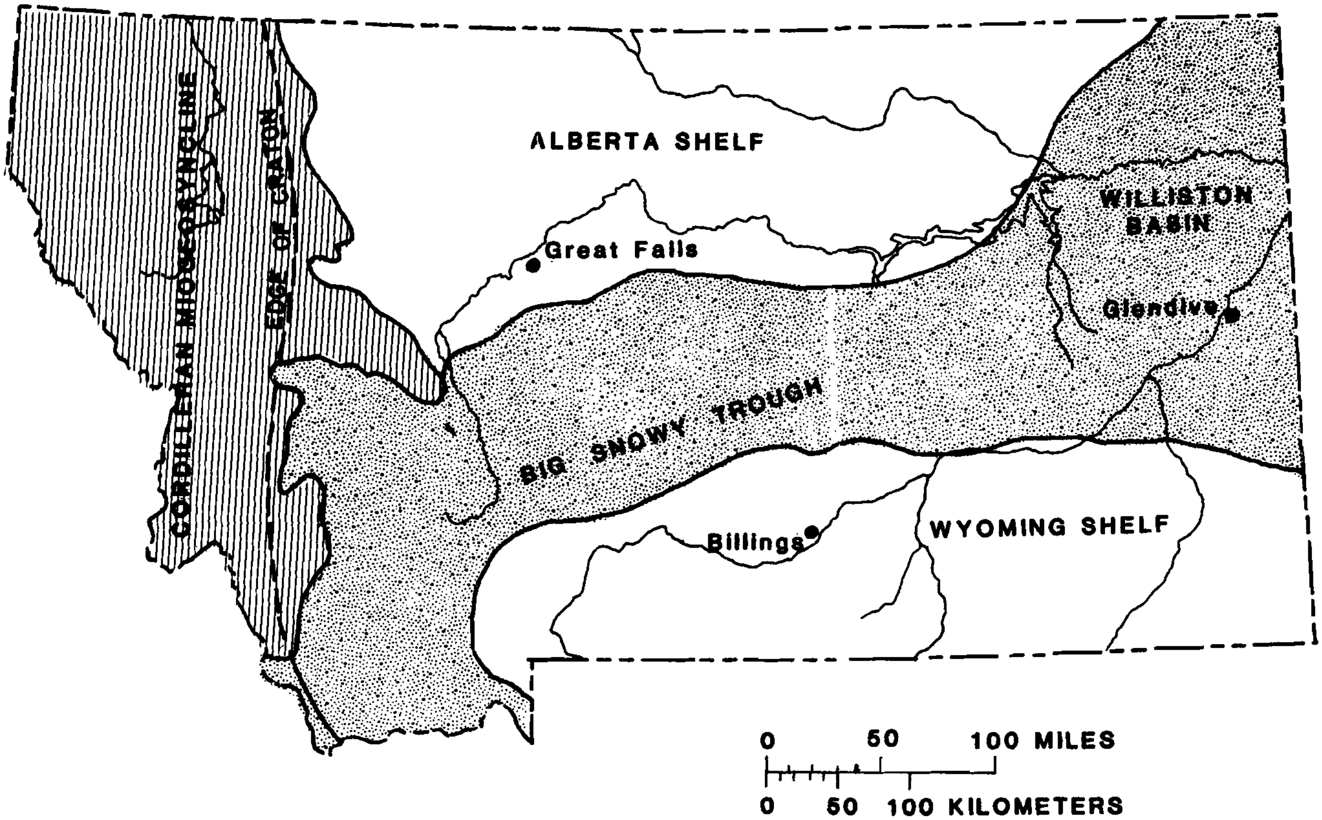

Figure 4. Mississippian-Pennsylvanian paleostructural features in Montana. Modified from Smith and Gilmour (1979, p. 9).

gradual thickening of the upper unit in a northerly to northwesterly, or seaward, direction is probably due to greater sedimentation in a shallow subtidal environment than in more landward environments that were either starved of sediment or periodically exposed. The gradual thickening to the north further indicates that a single depocenter was established only during deposition of the upper unit and that localized subsidence of Tyler sediments overlying structural lineaments is limited to lower unit time. The absence of linear trends of greater thickness in the upper unit probably indicates that post-Mississippian movement of Williston Basin structures, documented by Gerhard et al. (1982, p. 1008-1010), is responsible only for lower Tyler sedimentation patterns.

Previous Work on the Tyler Formation in North Dakota

Interpretation of depositional environments in the Tyler Formation has progressed from generalized regional studies in the 1950s and early 1960s to more detailed studies in the 1970s. Willis (1959, p. 1959) stated that the presence of coaly beds and a varied fauna indicated that depositional environments "were far from consistent, and fluctuated many times between normal marine and brackish marine conditions." He characterized (p. 1959) environmental conditions as "restricted lagoonal" in which water salinity fluctuated due to rainfall and runoff, anoxic environment conditions persisted due to poor water circulation, and hydrogen sulfide was generated from the degradation of organic matter by anaerobic bacteria. Ziebarth (1962, 1964) noted the variety of fossils that had little tolerance for salinity changes. He interpreted (1964, p. 125) environments of deposition in southwestern North Dakota to have been in "some form of marsh, lagoon, swamp, or tidal flat area not generally subjected to great amounts of current agitation." Ziebarth (1962) interpreted the upper sandstone (or "Fryburg sand" of Willis' 1959 terminology) in the Tyler Formation to have been deposited as a beach-bar complex, and the middle sandstone (or "Fritz sand" of Willis, 1959), to have been deposited as a channel-fill deposit. However, Ziebarth (1964) said that the upper sandstone may represent either a nonmarine channel sandstone or marine beach-bar complex, and the middle sandstone a nonmarine channel-fill deposit or possible beach environment. No mention was made of the sandstone developed at the base of the Tyler Formation. Ziebarth (1972) recognized several broad categories of depositional environments in the Tyler Formation based on sedimentary and paleontological evidence. These environments include sandstone deposition in channels and associated natural levees, shoreline, and offshore deposition. Ziebarth suggested that the Tyler Formation was deposited in a deltaic complex, similar to the "upper alluvial valley portion of the Mississippi River delta." A major sandstone trend, identified by mapping sandstone/shale ratios, is present in an arcuate trend through Golden Valley, Billings, Stark, Dunn, and Mountrail Counties. A second trend was identified, roughly perpendicular to the first, through Emmons, Burleigh, and Stark Counties. However, Ziebarth (1972) did not correlate these sandstone trends with depositional environments or suggest either landward or seaward directions for depositional environments of the Tyler Formation.

Oscillating brackish to shallow-marine depositional environments were recognized in the Rocky Ridge Field (Billings County) by Roux and Schindler (1973). They suggested that lithologic sequences are similar to cyclothemic units in Illinois and Kansas, but that the complete succession of the members of the "classic cyclothem" was recognized in very few places. Land (1976, 1979) stated that oil production in the Dickinson area (Stark County) was from "a multiple sequence of quartzose sandstones, deposited as barrier islands along regressive shorelines." He also suggested (1976, 1979) that porosity and permeability in the sandstones may be reduced, up to 50 percent, by the development of caliche paleosols.

In a detailed study of the fauna and flora of the Tyler Formation in southwestern North Dakota, Grenda (1977) indicated that the area was subject to fluctuations in depth and salinity, and deposition occurred in a deltaic complex. Excellent preservation of delicate structures in most Tyler invertebrates indicates that they were not transported long distances or deposited in agitated water or actively reworked. However, Grenda (1977, p. 30) stated that localized, aviculopectenid communities implied high-velocity currents.

Methods of Study

This study is based on cores from the Wilson M. Laird Core and Sample Library and well log files maintained by the North Dakota Geological Survey. Forty-two cores were chosen for a wide geographic distribution and stratigraphic variation of the cored interval. Most of the available cores are from Stark and southern Billings Counties (fig. 5). Cores were studied using a hand lens and a binocular microscope.[1] Tyler Formation clastic rocks were classified according to Folk (1974). Carbonates were classified according to Dunham (1962) except that 'micritic limestone' was substituted for the term 'mudstone' to avoid confusion between terminology of clastic and carbonate rocks. Color of Tyler rocks mentioned in this study are those represented in the rock-color chart (Goddard et al., 1948).

Approximately 900 well logs were studied (pl. 3) to determine thickness, map sandstone distribution, and to permit correlation and lithologic interpretation from core data.

In this study, the Tyler Formation was divided (fig. 6) into upper and lower units based on log character and lithology. Sandstones in the Tyler Formation (fig. 6) occur at three stratigraphic positions: at the base of the Tyler, in the middle of the lower unit, and at the base of the upper unit. The geographic distribution and thickness of each of the three sandstones is mapped separately in part of the study area (pls. 4, 5, and 6).

[1]The descriptions of the cores and thin sections used in this study are not included in this report. However, they are on file at the North Dakota Geological Survey offices. Also on file at the North Dakota Geological Survey are complete listings of the names and locations of all wells used in the study, the names and locations of cores that were used, the formations and unit top picks, and the thicknesses of the units described.

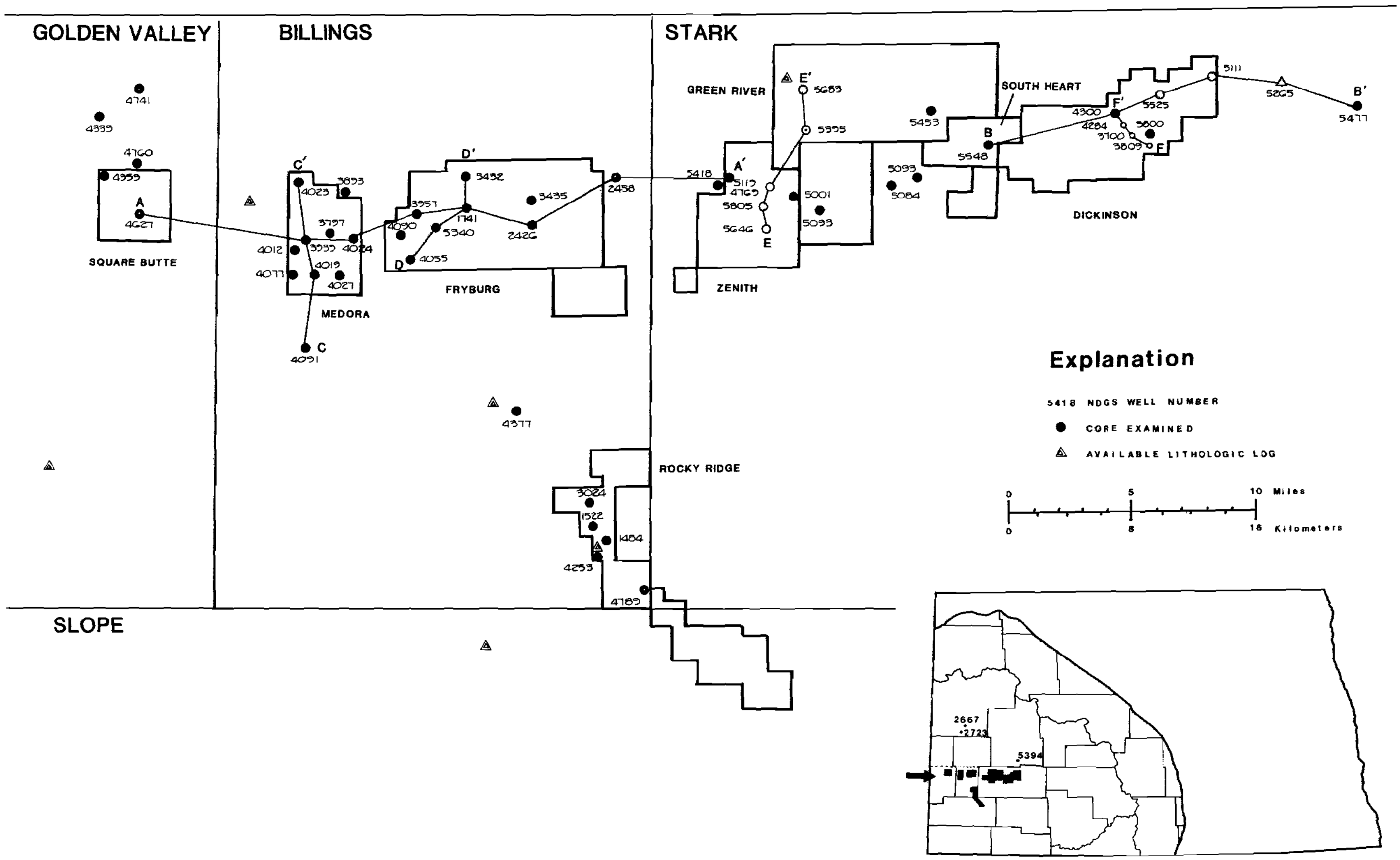

Figure 5. Location map of cores studied and index map to names of oil fields and stratigraphic cross sections.

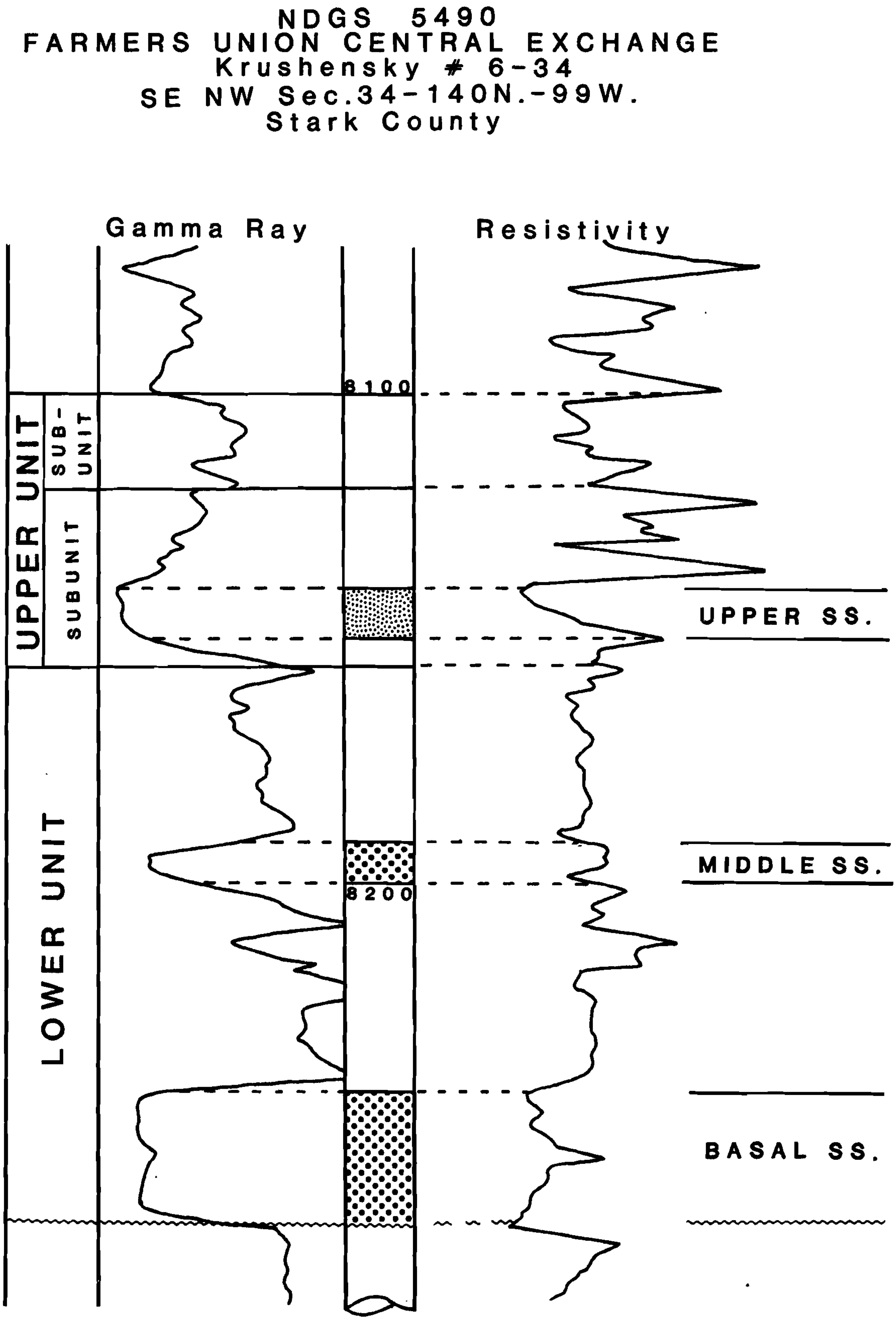

Figure 6. Subdivision of the Tyler Formation and stratigraphic position of sandstones used in this study, together with typical log response.

Six detailed stratigraphic cross sections were constructed in the area where most of the available core were located to permit correlation and lithologic interpretation from core data, and to aid in the interpretation of depositional environments and depositional history of the Tyler Formation.

LITHOFACIES DESCRIPTION

Introduction

In southwestern North Dakota, the Tyler Formation may be divided into two units (fig. 6) based on log character and lithology. The lower unit is highly variable, both lithologically and in color. Five major lithofacies have been recognized in the lower unit that are characterized either by one dominant lithology, a combination of lithologies, or a distinct change in color. These lithofacies are not restricted to a certain stratigraphic position, nor are they always present in the lower unit. The five lithofacies and their dominant physical characteristics are: (1) lithofacies A, grayish-black to dark-gray shale; (2) lithofacies B, varicolored mudstones; (3) lithofacies C, coal and carbonaceous mudstone; (4) lithofacies D, reddish-brown sandstone; and (5) lithofacies E, grayish-brown sandstone.

The upper unit in the areas of the Square Butte, Medora, and Fryburg Fields (fig. 5) may be divided into two subunits (fig. 6). Three major lithofacies have been recognized in the area of these fields. These lithofacies are restricted to stratigraphic position in the upper unit. The three lithofacies are: (1) lithofacies F, fine-grained quartz arenite, developed at the base of the lower subunit; (2) lithofacies G, dark-gray, argillaceous, micritic limestone, comprising the remainder of the lower subunit; and (3) lithofacies H, anhydritic limestone and varicolored calcareous shale, comprising the upper subunit. In the Green River, Zenith, and Dickinson Fields, lithofacies G is either not developed or constitutes such a small portion of the stratigraphic section that it does not necessitate recognition as a distinct lithofacies in the area of these fields. In this area, lithofacies H, which directly overlies lithofacies F, is very well developed and lithologically more complex than in the former area.

Lower Unit Lithofacies

Lithofacies A

Lithofacies A is characterized by grayish-black, noncalcareous to calcareous carbonaceous shales and minor dark-gray to grayish-black, argillaceous, micritic limestones. Shales and limestones are predominantly finely laminated (even-parallel), and are often found interlaminated with one another. Very few, if any, disruptions in laminae, such as might be caused by bioturbation, desiccation, or dewatering structures, are present. Disseminated pyrite is present throughout the rocks in this lithofacies. Lenses, concretions, and pyrite "beds" up to 0.6 cm thick (fig. 7) are also common.

Fossils are commonly restricted to relatively thin horizons within this lithofacies and are limited to bedding-plane surfaces, usually concave down, and are commonly well preserved. Fragmented plant fossils are quite common in grayish-black, carbonaceous shales.

Lithofacies B

Lithofacies B is composed of varicolored, silty, slightly calcareous mudstones. Primary depositional textures have been almost totally obliterated by a combination of processes, such as de-watering, compaction, solution brecciation, desiccation, and late-stage displacive anhydrite (fig. 8). Colors are often mottled, with red and green hues dominating. Subordinate colors include greenish-gray, maroon, and various shades of yellow.

Varicolored, intraclastic, calcareous mudstones, resembling flat-pebble conglomerates, are very common in this lithofacies. The tabular clasts, however, were probably formed by compaction and de-watering, as shown in figure 9. Clasts are commonly light colored and gradually darken upwards, probably reflecting a change in Eh during deposition (Krauskopf, 1979, p. 211-214).

Mottling is also a result of compaction, especially in mudstones that were deposited in a wet environment and composed exclusively of clay. Compaction, aided by the plasticity of saturated clays, resulted in randomly

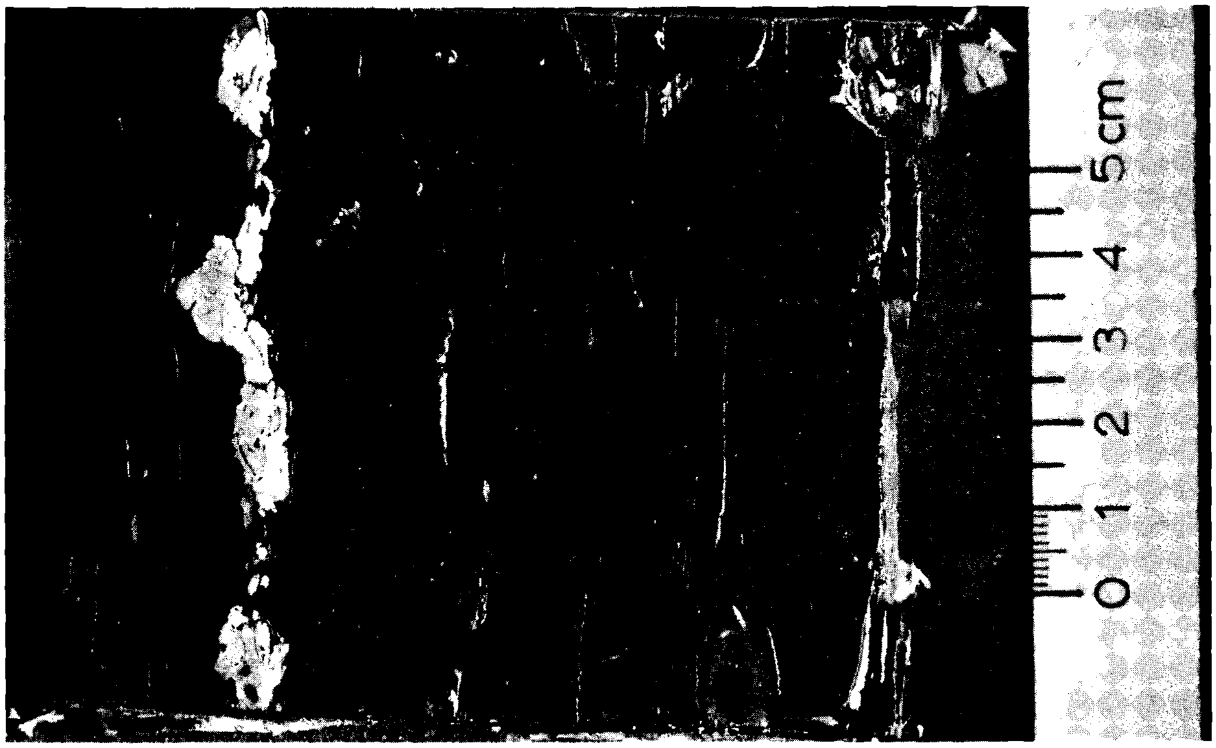

Figure 7. Photograph of finely laminated, grayish-black shale (lithofacies A) from the lower unit. Note convoluted pyrite "bed" in upper portion of photograph. NDGS well #4789--8,003 ft.

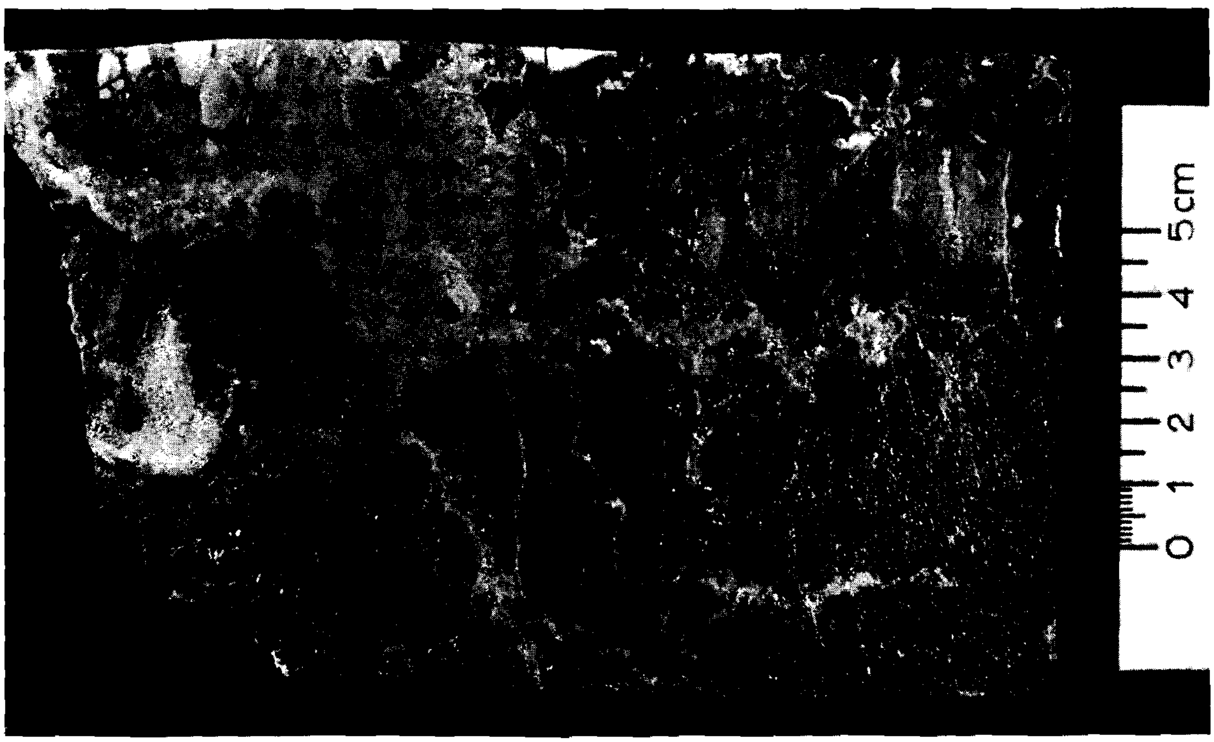

Figure 8. Photograph of brecciated mudstone (lithofacies B) from the lower unit. Fabric is the result of compaction, desiccation, and late-stage displacive anhydrite. NDGS well #5405--8,013 ft.

oriented slickensided surfaces and extremely mottled textures (fig. 10).

Lithofacies C

Lithofacies C is characterized by relatively thin bituminous coal that commonly overlies medium-gray to medium-dark-gray, carbonaceous mudstone. Well-developed, randomly oriented, compaction slickensides extend throughout the mudstone in this lithofacies. Maximum thickness of the coal of this lithofacies is 4 inches (10.0 cm) and the combined thickness of coal and underlying mudstone is 1.5 to 4 feet (0.46 to 1.23 m). Fragmented plant remains are common on bedding planes in the coal and randomly scattered throughout the mudstone, probably as a result of post-depositional compaction. This lithofacies is most commonly overlain by lithofacies A and underlain by lithofacies B.

Lithofacies D

Reddish-brown, medium-grained quartz arenite is the dominant lithology in lithofacies D. This sandstone is composed of well-rounded, well-sorted quartz grains that have been cemented predominantly by pervasive anhydrite and, locally, hematite and quartz. Small-scale trough and planar crossbed sets are the dominant sedimentary structures in this lithofacies (fig. 11). The sandstone is 5 to 10 feet (1.5 to 3.0 m) thick, except for localized thickening in the Green River and Square Butte Fields, and these thickenings are oriented east-west in the Square Butte to the Dickinson Field area (pl. 4). Stratigraphically, this lithofacies is found at the base and in the middle of the lower unit of the Tyler Formation.

This sandstone is generally not bioturbated, and fragmented ostracod shells are the only identifiable fossils in this lithofacies. Associated with the sandstone is a yellowish-brown to varicolored, calcareous mudstone that is characterized by a convoluted texture. The mudstone is relatively thin, in comparison to the sandstone, and may overlie or underlie the sandstone (fig. 12). This lithofacies is overlain and underlain by lithofacies B.

Lithofacies E

Lithofacies E is composed of light-brown to grayish-brown, fair to poorly sorted, texturally immature, medium- to coarse-grained quartz arenites occurring in multiple-stacked, fining upward planar crossbed sets (fig. 13). Basal lag conglomerates, and lenticular clasts oriented parallel to bedding are common. This sandstone is an average 10 feet (3.0 m) thick in southwestern North Dakota, but it may thicken to 50 feet (15.2 m) in the Rocky Ridge Field in southern Billings County (pls. 4 and 5). This sandstone is geographically restricted to the area south of T139N and trends predominantly northwest-southeast. The reddish-brown sandstone, to the north, represents a more texturally mature, lateral equivalent of this sandstone. This lithofacies is most closely associated with lithofacies A and, to a lesser extent, greenish-gray to medium-dark-gray mudstones of lithofacies B.

Upper Unit Lithofacies

Lithofacies F

Lithofacies F is characterized by very light gray to brown, fine-grained, well-sorted quartz arenites and intraclastic quartz, calcareous mudstones here interpreted to be paleosols and caliches. The sandstone is dominantly massively bedded with discontinuous, carbonaceous, shale partings. Other sedimentary structures include low-angle planar and herringbone crossbeds, ripple and horizontal laminae (figs. 14 and 15). In the area of the Medora and Fryburg Fields, the sandstone directly overlies lithofacies A, and is overlain by lithofacies G. In the Dickinson Field, the underlying lithofacies B grades upward into the sandstones of lithofacies F and the latter is overlain by intraclastic mudstones, yellowish to maroon mudstones, quartzose sandstones with nodular anhydrite, silty mudstones, and very fine grained sandstones with plant rootlets.

The boundaries of the Medora, Fryburg, Green River, Zenith, South Heart, and Dickinson Fields are related to the distribution of lithofacies F. In each oil field, the sandstone body thins to a zero close to the field boundary and thickens to approximately 20 feet (6.1 m) toward the center of the field. The distribution and thickness in each oil field area is shown on plate 6.

Figure 9. Photograph of intraclastic mudstone (lithofacies B). Fabric is the result of compaction and de-watering. NDGS well #4741--7,901 ft.

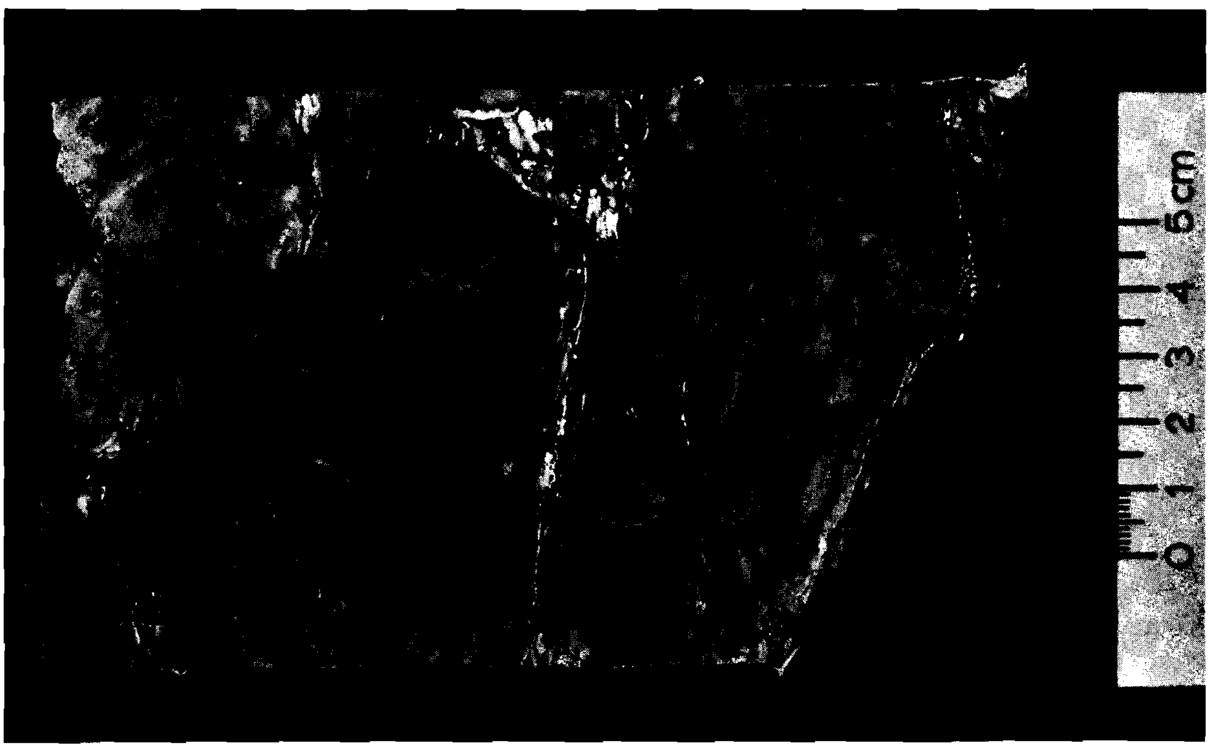

Figure 10. Photograph of mottled mudstone (lithofacies B). Mottled fabric is the result of compaction that has led to randomly oriented compaction slickensides. NDGS well #4789--8,092 ft.

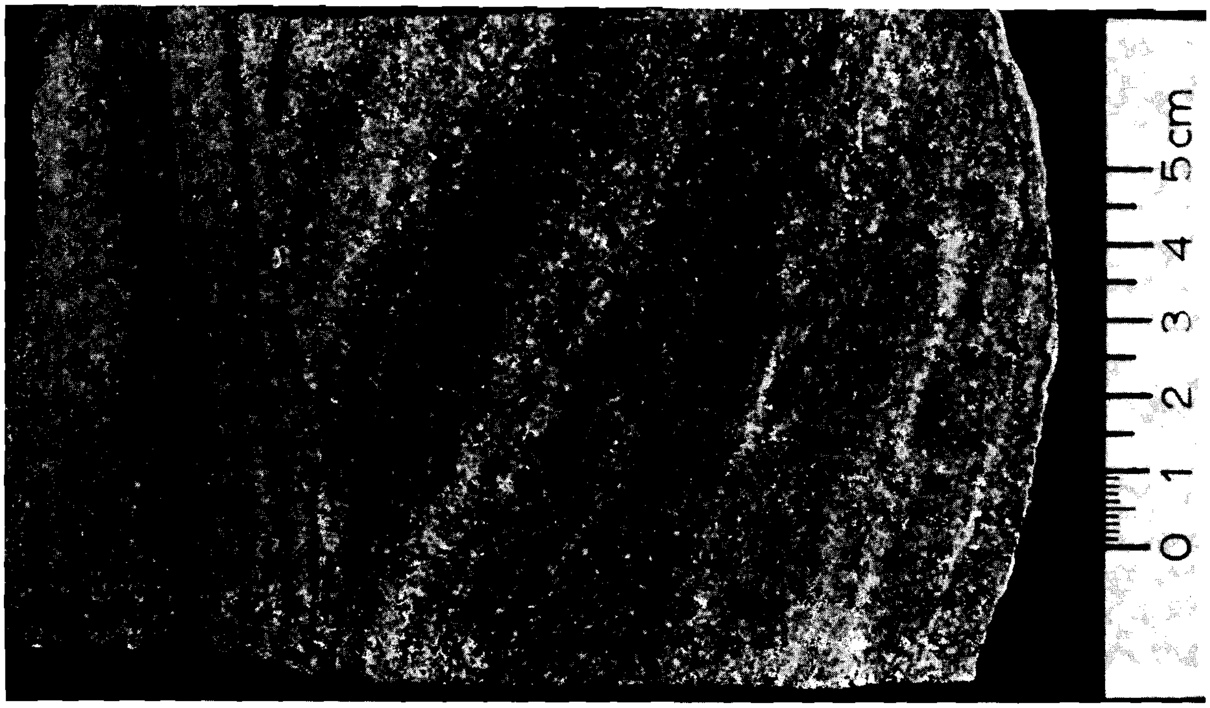

Figure 11. Photograph of crossbedded delta-front sandstone (lithofacies D) from the lower unit. NDGS well # 5084--8,086 ft.

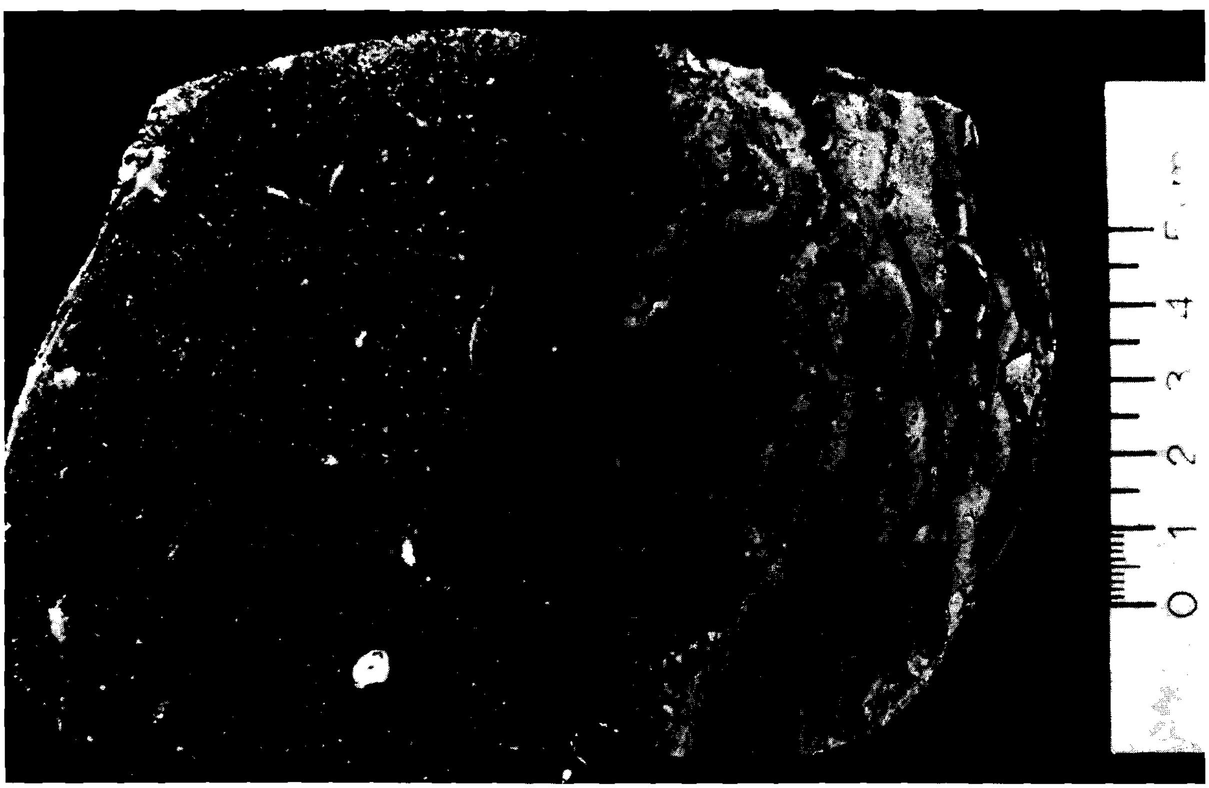

Figure 12. Photograph of delta-front sandstone overlying convoluted, calcareous mudstone; interpreted as a paleosol (lithofacies D). NDGS well # 4339--7,941 ft.

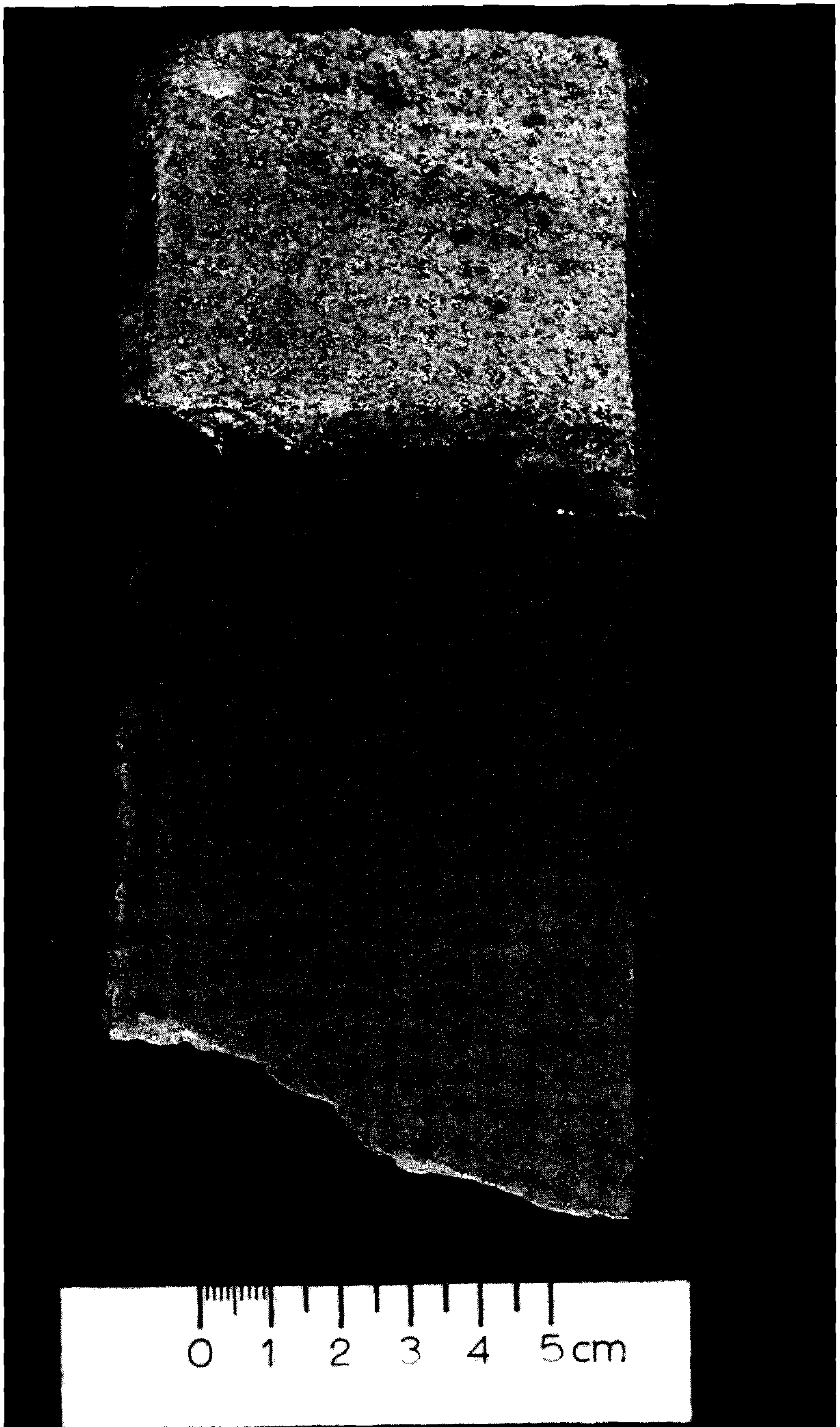

Figure 13. Photograph of crossbedded channel sandstone (lithofacies E). Shale laminae separate upper medium to coarse-grained, texturally immature quartz arenite from the lower, fine-grained, texturally mature quartz arenite. Hydrocarbon is present only in the lower, fine-grained portion of this sandstone. NDGS well # 4789--8,036 ft.

Figure 14. Photograph of massively bedded, barrier-island sandstone (lithofacies F) from the upper unit. Note discontinuous shaly laminations and brachiopod fossils. NDGS well #4090--7,858 ft.

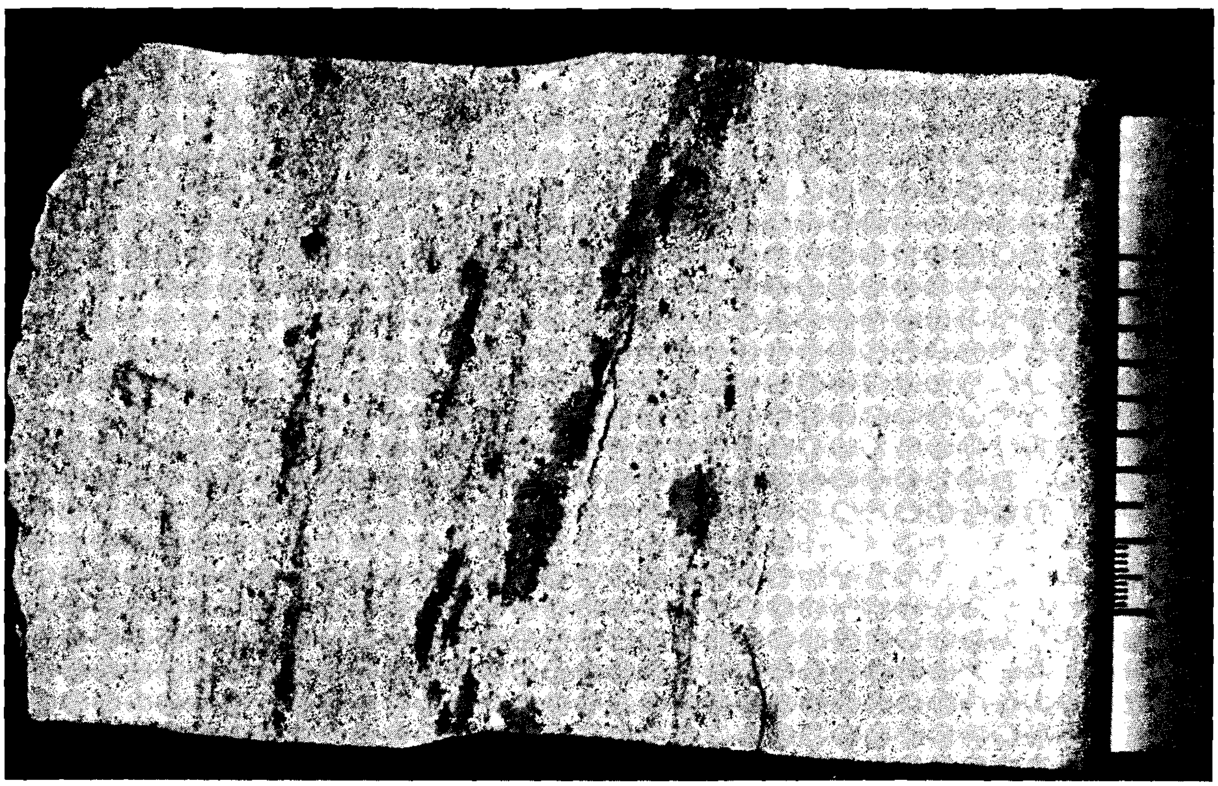

Figure 15. Photograph of crossbedded barrier-island sandstone (lithofacies F). NDGS well #4090--7,849 ft.

Bioturbation in the sandstone is generally absent from the area of the Medora and Fryburg Fields but is extensive in the upper portion of the sandstone in the Zenith and Green River Fields (fig. 16). In bioturbated horizons, the sandstone is extremely friable, and burrows are commonly pyritized.

The most common fossils found in lithofacies F are well-preserved, articulated ostracods and brachiopods (fig. 14). Ostracods generally have been filled with calcite, whereas brachiopods have been filled with anhydrite.

Lithofacies G

Dark-gray to grayish-black, argillaceous, micritic limestone and calcareous shale are the dominant lithologies in lithofacies G. Most noticeable, aside from the dark color, are the very fine, even to wavy parallel laminations throughout this lithofacies. The only disruptions in laminae occur in thin horizons where de-watering structures are present. No bioturbation is present in this lithofacies. As in lithofacies A, well-preserved fossils (pelecypods, brachiopods, and ostracods) are present on bedding plane surfaces. Thin concentrations of ostracods trapped in algal mats are present throughout this section (figs. 17 and 18), and ostracods are clearly the most abundant fossil in the Tyler Formation. Relatively thin zones of carbonate mud-supported "shell hash" are also present, but constitute a very small portion of this lithofacies. Locally, cone-in-cone anhydrite and euhedral, ankerite crystals are present in the upper part of this lithofacies.

Lithofacies G is best developed in the Square Butte, Medora, Fryburg, and Rocky Ridge Fields, where it reaches a maximum thickness of 40 feet (12.2 m) and is recognized as the lower subunit of the upper unit in this report. Thinning occurs to the south and west, where, in the Dickinson Field, lithofacies G generally does not exceed 10 feet (3.0 m). In this area, lithofacies G becomes very carbonaceous, and grayish-black shale is dominant over micritic limestone. In the Square Butte, Medora, and Fryburg Fields, micritic limestone is dominant over shale. In the Green River and Zenith Fields there is a transition from one extreme to the other. In the south, lithofacies G directly overlies lithofacies A and distinguishing between the two is difficult in this area.

Lithofacies H

Lithofacies H is characterized by a change in the upper unit from dark-gray to grayish-black shales and limestones to predominantly grayish-red and reddish-brown, anhydritic limestones and calcareous shales. In the Square Butte, Medora, and Fryburg Fields, lithofacies H corresponds to the upper subunit in the Tyler Formation (fig. 5). Dominant lithologies in this area are grayish-red, anhydritic, micritic limestones with well-developed desiccation structures, reddish-brown, calcareous shales with desiccation structures, and thin, grayish-pink, nodular anhydrite (fig. 19). In the Green River, Zenith, and Dickinson Fields, lithofacies H thickens eastward considerably from a maximum of 25 feet (7.6 m), in the previously mentioned area, to approximately 45 feet (13.7 m). In the Dickinson Field, lithofacies H is highly variable both lithologically and in color. No one lithology is dominant over another. These lithologies include yellowish-brown, mudstone-pebble conglomerate (fig. 20); dusky-red to greenish-gray, calcareous mudstones with iron-rich concretions; greenish-gray to light-brown wackestones containing ostracods; medium-gray grainstones containing pelecypods, gastropods, and ostracods; medium-gray grainstones containing pelecypods and oncolites (fig. 21); and reddish-brown to yellowish-brown, calcareous mudstones with well-developed desiccation structures.

PALEOENVIRONMENTAL INTERPRETATION

Lower Unit Lithofacies

Introduction

The lower unit of the Tyler Formation is a lithologically complex sequence of varicolored mudstones, dark-gray shales and limestones, carbonaceous mudstones and coal, and sandstones. The two sandstones of the lower unit, which are present in different stratigraphic positions, are lithologically very similar (in the same

Figure 16. Photograph of bioturbated barrier-island sandstone. Burrows have been pyritized. NDGS well #5405--7,995 ft.

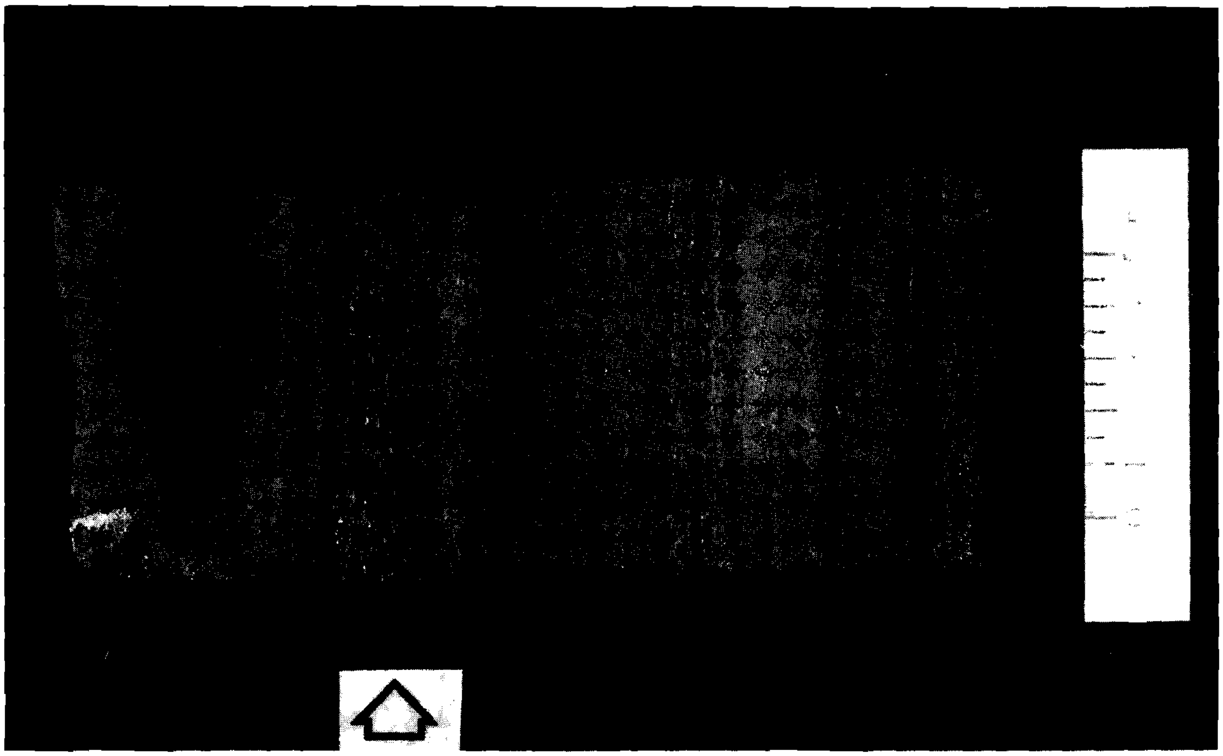

Figure 17. Photograph of finely laminated, dark-gray, argillaceous limestones (lithofacies G) from the upper unit. NDGS well #4339--7,908 ft. Arrow indicates the exact location of thin section shown in figure 18.

Figure 18. Photomicrograph (35X) of ostracods trapped in algal mats. Thin section was made from slab shown in figure 17 at the position of the arrow. NDGS well #4339--7,908 ft.

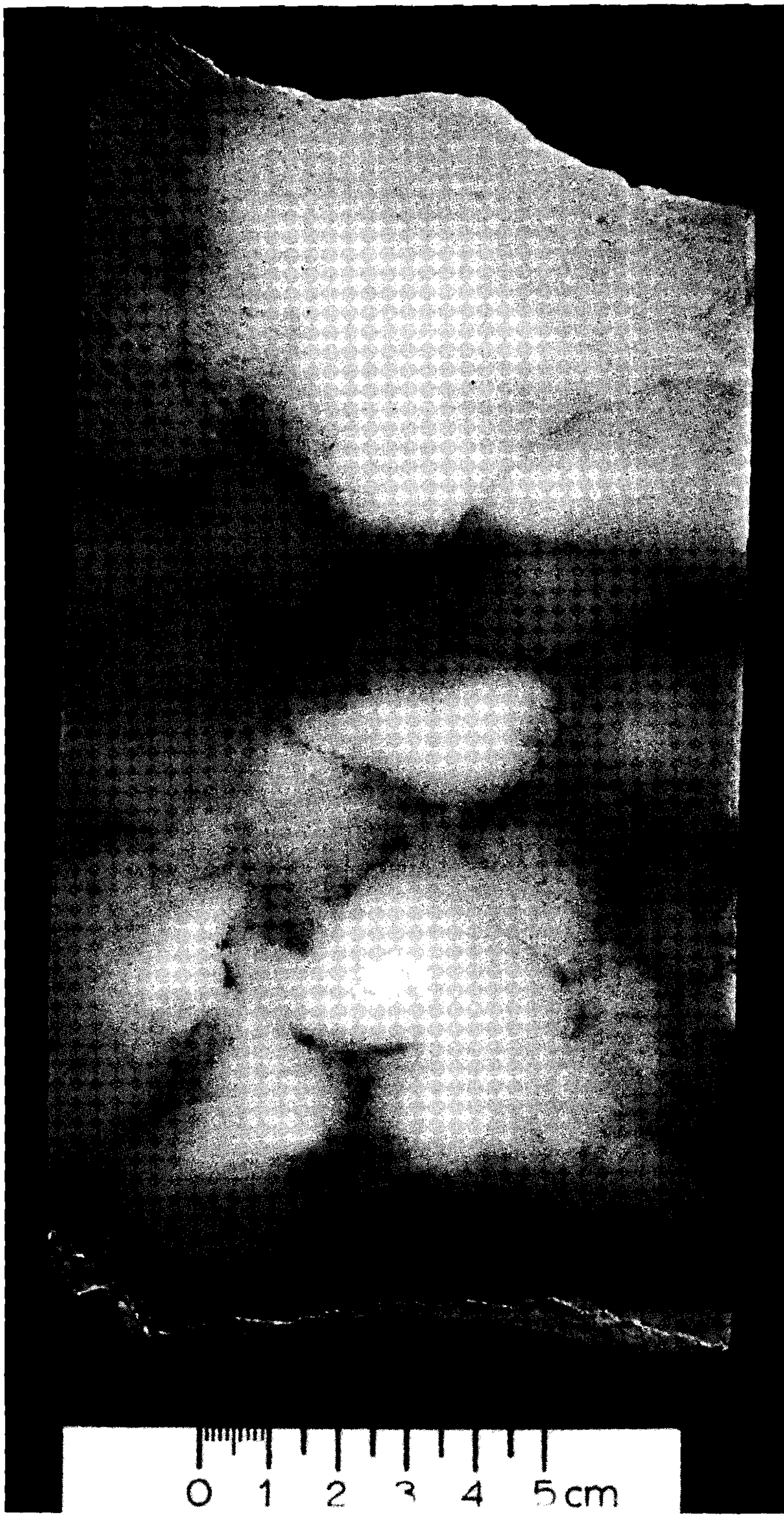

Figure 19. Photograph of nodular anhydrite (lithofacies H) from the upper unit. Nodular anhydrite probably formed in shallow, hypersaline lakes or ponds in the tidal-flat environment. NDGS well #4339--7,904 ft.

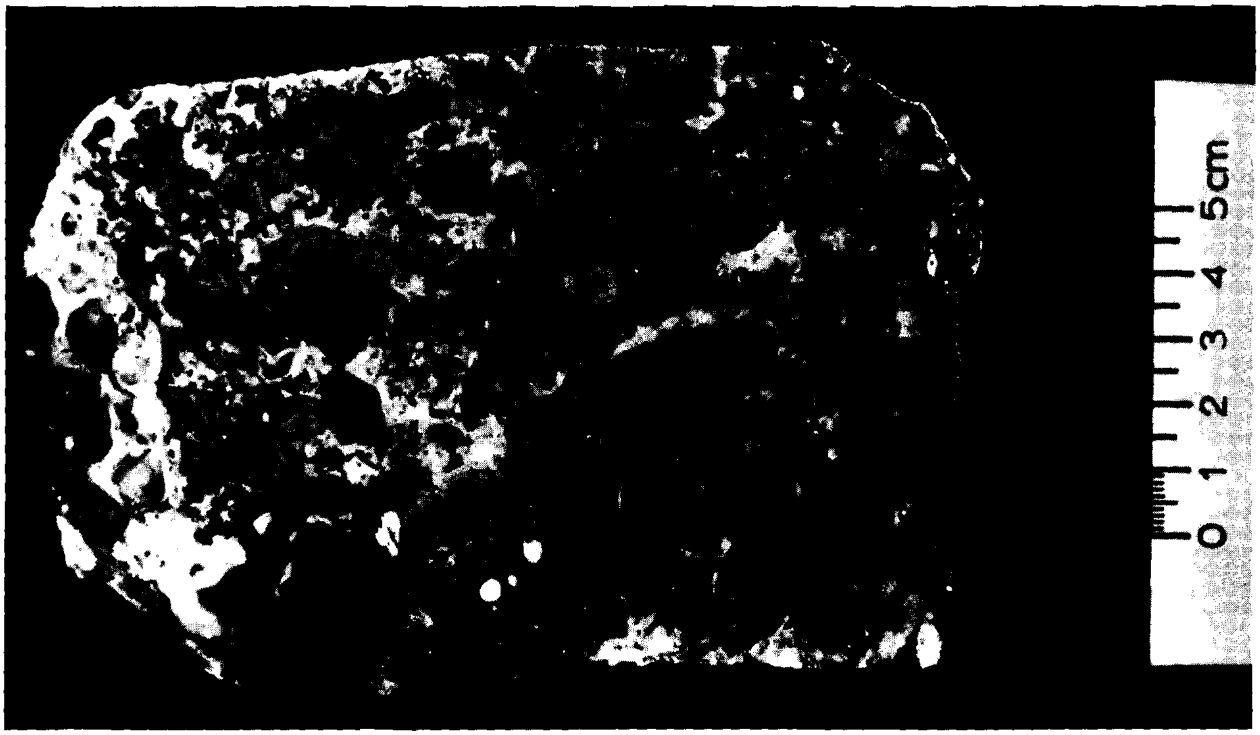

Figure 20. Photograph of mudstone-pebble conglomerate (lithofacies H) interpreted as channel-lag in a tidal-flat environment. NDGS well #5374--7,420 ft.

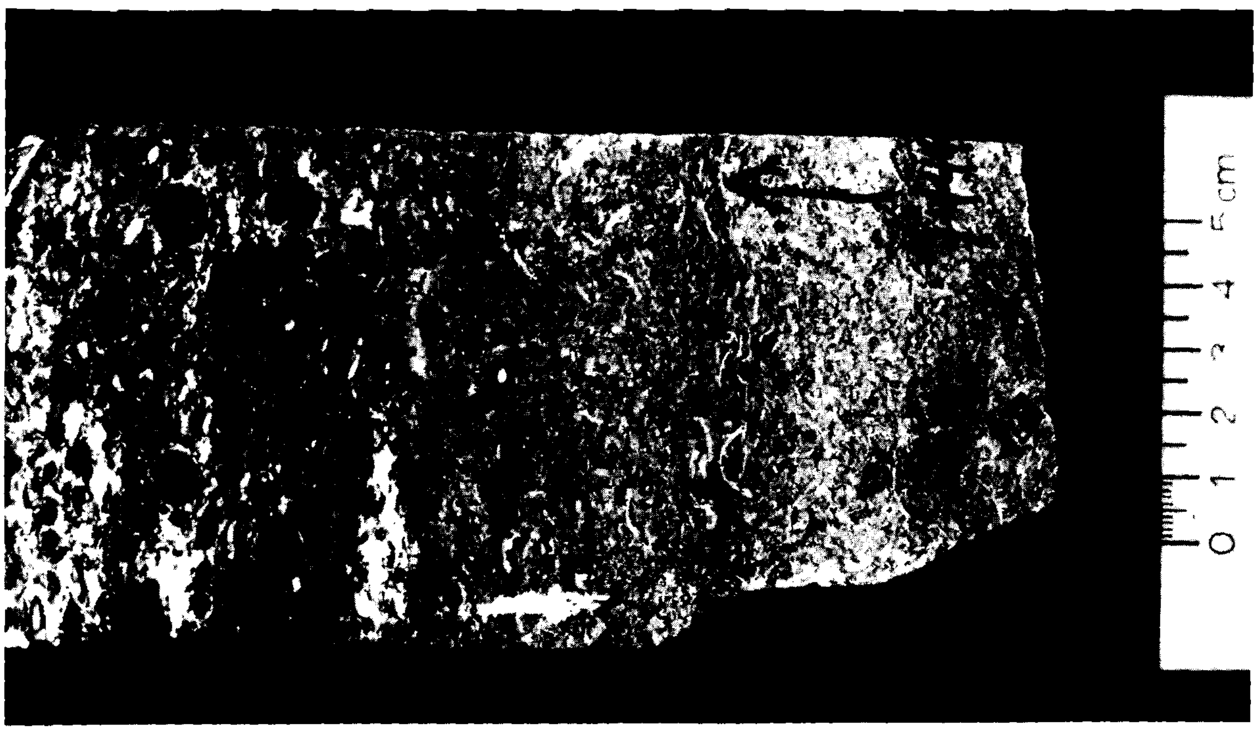

Figure 21. Photograph of pelecypod, oncolite grainstone (lithofacies H), probably deposited in a lagoonal environment. Shelter porosity obliterated by anhydrite cementation. NDGS well #5374--7,444 ft.

geographic areas) and are presumed to have been deposited under similar conditions. Distribution patterns of the sandstones developed at the base and in the middle of the lower unit (pls. 4 and 5) suggest a fluvial-deltaic depositional system with lithofacies D interpreted as delta-front deposits and lithofacies E interpreted as channel-fill deposits. Lithofacies A, B, and C represent associated fluvial-deltaic deposits.

Lithofacies A

The dark-gray to grayish-black, carbonaceous shales and argillaceous limestones in lithofacies A are interpreted to have formed in the interdistributary-bay environment. This includes areas of open water in the active delta, which may be surrounded on three sides by marsh and tidal flats and, either partially or completely, open to the sea on the remaining side (fig. 22).

In addition to the paleoecology discussed by Grenda (1977), finely laminated shales and limestones, and carbonaceous matter and plant fragments on bedding planes, suggest that interdistributary-bay waters were relatively shallow and calm. The lack of bioturbation, the presence of pyrite "beds," lenses, and concretions, and the dark-gray to grayish-black color also suggest that bottom waters were anoxic and that reducing conditions existed in the bottom sediments (Demaison and Moore, 1980).

The thickness and wide-scale persistence of lithofacies A is believed to be a result of both progradation and lateral migration of the delta front. Abrupt changes in lithology from shale to limestone, and in faunal characteristics in this lithofacies, suggest fluctuations in depth and salinity as first proposed by Willis (1959) and later Grenda (1977). This reflects active depositional processes throughout the lower unit of the Tyler Formation.

Lithofacies B

Lithofacies B represents predominantly delta-plain deposits. Greenish-gray to reddish-brown to varicolored, mottled, carbonaceous mudstones with well-developed, randomly oriented, compaction slickensides are interpreted as marsh deposits. The marsh environment is characterized by periodic flooding and an abundance of plant life. Production and preservation of organic material in this environment is considered high, and inorganic content of discharged water is so high that organic muds are deposited instead of peat (Coleman, 1980). Ziebarth (1972) recognized the varicolored rocks in the Tyler Formation, and he suggested that the colors could be explained by applying Walker's (1967) stability field diagram comparing the aqueous ferric-ferrous system with the Eh-pH distribution of groundwater. In general, red, brown, and varicolored lithologies are the result of high pH and low Eh conditions, whereas gray- to grayish-black lithologies are the result of low pH and high Eh conditions. Considering that the delta-plain is a dynamic environment where dramatic differences in salinity, water depth, pH, and Eh may exist, the resultant differences in color would be expected. Areas not subjected to continually changing physical conditions probably existed on the delta plain. High tracts of land, or hummocks, were probably flooded over during storm tides or spring flooding. A woody vegetation probably existed in these areas in contrast to the non-woody plants, such as sedges and reeds, in the marsh environment.

Varicolored, intraclastic, calcareous mudstones (fig. 9) are interpreted to have been formed in the marsh environment marginal to interdistributary bays. In several cores, carbonate clasts were light colored and gradually became darker upwards. The change in color is interpreted to be a result of periodic denundation of this environment by anoxic interdistributary-bay waters, thereby causing a change from oxidizing to reducing conditions in these sediments.

Lithofacies C

Coals and associated medium-dark-gray, carbonaceous mudstones are interpreted to have formed as peat and root-penetrated clays in swampy areas, most likely on abandoned delta lobes (fig. 22). Ferm (1970) recognized abrupt abandonment and the eventual decay of delta lobes as static marsh and swamp deposits overlap the subaerial surface. The model applied by Ferm (1970), based on recent investigations to explain Allegheny deltaic deposits, is accepted by the writer as

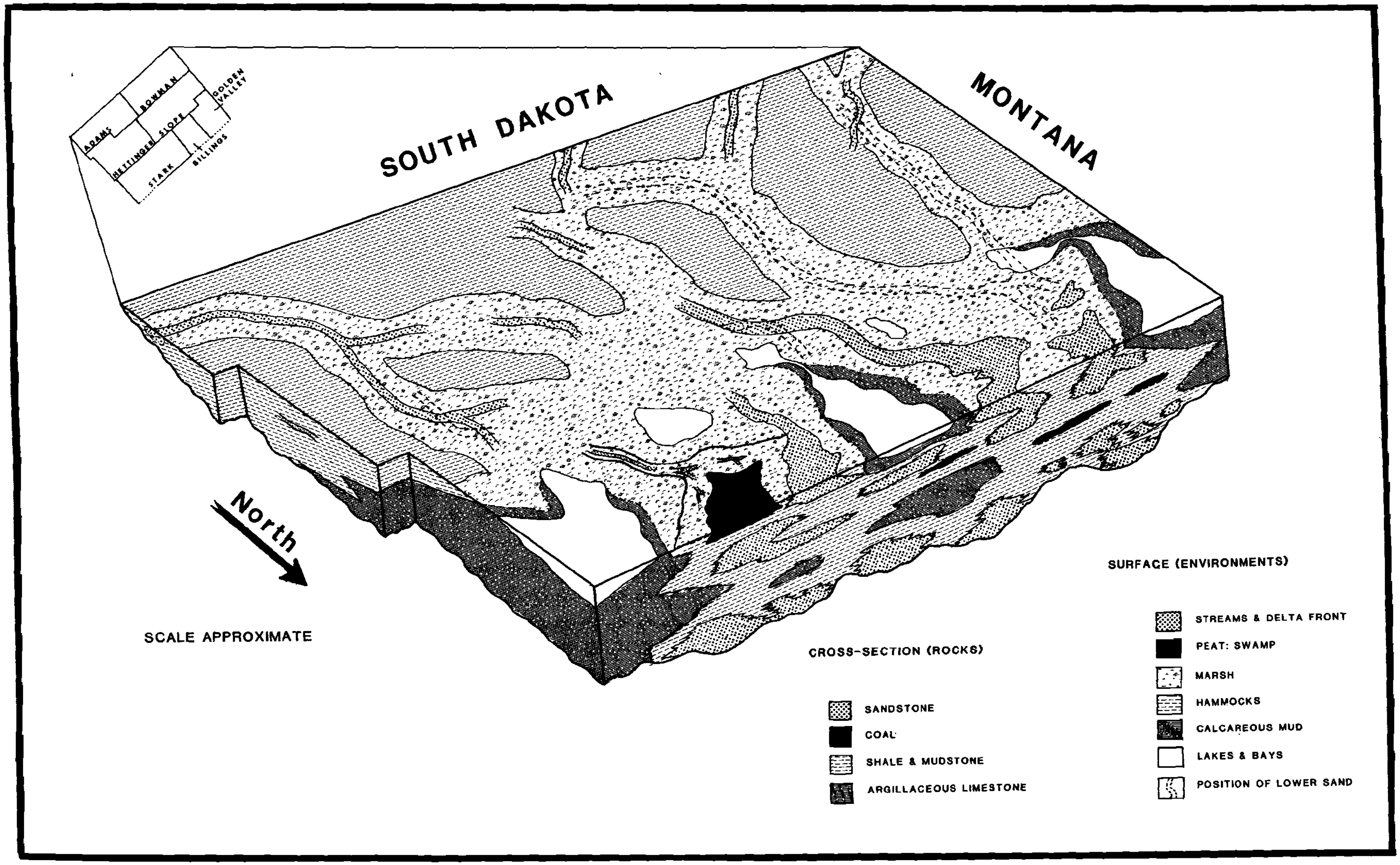

Figure 22. Paleogeographic reconstruction of the depositional environment and distribution of facies relationships during deposition of the lower unit of the Tyler Formation in southwestern North Dakota.

a viable explanation for coal deposits in the Tyler Formation.

Lithofacies D and E

Lithofacies D and E are interpreted as fluvial-deltaic sandstone deposits and lateral equivalents of one another. The relatively immature, multiple-stacked, crossbed sets of quartz arenites trending dominantly northwestward (lithofacies E) are interpreted as channel-fill deposits. Basal lag conglomerates, fining upward sequences, and the presence of lenticular clasts oriented parallel to horizontal laminations are indicative of channel deposits. Distribution of channel-fill deposits in the lower unit of the Tyler Formation suggests that deposition occurred in streams of low to moderate sinuosity. Individual channel fills are generally 5 to 15 feet (1.5 to 4.6 m) thick, except in the Rocky Ridge Field where sandstone thickens to 50 feet (15.2 m), and the bodies are separated by greenish-gray to medium-dark-gray mudstones of lithofacies B (interpreted as marsh deposits). Compaction slickensided mudstones associated with channel-fill deposits have been interpreted as possible overbank deposits by Ziebarth (1972). The writer recognizes this possibility, but also recognizes that overbank deposits are hard to distinguish from marsh deposits. Overbank deposits should be siltier and exhibit better graded bedding than marshal deposits if primary depositional structure is preserved. Grayish-black shale and gray mudstone-pebble conglomerates found at the base of channel-fill deposits indicate that streams migrated laterally over marsh and pre-existing interdistributary-bay environments.

Lithofacies D, composed of reddish-brown, well-sorted, texturally mature quartz arenites and yellowish-brown to varicolored, convoluted mudstones, is interpreted as delta-front deposits in a number of different cases. These deposits occur as discontinuous bodies in an east-west trend in southwestern North Dakota. Individual deposits are lenticular, and are 5 to 15 feet (1.5 to 4.6 m) thick. Recognition of lithofacies D as deposited in delta-front areas is primarily based on sandstone geometry and textural maturity, in comparison to lithofacies E which is laterally equivalent. Delta-front subenvironments, such as the prodelta, lower and upper shoreface, and foreshore environments, were not recognizable. The relative thinness of lithofacies D suggests that the delta-front area was starved of sediment, or that tidal processes transported sediment seaward, or a combination of these effects.

Lateral migration, as well as progradation along delta-front areas, is a major aspect of deltaic sedimentation (Ferm, 1970). The result is active decay of the abandoned delta lobe, and formation of an active, prograding delta lobe adjacent to the abandoned one. The end product is an en echelon pattern of sandstones and coals encased in marine to nonmarine shales and mudstones (Ferm, 1970). The reconstruction of the delta-front area (fig. 22) is based on sandstone distribution patterns, associated strata, and stratigraphic cross sections that clearly indicate lateral migration was a dominant process in the lower unit. Yellowish-brown to varicolored mudstones associated with sandstones in lithofacies D are interpreted as paleosols developed on exposed portions of the delta plain. The presence of sandstone, overlying and underlying the paleosols, further suggests that lateral migration was an important physical process in the delta-front area.

Upper Unit Lithofacies

Lithofacies F

Lithofacies F is interpreted as having been deposited in a barrier-island system. Stratigraphic cross sections and isopach maps (pl. 6) both indicate the presence of isolated, lensoid, sandstone bodies oriented east-west between the Medora and Dickinson Fields. Sedimentary structures, textural maturity of the sandstones, and the presence of marine fossils in the sandstone are further evidence that lithofacies F is a barrier-island deposit. Land (1976, 1979) interpreted the sandstones in Stark County to have been deposited as barrier islands along shorelines of a regressive sea. Where a shoreline was fully developed, Land (1976, 1979) recognized particular lithologies indicative of five subenvironments of deposition. In ascending order these environments are: (1) shallow-neritic (shale and mudstone), (2) lower shoreface (fine-grained sandstone), (3) upper shoreface (medium-grained sandstone), (4) foreshore (fine- to medium-grained sandstone), and (5) marsh (coal). This overall sequence was recognized in several cores (from the Green River and Dickinson Fields) studied for this report, except that varicolored mudstones and mottled mudstones with root structures (fig. 23), interpreted to be paleosols, were commonly found to overlie massive sandstones (foreshore environment) instead of coal (marsh environment). In cores from the Medora and Fryburg Fields, depositional subenvironments of the barrier-island sequence were not recognized. Noticeably missing are paleosols or coals associated with marsh or swamp environments.

Lithofacies G

Lithofacies G, which is best developed in the area of the Square Butte to Fryburg Fields, is interpreted as both a lagoonal-estuarine and a shallow-marine to marginal-marine deposit. Dark-gray to grayish-black, calcareous shales and carbonaceous, argillaceous limestones represent lagoonal-estuarine deposition behind barrier islands. Dark-gray, argillaceous, micritic limestones represent deposition in front of barrier islands in shallow, anoxic, marine to marginal-marine waters. Dark-gray, argillaceous, micritic limestones, overlying barrier-island sandstones in the Medora and Fryburg Fields, suggest a transgressive event following barrier-island development in this area. Algal mats binding ostracods, de-watering structures, and ripple to planar laminations throughout the lower subunit indicate a predominance of shallow-water deposition.

In the Green River to Dickinson Fields, lithofacies G gradually thins and becomes very carbonaceous. The writer believes that thinning and the transition from limestone to shale reflects a change in environments--from marine to marginal-marine, and finally, to restricted lagoon.

Lithofacies H

Lithofacies H is interpreted as a tidal-flat and marsh deposit. In the Square Butte, Medora, and Fryburg Fields, lithofacies H overlies lithofacies G and is recognized as the upper subunit of the upper unit in this report. Reddish-brown, calcareous shales and grayish-red, anhydritic, micritic limestones are present throughout the area and are interpreted as extensive tidal-flat deposits. Desiccation structures in both limestone and shale indicate periodic subaerial exposure in this environment. Relatively thin, nodular anhydrites were originally precipitated as gypsum in local hypersaline lakes or ponds and, after burial, dehydrated to anhydrite.

To the east, in the areas of the Green River, Zenith, and Dickinson Fields, lithofacies H makes up most of the upper unit of the Tyler Formation and is the lateral equivalent of lithofacies G and H in the area to the west. The varied lithology in this area is interpreted as a back-marsh environment that prograded north to northwestward over pre-existing barrier islands. Greenish-gray to light-brown wackestones containing ostracods, medium-gray grainstones containing pelecypods, gastropods, and ostracods; and medium-gray grainstones containing pelecypods and oncolites are interpreted to have been deposited in shallow, restricted lagoons and ponds to deeper, open lagoons and bays. Yellowish-brown, mudstone-pebble conglomerates are interpreted to have been deposited as channel lag in a tidal-flat subenvironment. Reddish-brown to gray and yellowish-brown, calcareous mudstones with well-developed desiccation structures are also indicative of this subenvironment.

DEPOSITIONAL HISTORY OF THE TYLER FORMATION

Deposition of the lower unit of the Tyler Formation in southwestern North Dakota was in a deltaic environment. During the beginning stages of sedimentation, a major fluvial system flowed predominantly northwestward across a low-lying delta plain and transported quartz sand toward the delta-front area where the major streams broke up into distributaries (fig. 22). The writer believes that fluvial deposition and stream channel trends in the lower unit may be controlled by structural lineaments identified by Thomas (1974) and Brown (1978). Channel-sandstone deposits are coincident with northwest-southeast and east-west trends of greater thickness (pl. 2) in southwestern North

Figure 23. Photograph of an area interpreted as a paleosol developed on top of barrier-island sandstone (lithofacies F). Dark area at the top of slab is interpreted as a lateritic soil horizon being displaced by nodular anhydrite. Also note rootlets extending down from the soil horizon. NDGS well # 5477--7,645 ft.

Dakota. Location of stream channels and continuing subsidence during their development, due to basement-block faulting, would explain linear trends of greater thickness seen on the isopach map of the lower unit (pl. 2).

As previously mentioned, lateral migration is a major aspect of deltaic sedimentation. This is reflected in the paleogeographic reconstruction of the facies relationship and depositional environment in the lower unit of the Tyler Formation in southwestern North Dakota (fig. 22). Progradation of the delta front is equally important and is related to: (1) the rate of supply of sediment, (2) rate of subsidence along the delta-front area, and (3) sea-level fluctuations. The writer believes that sea-level fluctuations in the Williston Basin, during the deposition of the lower unit, played a most important role, resulting in rapid shifts of the Tyler shoreline. Distribution of sandstones throughout the lower unit in southwestern North Dakota indicates that four major shifts of the shoreline occurred during deposition.

During the initial stages of Tyler sedimentation, streams transported quartz sand northward (the position of these streams is depicted in figure 22) toward the delta front, oriented east-west in what is now the area of the Square Butte to Dickinson Fields (fig. 24). A subsequent regression shifted the shoreline northward, and streams transported quartz sand to a new shoreline at approximately T142N, a shift of 12 miles (19.3 km). Scattered sandstone deposits are found as far north as T148N and are interpreted as offshore-bar deposits. Prodelta deposits exposed upon regression were transformed into a tidal-flat environment (fig. 25).

To determine how much sea level would have to fall in order to shift the Tyler shoreline 12 miles (19.3 km), the Tyler depositional slope must be known. The depositional slope on the Tyler seashore can be estimated by using modern coastlines as an analogy. Similarly, the drop in sea level that would be necessary to shift the shoreline of the Tyler sea 12 miles can be calculated. Irwin (1965, p. 447) has shown that the depositional slope of the Texas coastline is between 1.3 and 10.5 feet/mile and the depositional slopes of epeiric sea coastlines are less than 1.0 feet/mile. Since the Williston Basin during the Pennsylvanian was an epeiric sea, the Tyler depositional slope is thought to have been between 1.0 and 4.0 feet/mile. Therefore, sea level during Tyler time would have to fall a minimum of 12 feet (3.6 m) and a maximum of 48 feet (14.6 m) in order to shift the shoreline 12 miles.

The next phase in the depositional history of the Tyler Formation is a transgressive event that resulted in the return of the Tyler shoreline to the area of the Square Butte to Dickinson Fields (fig. 26). Figure 22 is a detailed paleogeographic reconstruction at this time in the lower unit. The stream channel that flowed through what is now the Rocky Ridge Field probably supplied sediment to the delta front along the line of the Square Butte, Medora, and Fryburg Fields. Another major stream flowed from the Adams and Hettinger County area, probably supplying sediment to the delta front at the location of the present Dickinson Field.

A later event that occurred during the time of the lower unit was a second regression. The Tyler shoreline again shifted northward to approximately T145N, a distance of 30 to 35 miles (48.3 to 56.3 km). Sandstone distribution patterns suggest the presence of east-west trending channels and a delta front in Dunn County at this time. In present Billings County, streams cut through previous delta-front deposits, possibly eroding and transporting some of that material northward to the new shoreline. Exposed prodelta deposits were again transformed into tidal-flat environments that were periodically inundated by the sea. Scattered sandstone deposits north of the shoreline, at this level, are again interpreted as offshore bars (fig. 27).

From the time of the last regressive phase of deposition of the lower unit and the end of lower unit time, the Tyler sea began to slowly transgress onto the delta plain again. To the south on the delta plain and previously abandoned delta lobes, peat accumulated in marsh and swamp areas. An en echelon coal pattern in cross-section A-A' (fig. 28) indicates that lateral migration along the delta front was significant near the end of lower unit time. For reasons that are unclear, channels that transported sediment early in the time of deposition of the lower unit ceased to exist by the end of lower unit time. Dark-gray

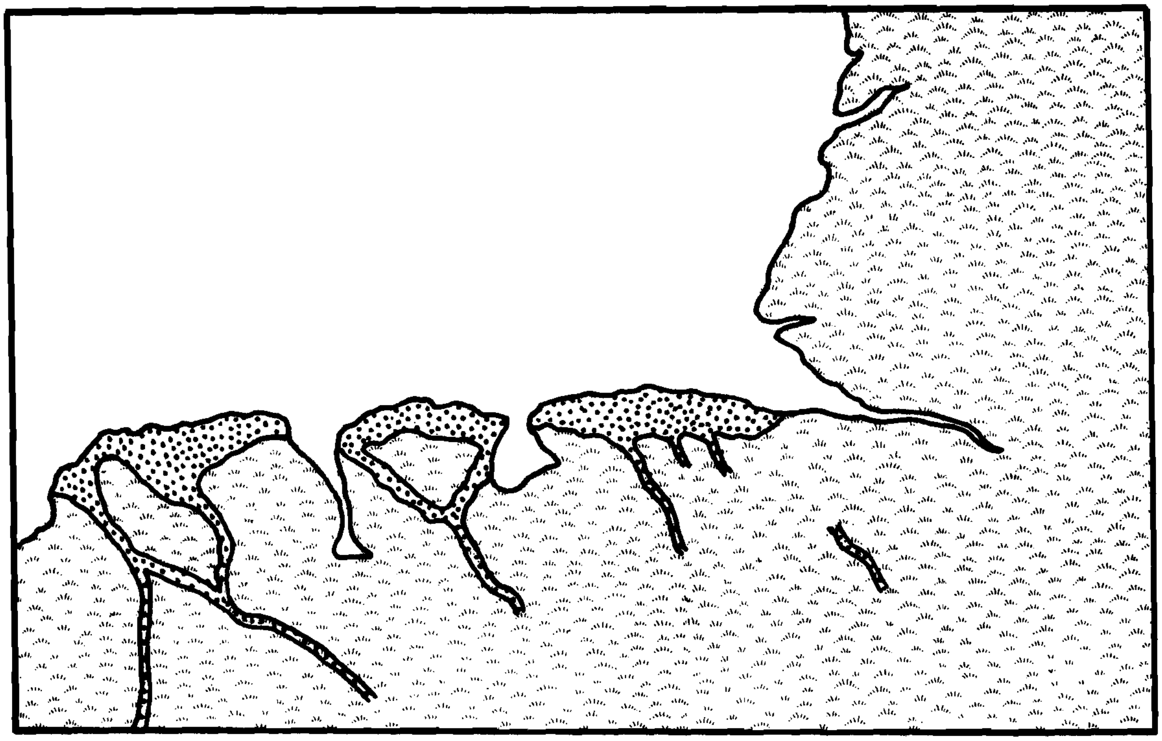

Figure 24. Generalized interpretation of paleogeography and depositional environments at the beginning of lower unit deposition. Diagram approximately corresponds to the study area. Stippled pattern represents sand; vegetation pattern represents a combination of marsh, lagoon, and estuary environments.

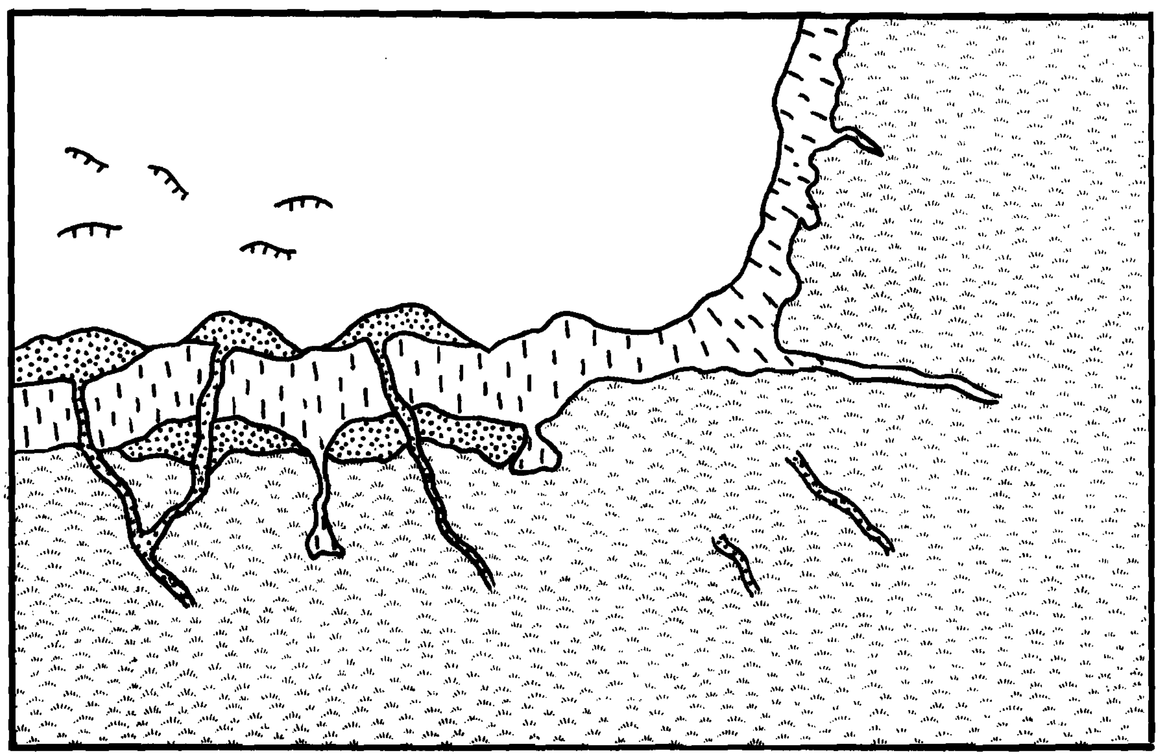

Figure 25. Generalized interpretation of paleogeography and depositional environments after the first regression in the lower unit. The prodelta environment is exposed and transformed into a tidal-flat environment (dashed pattern). Hachured lines represent offshore sand bars. Other symbols as in figure 24.

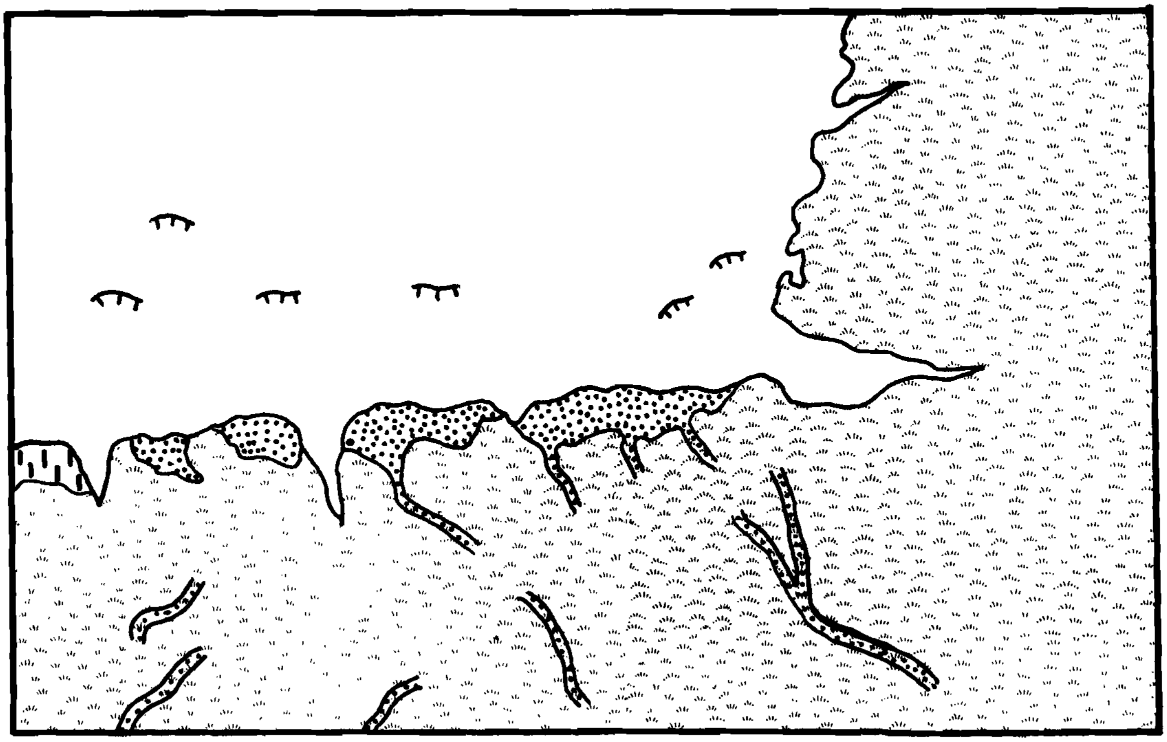

Figure 26. Generalized interpretation of paleogeography and depositional environments after first transgressive event causes the shoreline to shift back to the position occupied in figure 24. Symbols as in figure 25.

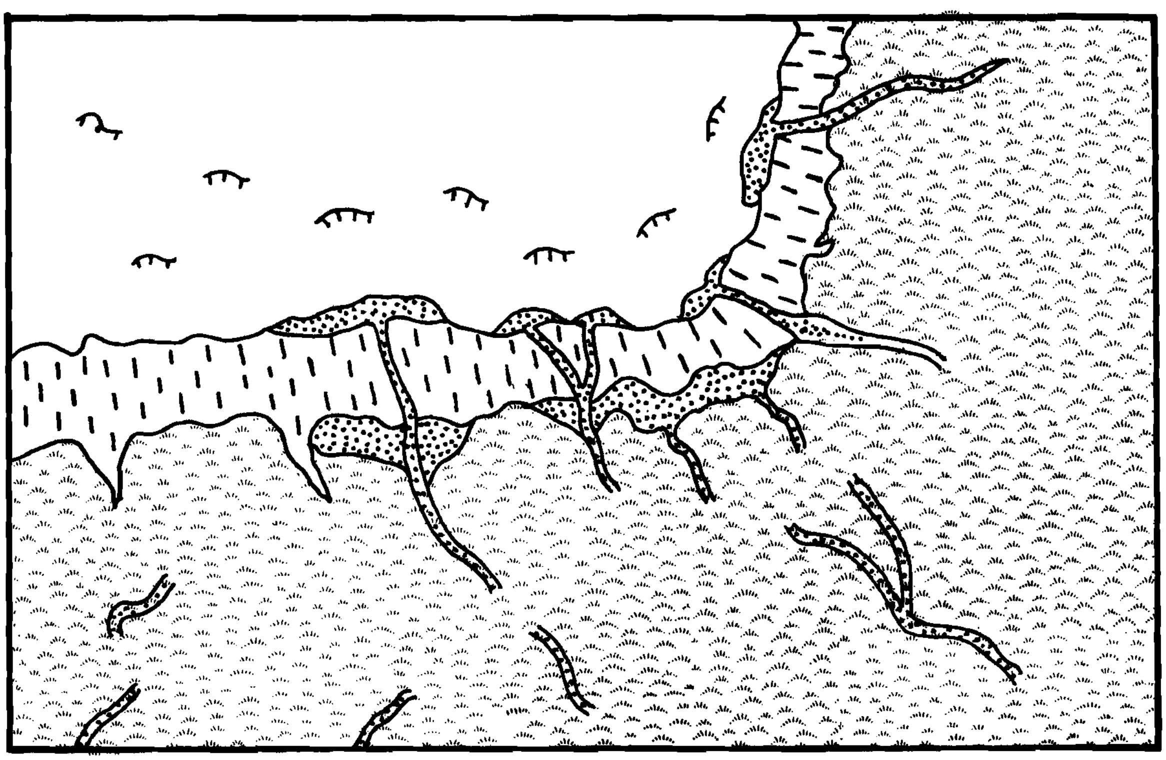

Figure 27. Generalized interpretation of paleogeography and depositional environments after the second regression in the lower unit. Deposition of delta-front sands begins along the eastern shoreline of the Tyler sea. Symbols as in figure 25.

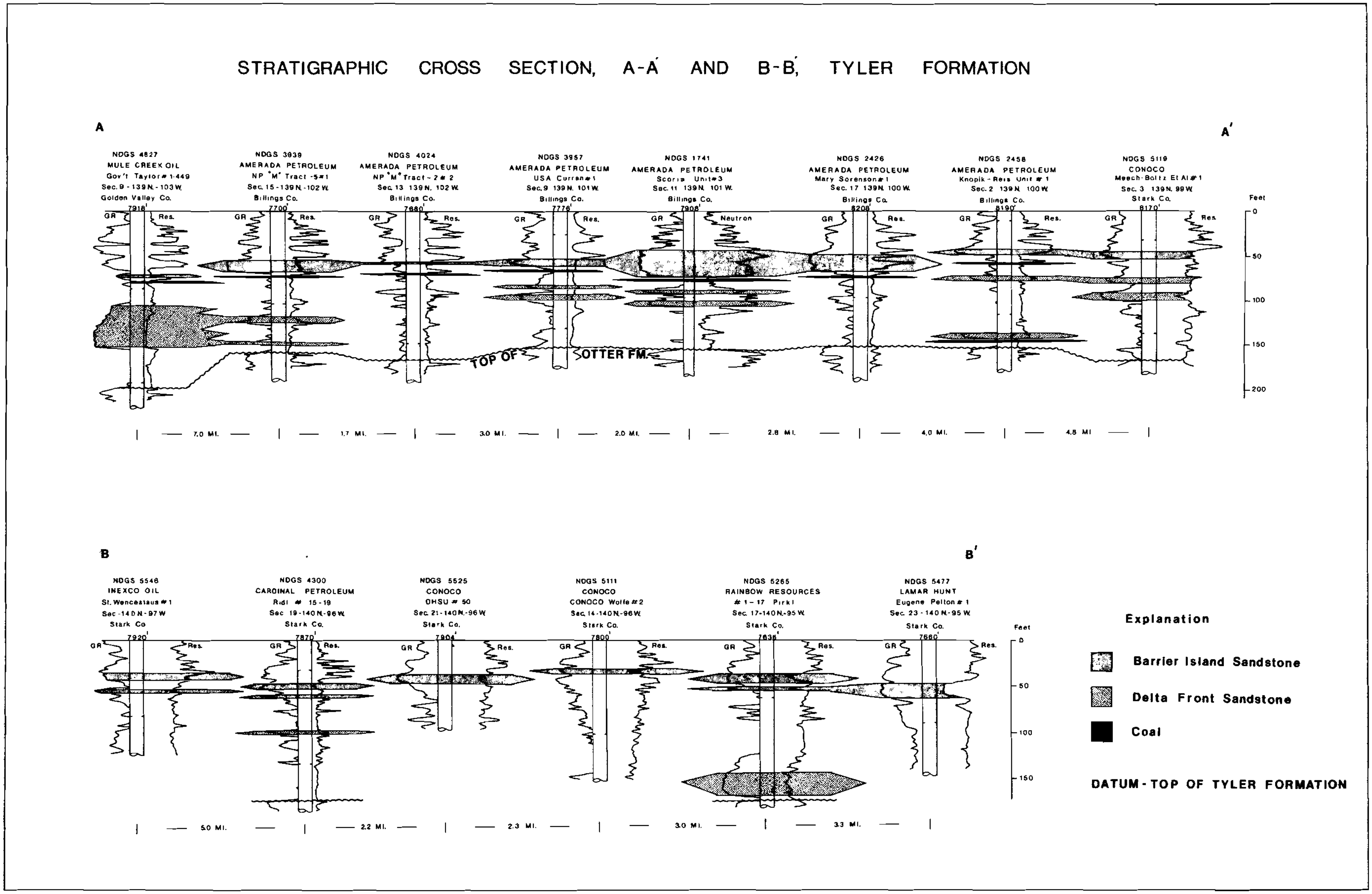

Figure 28. Stratigraphic cross sections, west-east across the Medora and Fryburg Fields (A-A') and the South Heart and Dickinson Fields (B-B').

to grayish-black shales and limestones present at the top of the lower unit in the Square Butte, Medora, and Fryburg Fields indicate that a relatively large, anoxic sea was present at the close of lower unit time.

At this time, or shortly thereafter, a northwestward-flowing stream began to bring sand into the Tyler sea east of the Dickinson Field (fig. 29). The trend and location of this channel is shown on the isopach map of the upper sandstone (pl. 6). The writer believes that longshore currents transported sand to the west and barrier islands developed in the areas of the present Dickinson, South Heart, Green River, Zenith, Fryburg, and Medora Fields (fig. 30). A detailed paleogeographic reconstruction of this time in the study area is shown in figure 31. An extensive estuarine-lagoonal environment existed to the south, in a landward direction, and a shallow, anoxic sea was present to the north. Barrier-island formation was subsequently followed by north-to-northwestward shoreline progradation in the Dickinson Field area but by a marine transgression in the Medora and Fryburg Fields (figs. 32 and 33). Detailed stratigraphic cross-sections E-E' and F-F' (fig. 34) demonstrate north-to-northwestward migration of barrier islands in Stark County. Paleosols (figs. 23 and 35) commonly overlie barrier-island sandstones, which are in turn overlain by variable estuarine or lagoonal deposits (figs. 20 and 21). Stratigraphic cross-sections C-C' and D-D' (fig. 36) demonstrate that the barrier islands in what is now the Medora and Fryburg Fields did not migrate northward. The writer believes that the barrier islands present in these areas developed rapidly in a shallow, anoxic sea. The absence of paleosols overlying sandstones in these two areas may indicate that barrier-island development was a relatively short-lived event that interrupted deposition of dark-gray to grayish-black, calcareous and carbonaceous muds in a shallow, anoxic sea. Barrier-island sandstones in the area of the Medora and Fryburg Fields are overlain by dark-gray, argillaceous, ostracodal limestones (figs. 17 and 18), which are also laterally equivalent to barrier-island sandstones to the north, in a seaward direction.

Tyler time culminated with the withdrawal of the shallow sea in the area of the Square Butte, Medora, and Fryburg Fields, exposing shallow, subtidal deposits and transforming this area into an extensive tidal flat. In the area of the Dickinson Field, northward-to-northwestward shoreline migration continued and estuarine-lagoonal environments prograded over pre-existing barrier islands (figs. 32 and 33). Sandstone distribution patterns indicate the possibility of barrier-island development in an arcuate trend through Billings, Stark, and Dunn Counties. Another sandstone trend, approximately perpendicular to the first, extends from Dunn County through Mercer County and is interpreted as a channel deposit. Depositional environments of the uppermost Tyler Formation are characterized as extensive tidal-flat environments in the area of the Square Butte to Fryburg Fields, and marsh environments in the remaining areas bordering the Tyler sea.

SANDSTONE DIAGENESIS

Three environments of sandstone deposition, stream channels, delta front, and barrier islands, have been identified in the Tyler Formation. Megascopic differences in color, grain size, and textural maturity in each sandstone have been discussed. The following discussion will concentrate on the relationship between depositional environment and sandstone diagenesis.

Channel Sandstones

Recent exploratory interest in the Tyler Formation has been concentrated in locating channel sandstones as potential petroleum reservoirs. A prime source of information, with regard to depositional environments and diagenesis in channel sandstones, is present in the Rocky Ridge Field. Production is from the sandstone developed in the middle of the lower unit. This sandstone is predominantly a medium- to coarse-grained, texturally immature quartz arenite (figs. 37 and 38). In local zones, which are saturated with hydrocarbons, the sandstone is a fine-grained, well-sorted, texturally mature quartz arenite.

The most important influence toward porosity reduction in this sandstone is the presence of detrital and authigenic clay. Organic-rich clay occurs as a well-dispersed matrix

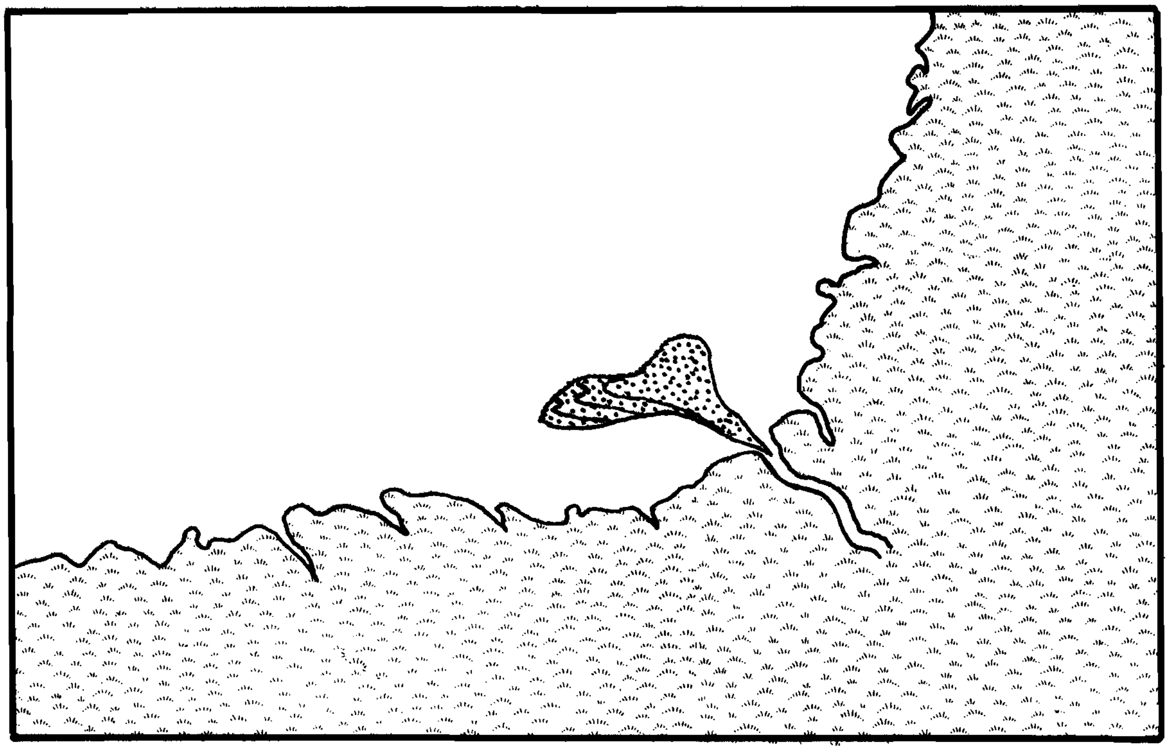

Figure 29. Generalized interpretation of paleogeography and depositional environments at the beginning of barrier-island formation. Sands are transported and deposited by a northwest trending stream into the Tyler sea east of what is now the Dickinson Field. Symbols as in figure 24.

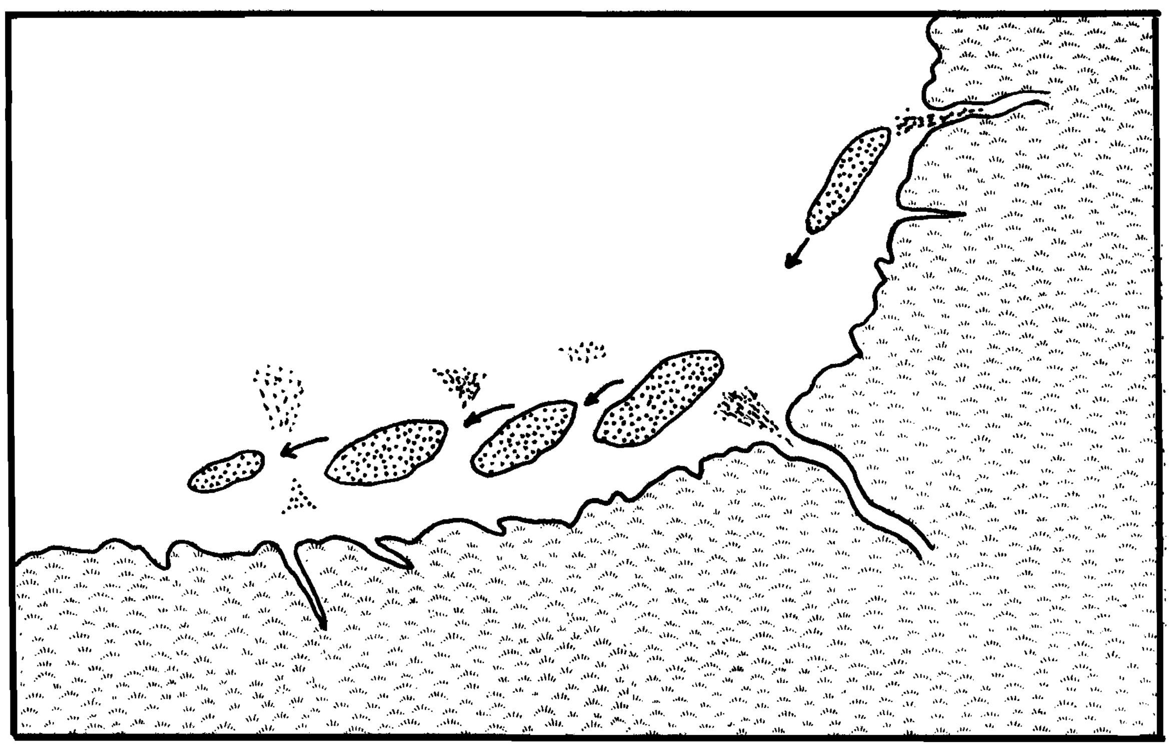

Figure 30. Sands are moved by longshore current from east to west; and several barrier islands are formed in what is now the area of the Dickinson, South Heart, Green River, Zenith, Fryburg, and Medora Fields. Tidal channels (splayed dots) were most likely present between barrier islands; other symbols as in figure 24.

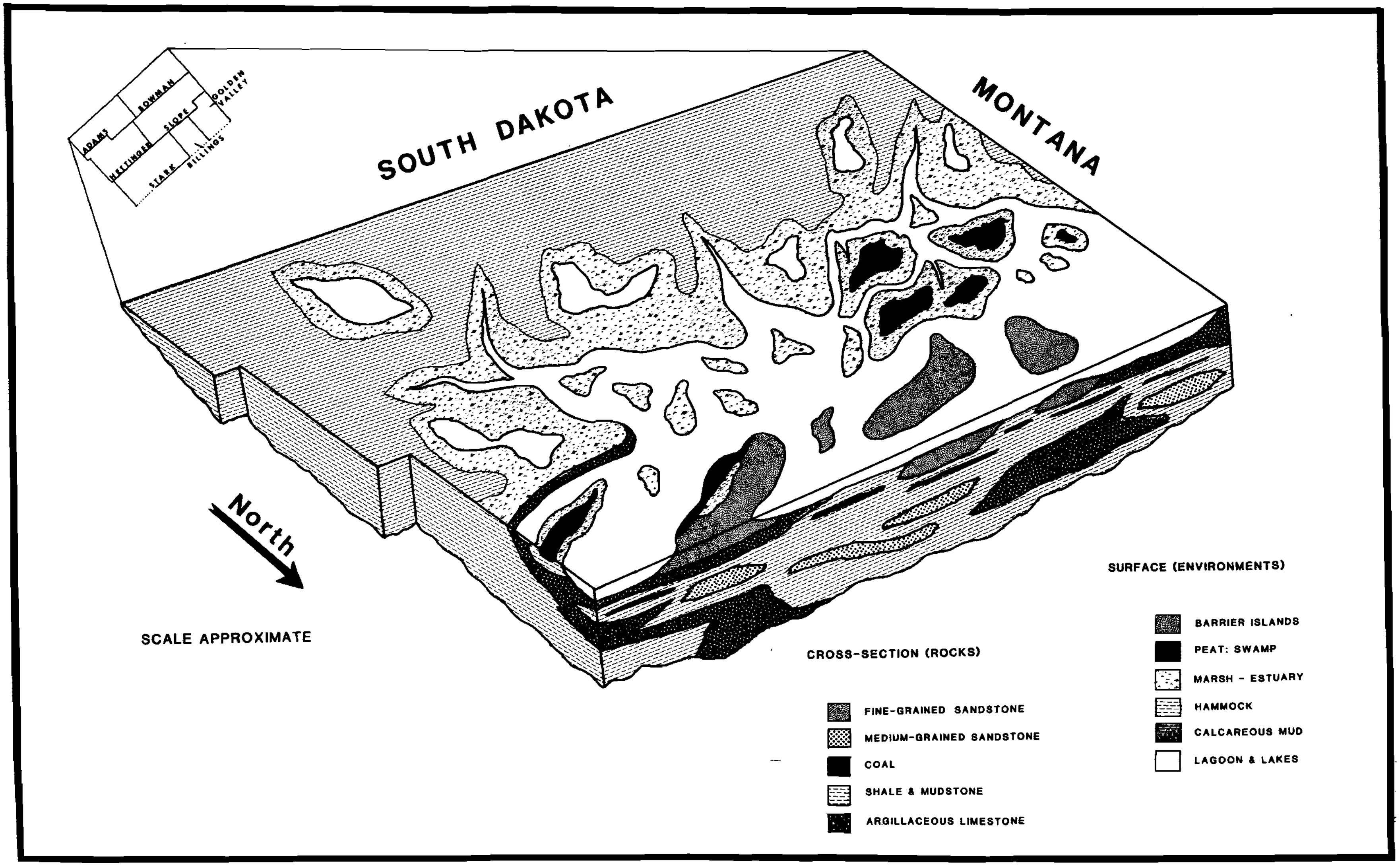

Figure 31. Paleogeographic reconstruction of the depositional environments and distribution of facies relationships at the time of barrier-island development in southwestern North Dakota.

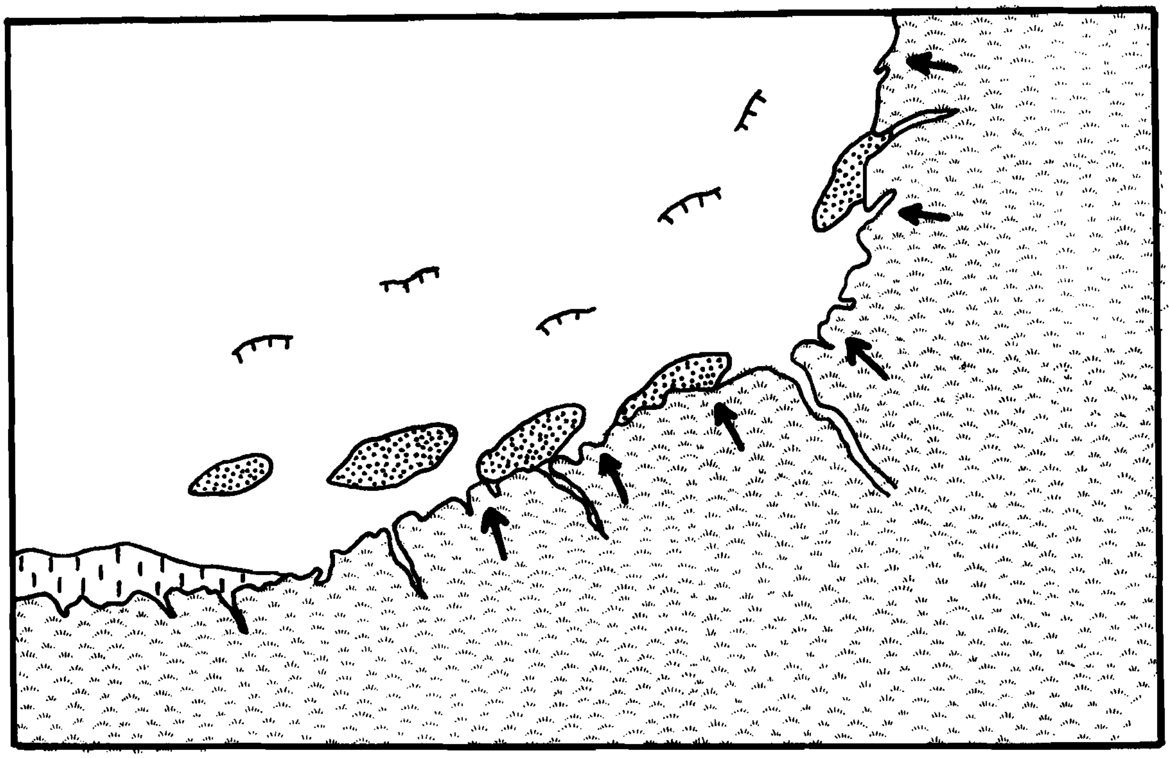

Figure 32. Generalized interpretation of paleogeography and depositional environments after barrier-island development. Shoreline begins to prograde north-to-northwestward in the east as the Tyler sea transgresses in the west.

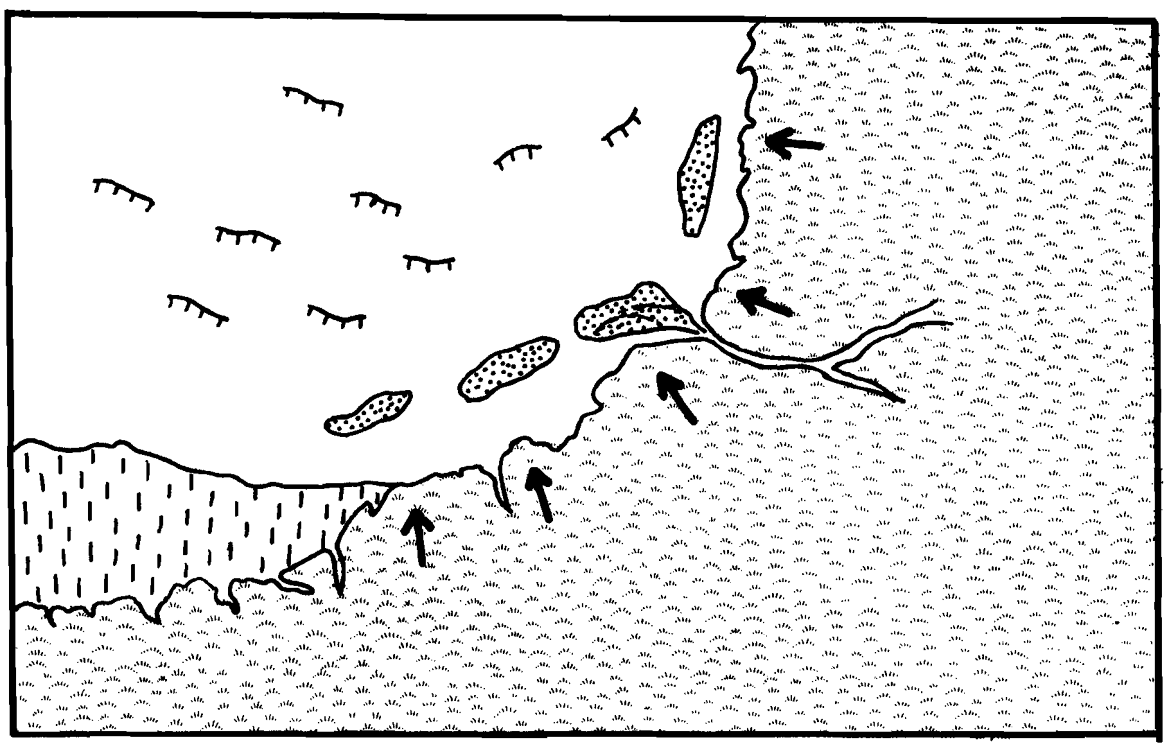

Figure 33. Barrier islands that developed at the beginning of upper unit time are covered by estuarine-lagoonal deposits. Shoreline progradation continues in the east as the Tyler sea withdraws in the west. Numerous offshore sand bars are formed as far north as T148N.

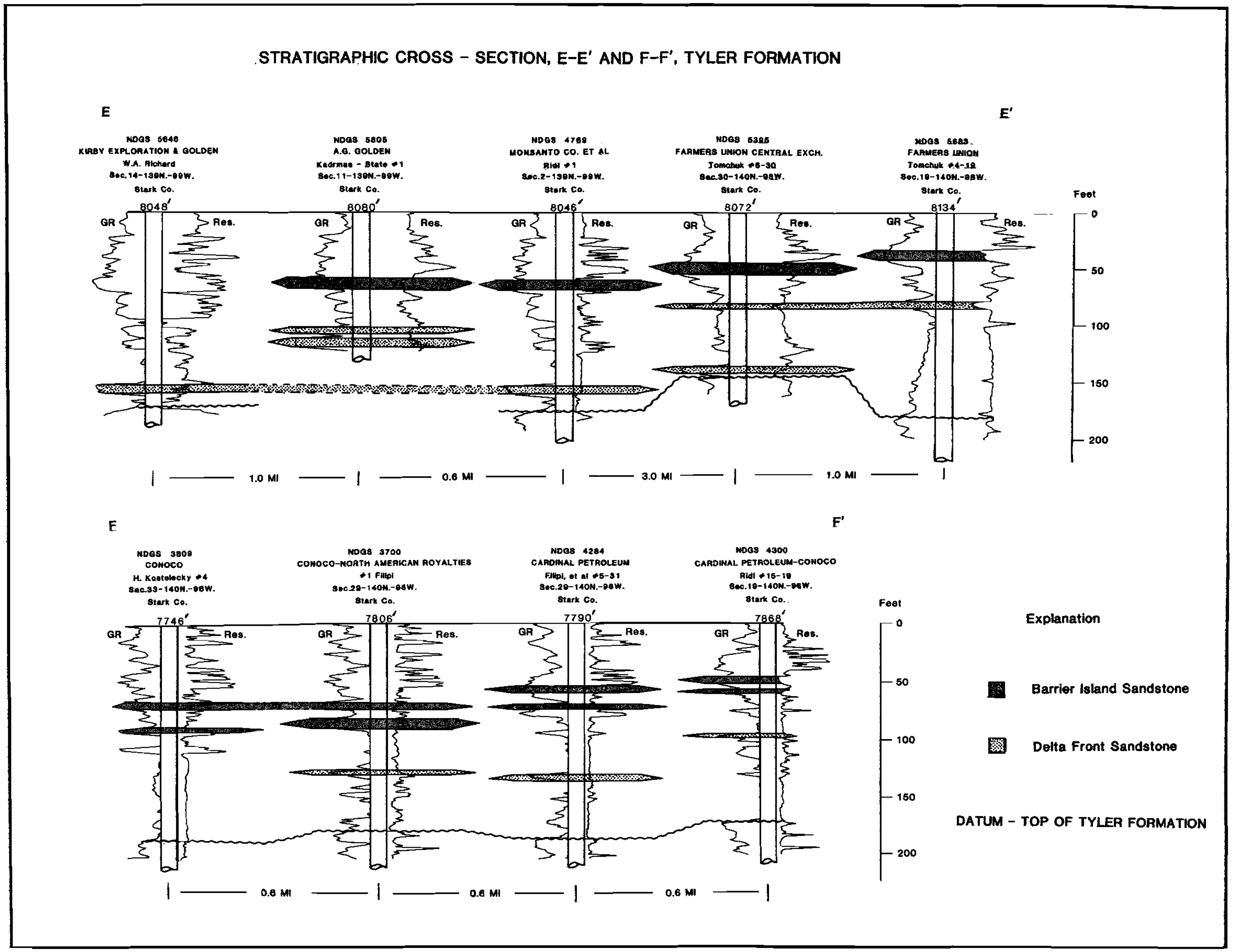

Figure 34. Stratigraphic cross sections, south-north across the Zenith and Green River Fields (E-E') and Dickinson Field (F-F'). Note the movement of barrier-island sandstones up-section to the north.

Figure 35. Photograph of brecciated, calcareous mudstone interpreted as a paleosol developed on top of barrier-island sandstone. NDGS well #4300--7,907 ft.

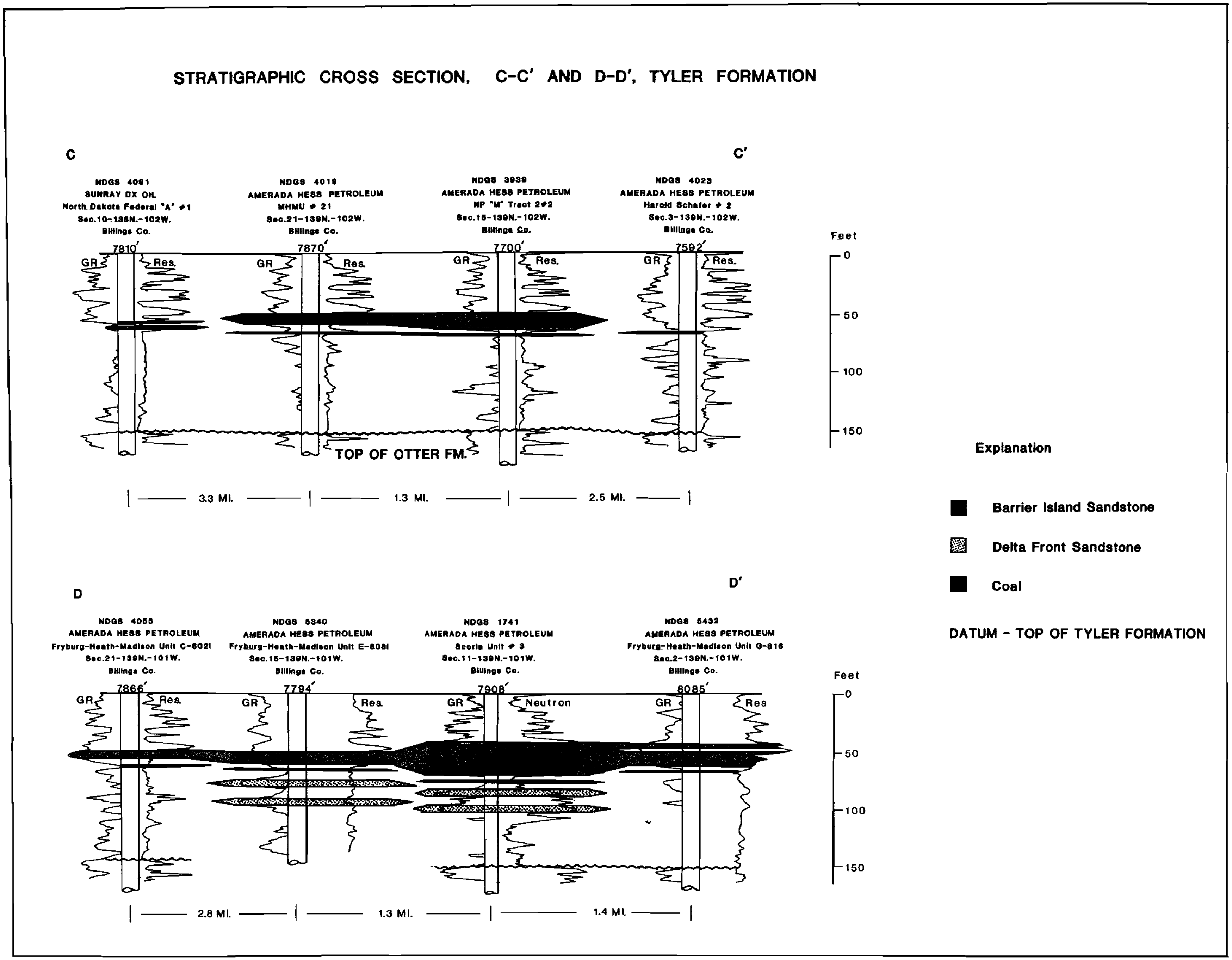

Figure 36. Stratigraphic cross sections, south-north across the Medora (C-C^{1}) and Fryburg (D-D^{1}) Fields.

throughout much of this sandstone. Commonly, a swirling, "porphyroblastic" texture enclosing quartz sand grains is present (fig. 38), characteristic of clay introduced during deposition (Wilson and Pittman, 1977). However, in localized areas where grain to grain contacts are present, primary inter-granular porosity is reduced by four diagenetic processes: (1) development of quartz overgrowths; (2) growth of authigenic quartz crystals in pores; (3) development of stacked plates and aggregates of authigenic kaolinite clay; and (4) development of late-stage ankerite cement. The result of these four processes are shown together in figure 39.

Stacked plates or aggregates of authigenic kaolinite are considered by the writer to be most responsible for the reduction of porosity and permeability in channel sandstones where grain to grain contacts are present. Various workers (Carrigy and Mellon, 1964; Shelton, 1964) have suggested that the formation of authigenic kaolinite is dependent on groundwater chemistry and movement in the surface environment prior to effective burial. Additional consideration must be given to alumina-rich solutions expelled from compaction of adjacent muds (Carrigy and Mellon, 1964). However, the sequence of diagenetic events must be considered in discussing the source of alumina ions necessary for kaolinite growth.

It is apparent that the first diagenetic event responsible for porosity reduction is the development of quartz overgrowths. This may be accomplished by dissolution of quartz at points and interfaces of grain contact and reprecipitation of the dissolved material within the sandstone as a pore cement (Siever and others, 1965; Schmidt and McDonald, 1980), or authigenic quartz overgrowths may form when silica is precipitated from supersaturated pore waters. The dissolved silica in supersaturated pore waters may come from a variety of sources. It may be derived from the dissolution of biogenic silica, diagenetic transformation of clay minerals and other silicates within the sandstones, or from adjacent shales and mudstones (Pettyjohn et al., 1973).

If porosity reduction is first accomplished by the dissolution of quartz at grain contacts and reprecipitation as overgrowths, the influence of sandstone mineralogy, temperature (geothermal gradient), and length of burial (residence time) must be considered in determining the depth of burial at which time chemical diagenesis (dissolution and reprecipitation) became significant. Schmidt and McDonald (1980, p. 71, fig. 50) have plotted "depth ranges of textural maturity grades of burial diagenesis versus mineralogical maturity of sandstones." Four basic assumptions of the plot are: (1) in a sedimentary basin, the subsidence rate is 30 metres per one million years; (2) the rate of sedimentation equals the sum of subsidence and compaction; (3) the geothermal gradient is 2.7 degrees Celsius per one hundred metres; and (4) the sandstones are medium grained. According to the Schmidt and McDonald (1980) plot, quartz cementation in the channel sandstone occurred at a minimum burial depth of 4,800 feet (1.46 km). The growth of authigenic kaolinite, which formed after the development of quartz overgrowths, occurred at a depth of at least 4,800 feet (1.46 km).

However, overgrowths may have formed from the precipitation of silica out of supersaturated pore waters. Pettyjohn and others (1973, p. 426) stated that such pore waters "are widespread in modern sediments, where the concentrations of dissolved silica may reach 80 ppm, greatly exceeding the solubility of quartz at 25 degrees Celsius, which is about 10 ppm." To reduce porosity 10 percent, "pore waters must circulate many times while precipitating the supersaturation excess as overgrowths." Therefore, quartz cementation may have occurred prior to effective burial. If this is the case, then the growth of authigenic kaolinite in this sandstone may have occurred prior to effective burial, but may have also occurred after significant burial.

The growth of authigenic kaolinite in channel sandstones in the Tyler Formation occurred after the development of quartz overgrowths. Due to the uncertainty of the depth of burial at the time quartz overgrowths occurred, only generalizations may be made concerning kaolinite development. If the growth of kaolinite occurred prior to effective burial, consideration must be given to the salinity, concentration of aluminum and silicon ions, and movement of groundwater. If the growth of kaolinite occurred after effective burial, consideration must be given to pore-water chemistry and movement, the release of aluminum and silicon ions from adjacent shales and mudstones, and the alteration of the detrital-clay matrix in the sandstone itself.

Further reduction in porosity is related to late-stage ankerite cement. Ankerite occurs as euhedral crystals or aggregates of euhedral crystals formed along the margins of quartz grains (fig. 40). Schmidt and McDonald (1980, p. 66-70) have suggested that the reduction of primary porosity by pore cements, such as siderite and ankerite, may be due to dissolution of detrital grains at points and interfaces of contact, and reprecipitation of the dissolved material. This is unlikely in this case, as the only detrital grains present are quartz. More likely, iron and magnesium ions were derived from adjacent organic-rich, detrital clays in the sandstone. Carbonate ions were available from either interstitial waters or from the dissolution of calcite cement.

Dissolution of calcite cement has created a secondary porosity in the channel sandstone. Schmidt and McDonald (1980) suggested that the formation of secondary porosity by dissolution of calcite may be related to the release of water from detrital-clay minerals and adjacent clays, and the production of carbon dioxide in associated black shales (lithofacies A) and coals (lithofacies C) resulting from decarboxylation of maturing organic matter. However, the growth of authigenic kaolinite, in addition to detrital clay, has greatly reduced the permeability and reservoir potential associated with the formation, in this way, of any secondary porosity in this sandstone.

Producing horizons of the channel sandstone are fine-grained, well-sorted, texturally mature quartz arenites (fig. 13). The absence of detrital clays in producing horizons may be the result of changes in stream velocity, discharge, and competency that would have favored the deposition of detrital clay either upstream or downstream, or winnowed the clay out of the sediment prior to burial. Lateral migration of channel subenvironments may also be responsible for the differences between producing and non-producing horizons. Non-producing horizons, which are commonly medium- to coarse-grained, texturally immature quartz arenites are interpreted by the writer to have been rapidly deposited and quickly buried, and may represent channel floor or thalweg deposits. Producing horizons, described previously, are interpreted to have been deposited in shallower parts of the stream, presumably on the upper slopes of point bars in a meandering stream setting. Producing horizons may also be interpreted as the sandy tops of channel-bar deposits of a braided stream. Detrital clays would be winnowed out of the sands at the bar-top by stream flow at high stages, leaving a fine-grained, well-sorted quartz sand.

Porosity in producing horizons is primarily intergranular, and is reduced by quartz overgrowths. The presence of authigenic kaolinite in association with the detrital clay matrix, and its absence where detrital clay is not present, suggests that authigenic kaolinite in producing horizons has formed at the expense of detrital clay, and not from alumina-rich solutions derived from adjacent muds (lithofacies B). The absence of authigenic kaolinite from producing horizons may be due to the presence of shale laminae between producing and non-producing horizons (fig. 13). The shale laminae, being impermeable, would act as a barrier to aluminum and silicon ions migrating from detrital clay, and necessary for the formation of authigenic kaolinite.

Delta-Front Sandstones

Delta-front sandstones are medium-grained, well-sorted, texturally mature quartz arenites, and are characterized megascopically by their predominant reddish-brown color, and microscopically by the occlusion of primary porosity. Reduction of primary porosity in these sandstones is the result of two separate, but related, processes: pervasive anhydrite cementation and quartz cementation that appears to be the result of primary depositional packing. In thin-section, anhydrite cement commonly accounts for 30 percent of the area in the field of view, and quartz grains appear to "float" in the anhydrite without any self-supporting framework (fig. 41). The writer suggests that at the time of deposition, sands were loosely packed. Reduction of primary porosity is attributed first, to precipitation of calcium sulfate (gypsum) and second, to

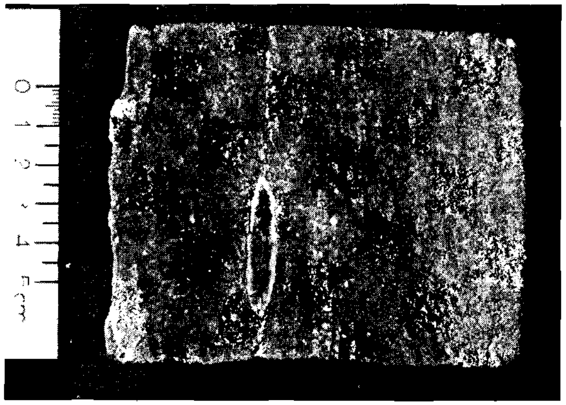

Figure 37. Photograph of horizontally bedded, texturally immature, channel sandstone. Note large, lenticular clast in the center of the slab. NDGS well #4789--8,042 ft.

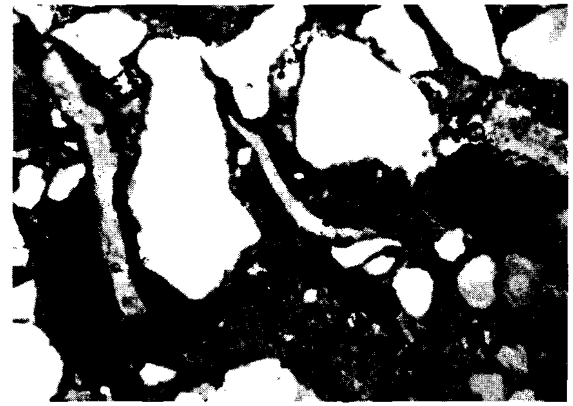

Figure 38. Photomicrograph (35X) of texturally immature, channel sandstone. Note subangular quartz "floating" in a well-dispersed, organic-rich, detrital clay matrix. NDGS well #4789--8,042 ft.

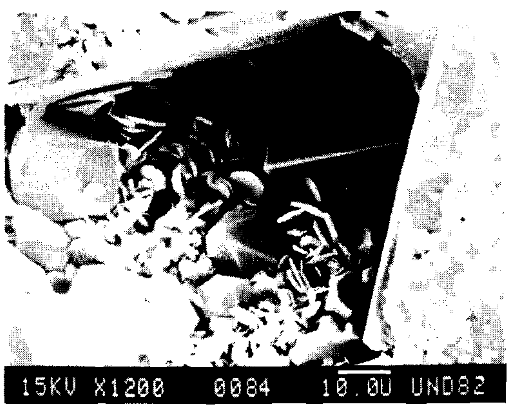

Figure 39. Scanning electron micrograph showing the four processes of porosity reduction in channel sandstones: (1) quartz overgrowths, (2) authigenic quartz, (3) authigenic kaolinite, and (4) late-stage ankerite cement. NDGS well #4789--8,050 ft.

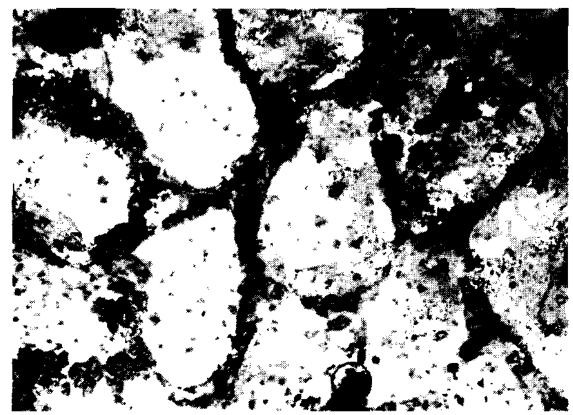

Figure 40. Photomicrograph (100X) of late-stage ankerite rim cement in channel sandstone. NDGS well #4789--8,043 ft.

authigenic iron oxide cement, probably formed at the expense of detrital iron-rich minerals (Walker, 1967). Original porosity for these sands must have exceeded 30 percent since there is approximately a 40 percent reduction in volume when gypsum is recrystallized to anhydrite after burial.

It is believed that the source of calcium sulfate was restricted hypersaline lakes or ponds located on abandoned delta lobes. Supersaturated solutions migrated laterally and vertically into adjacent, buried, loosely packed quartz sands, where precipitation occurred.

Where quartz sands were packed tighter upon deposition and subsequent burial, cementation and porosity reduction is a result of either dissolution of quartz at grain and interface contacts and reprecipitation elsewhere on the detrital grain surfaces that led to formation of quartz overgrowths (fig. 42), or of local pore waters supersaturated with respect to silica resulting in the precipitation of quartz overgrowths. In either case, the writer believes that tighter packing of quartz sand acted as a barrier to the migration of calcium sulfate solutions, resulting in minimal precipitation of gypsum (now dehydrated to anhydrite) in pore spaces and confining those solutions to loosely packed, delta-front sands. This suggests that loosely packed sands acted as aquifers for waters supersaturated with respect to calcium sulfate, while tightly packed sands remained supersaturated with respect to silica.

Two minor processes that are also responsible for porosity reduction are: (1) development of lateritic and caliche paleosols on top of delta-front sandstones, and (2) bioturbation of delta-front sandstones.

Paleosols developed on top of delta-front sandstones are commonly varicolored, silty to sandy, calcareous to hematitic mudstones. Microbrecciation, desiccation structure, calcareous and/or anhydrite nodules, and vugs and cavities are usually present. Porosity is occluded by several processes associated with these structures in this sandstone. Shrinkage porosity associated with desiccation structure is often completely reduced by infilling with reddish-brown mudstone (fig. 43). Porosity associated with vugs and cavities is most often occluded by calcite and anhydrite cements, as is any porosity associated with microbrecciation. Calcite and anhydrite nodules that have grown in situ are responsible for displacing sands and further reducing porosity.

Post-depositional porosity, which might be expected to originate from bioturbation, is not present in delta-front sandstones. Burrowing organisms were likely responsible for the reduction of porosity by incorporating reddish-brown muds into delta-front sands (fig. 44). The result is a nearly homogeneous mixture of medium-grained, well-rounded quartz grains "floating" in a reddish-brown mudstone matrix.

Barrier-Island Sandstones

Barrier-island sandstones are predominantly fine-grained, well-sorted, very mature quartz arenites. Cementation by quartz overgrowths is the dominant porosity-reducing process in this sandstone. Examination of barrier-island sandstones with the scanning electron microscope reveals a relationship between quartz overgrowths and the clay minerals not readily apparent with a petrographic microscope.

Clay coatings on quartz grains have long been considered to be partly responsible for inhibiting quartz overgrowths and hence for the presence of an oil reservoir (Heald and Larese, 1974; Heald and Baker, 1977). Heald and Baker (1977) stated that when quartz grains were well coated, quartz overgrowths were effectively blocked and that thin coatings of clay permitted limited to moderate quartz overgrowths with resulting porosity loss. The writer suggests that the distinct differences in hydrocarbon saturation that commonly exist in barrier-island sandstones that have no appreciable differences in grain size, shape, sorting, or sedimentary structures, may be explained by the presence or absence of detrital clay coatings on quartz grains. In sandstones that are saturated with respect to hydrocarbon, quartz grains were found to be well coated with detrital clay; and quartz overgrowths occurred as well-developed crystals only on part of the quartz grain (fig. 45). These sandstones are friable as a result of detrital clays inhibiting quartz cementation and intergranular porosity is preserved (fig. 46).

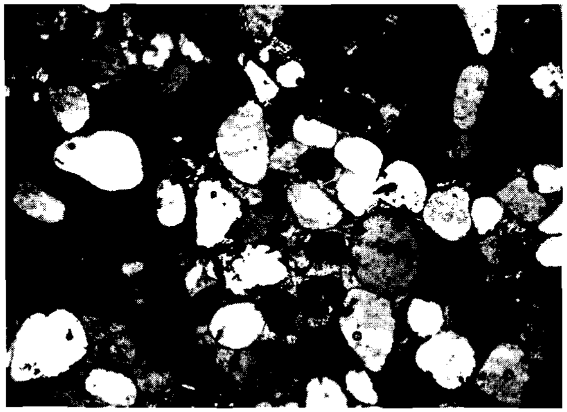

Figure 41. Photomicrograph (35X) of delta-front sandstone. Quartz grains are well-rounded and "floating" in pervasive anhydrite cement. NDGS well #4023--7,664 ft.

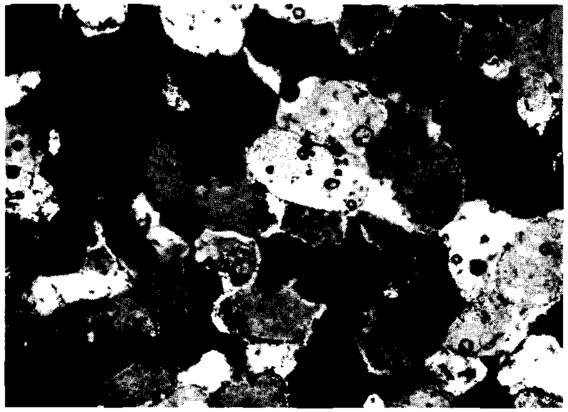

Figure 42. Photomicrograph (35X) showing obliteration of porosity by quartz cementation in delta-front sandstone. NDGS well #4023--7,664 ft.

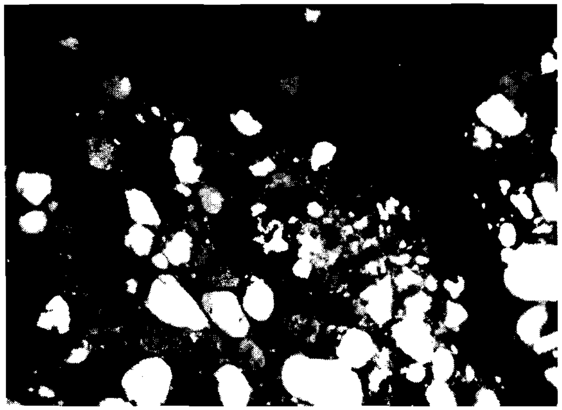

Figure 43. Photomicrograph (35X) showing desiccation and subsequent infilling with reddish-brown mudstone in delta-front sandstone. NDGS well #2458--8,261 ft.

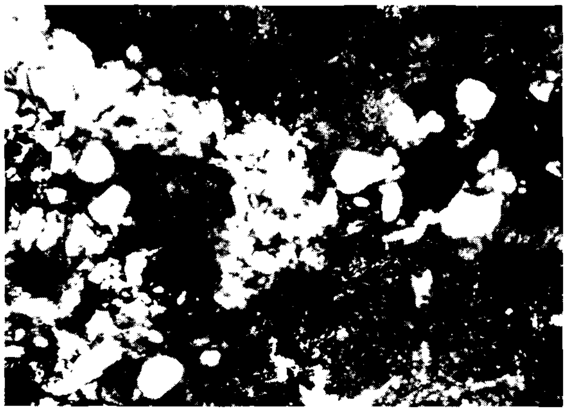

Figure 44. Photomicrograph (35X) of bioturbation in delta-front sandstone. Porosity and permeability are reduced as burrowing organisms mix sands with overlying mud. NDGS well #5340--7,867 ft.

By comparison, in barrier-island sandstones that have no hydrocarbon present, quartz overgrowths are present over the entire grain surface (fig. 47) and primary porosity is greatly reduced. Another factor that must be considered in porosity and permeability reduction is the presence of authigenic kaolinite. Ordinarily not visible during petrographic examination, scanning electron micrographs (figs. 47 and 48) show stacked plates and aggregates of kaolinite present in pore spaces. The presence of authigenic kaolinite in sandstones either not saturated or only moderately saturated with hydrocarbons suggests that the growth of authigenic clay may be of equal importance to the presence or absence of detrital clay coatings affecting porosity and permeability reduction in barrier-island sandstones.

According to the Schmidt and McDonald (1980, p. 72) plot of sandstone mineralogy on burial diagenesis of porosity, quartz cementation in barrier-island sandstones occurred at a minimum burial depth of 5,000 feet (1.52 km). Authigenic kaolinite which formed after the development of quartz overgrowths (fig. 48) occurred at a depth of at least 5,000 feet (1.52 km) and not at the time of barrier-island development as suggested by Sturm (1982, p. 260). Shelton (1964) has suggested that kaolinite forms in sandstones that have pore-water salinities less than normal sea water (35,000 ppm). Discontinuous shaly laminations within the sandstone probably acted as local barriers to water movement creating local variations in salinity as well as providing a source of alumina necessary for clay formation.

Two other processes have been recognized as contributing to porosity reduction in the barrier-island sandstones. First, Land (1976, 1979) stated that porosity and permeability in the sandstones had been reduced or obliterated by development of caliche paleosols in the Dickinson, South Heart, and eastern Green River Fields. Caliches are characteristically tan to reddish-brown, silty to sandy, calcareous mudstones that often have a brecciated fabric (fig. 35). Pyrite, hematite, and nodular anhydrite (fig. 23) are almost always associated with caliche paleosols.

A second lesser process recognized as contributing to porosity reduction is extensive pyritization, especially in the Medora and Fryburg Fields. Pyrite is often found in association with, and replacing, both calcite and anhydrite cements. Pervasive pyritization occurs where ostracod "shell hash" laminae occur in conjunction with shale partings in sandstones, in sandstones that have been bioturbated (fig. 16), and wherever a clay/cement matrix is present in barrier-island sandstones. The occurrence of pyrite as a replacement of anhydrite indicates a change from oxidizing conditions at the delta-front sedimentation and cementation (anhydrite-hematite association) to reducing conditions. This change is also reflected in the change from varicolored to reddish-brown rocks in the lower unit to dark-gray and grayish-black rocks in the upper unit, especially in the areas of the Square Butte, Medora, and Fryburg Fields.

PROBLEMS DESERVING FURTHER STUDY

It is hoped that many questions have been answered by this study. However, in the course of this study, other problems were identified that deserve further study utilizing cores and samples.

Of primary importance is the need for detailed interpretation of depositional environments in McKenzie, Mountrail, Williams, and Burke Counties, North Dakota. Sandstone/shale and clastic ratio maps constructed by Ziebarth (1972) suggest that another major fluvial system transported terrigenous sediment from the Canadian Shield into this portion of the Williston Basin during Tyler time.

The relationship between structural lineaments identified by several workers (Thomas, 1974; Brown, 1978; Shurr, 1982) and sedimentation patterns in the Williston Basin is another subject that should be investigated. Sedimentation patterns from the Mississippian Big Snowy Group through the Permian System should be mapped and compared to structural lineaments to see if a relationship exists between the maps and the lineaments.

Analysis of petroleum source rocks in the Tyler Formation is another area that should receive further attention. Dow (1974, p. 1255) stated that Tyler black shales were the source rock of Tyler oil. Analyses of grayish-black, carbonaceous shales in the lower unit

Figure 45. Scanning electron micrograph of barrier-island sandstone (hydrocarbon present). Relatively thick, detrital clay coatings on quartz grains inhibit the precipitation of quartz as overgrowths. NDGS well #4300--7,923 ft.

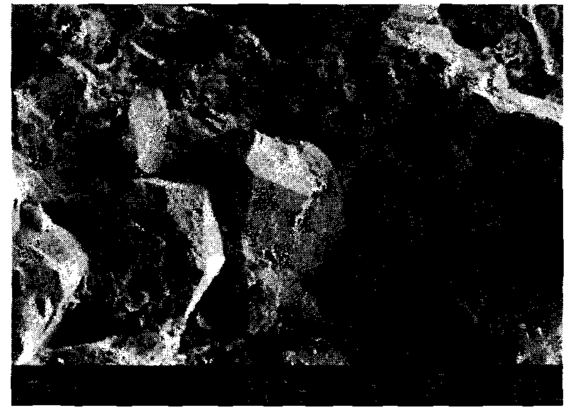

Figure 46. Scanning electron micrograph of barrier-island sandstone (hydrocarbon present). Intergranular porosity is preserved as quartz overgrowths occur as well-developed crystals only on part of the grain not coated with detrital clay. NDGS well #4300--7,923 ft.

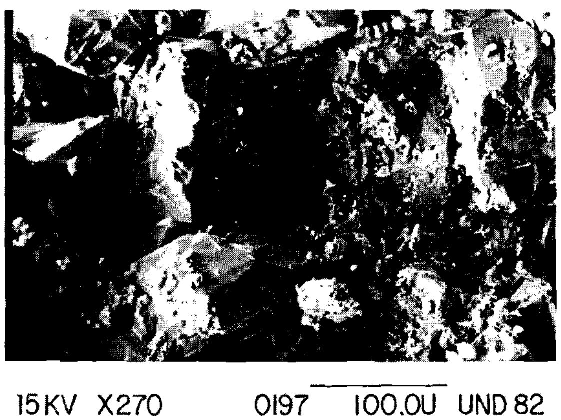

Figure 47. Scanning electron micrograph of barrier-island sandstone (no hydrocarbon present). Porosity is obliterated by quartz overgrowths and subsequent growth of authigenic kaolinite clay. NDGS well #4300--7,922 ft.

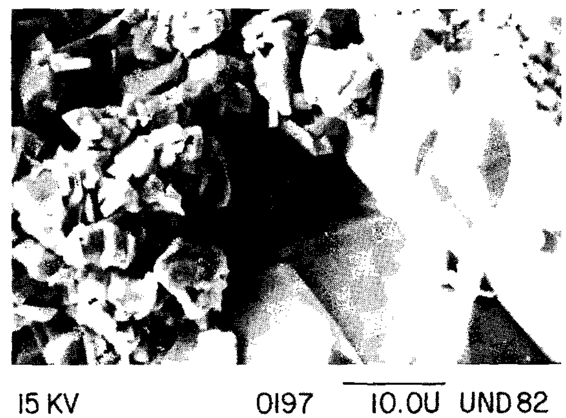

Figure 48. Scanning electron micrograph of barrier-island sandstone (no hydrocarbon present). Close-up of pore space reduced by quartz overgrowth, and late-stage authigenic kaolinite. NDGS well #4300--7,922 ft.

should be compared with dark-gray, calcareous shales and argillaceous, micritic limestones in the upper unit of the Tyler Formation. The writer believes that interdistributary-bay, grayish-black shales may be the source rock for oil in the Rocky Ridge Field, and dark-gray limestones and shales, deposited in shallow marine water, may be the source rock for Tyler oil in the Medora, Fryburg, Green River, Zenith, and Dickinson Fields.

Finally, a regional study of the Tyler Formation should be made with a view toward extending the model presented herein and information obtained from this study into South Dakota and Montana.

SUMMARY AND CONCLUSIONS

The following conclusions have been reached about the Tyler Formation in southwestern North Dakota:

1. Subdividing the Tyler Formation into upper and lower units, mapping the distribution and thickness of each unit, and treating individual sandstones within each unit aided in identification of two predominant depositional environments.

2. The lower unit was deposited in a deltaic environment. In the depositional model presented (fig. 22), marsh, streams, and associated overbank deposits have been identified on the delta plain; hummock environments within the marsh are inferred. In the delta-front area, abandoned delta lobes, marsh, interdistributary bays, localized hypersaline lakes, and location delta-front sands have been identified. Lateral migration of delta lobes is thought to have been the predominant shoreline process.

3. The position of streams trending north-northwest on the delta plain coincides with northwest-southeast linear thickening trends in the lower unit. The writer suggests that stream-channel trend, linear thickening, and deltaic sedimentation patterns are related to movement of basement-block faults in the Williston Basin.

4. Deposition of the upper unit was controlled largely by the development of an extensive barrier-island system in the area of the Medora to Dickinson Fields. An estuarine-lagoonal environment was present to the south, in a landward direction, and a shallow, anoxic sea was present to the north (fig. 31).

5. Tyler time culminated with the withdrawal of the shallow, anoxic sea in the area of the Square Butte, Medora, and Fryburg Fields and continued northward-to-northwestward shoreline migration in the area of the Dickinson Field. Depositional environments of the uppermost Tyler Formation are characterized as extensive tidal flats in the area of the Square Butte to Fryburg Fields, and marsh environments in the remaining areas bordering the Tyler sea.

6. Three environments of sandstone deposition have been identified in the Tyler Formation: stream channel, delta front, and barrier island. Each environment had its own effect on diagenesis and porosity development.

7. The most important phenomenon causing reduction of porosity in channel sandstones is the presence of either detrital and/or authigenic clay. Organic-rich, detrital clay occurs as a well-dispersed matrix throughout much of this sandstone. Kaolinite occurs as stacked plates or aggregates in pore spaces where detrital clay is not present, and is responsible for most of the reduction of porosity and permeability. Formation of authigenic kaolinite is believed to be the result of recrystallization of alumina-rich solutions released from the alteration of detrital clays within the sandstone.

8. Porosity in delta-front sandstones has been obliterated by anhydrite cementation. It is believed that loosely packed sands acted as aquifers for supersaturated waters; up to 30 percent reduction in original porosity is attributed to precipitation of gypsum, the source of which was hypersaline lakes on abandoned delta lobes. Tighter packed sands acted as a barrier to migration of calcium sulfate-rich brines. Dissolution and reprecipitation of quartz caused localized quartz cementation.

9. Detrital clay coatings on quartz grains is considered to be the most important factor in inhibiting cementation and porosity reduction in barrier-island sandstones. In sandstones that are saturated with respect to hydrocarbons, detrital quartz grains were found to be well coated with detrital clay and quartz overgrowths occurred as well-developed crystals only on part of the grain. Thus, original intergranular porosity was largely preserved. In barrier-island sandstones that have

no hydrocarbons present, quartz overgrowths were found to be present over the entire grain surface and primary intergranular porosity was greatly reduced.

Porosity and permeability were further reduced in some places by authigenic kaolinite, which formed after the development of quartz overgrowths. Kaolinite growth is most likely dependent on pore-water salinity at a minimum burial depth of 5,000 feet (1.52 km).

10. Further search for petroleum in the Tyler Formation might be best carried out by searching for basement structural controls of other possible channel sandstones, recognizing barrier-island sandstones, and realizing that sandstones must be in close proximity to dark-gray to grayish-black shales and limestones.

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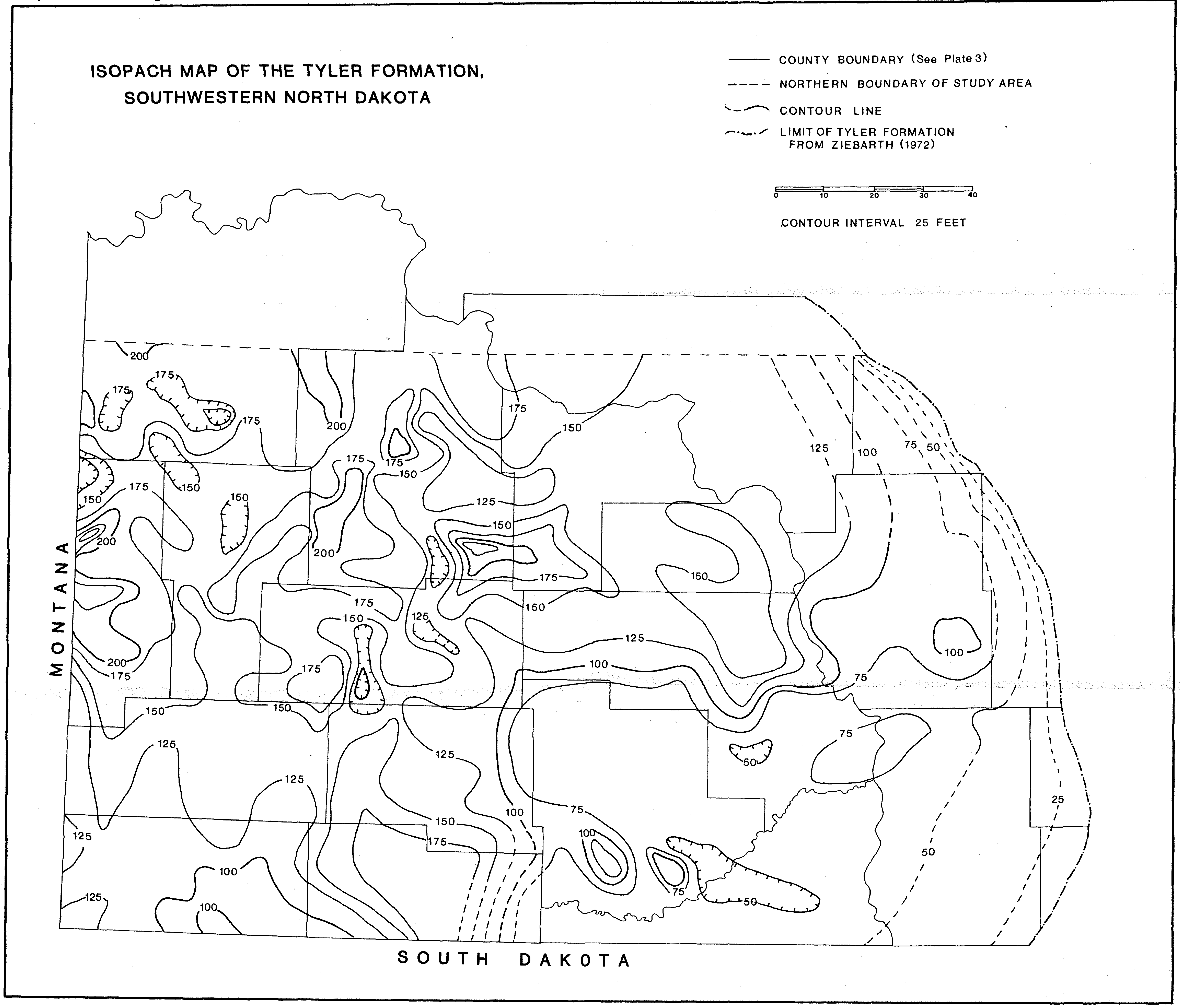
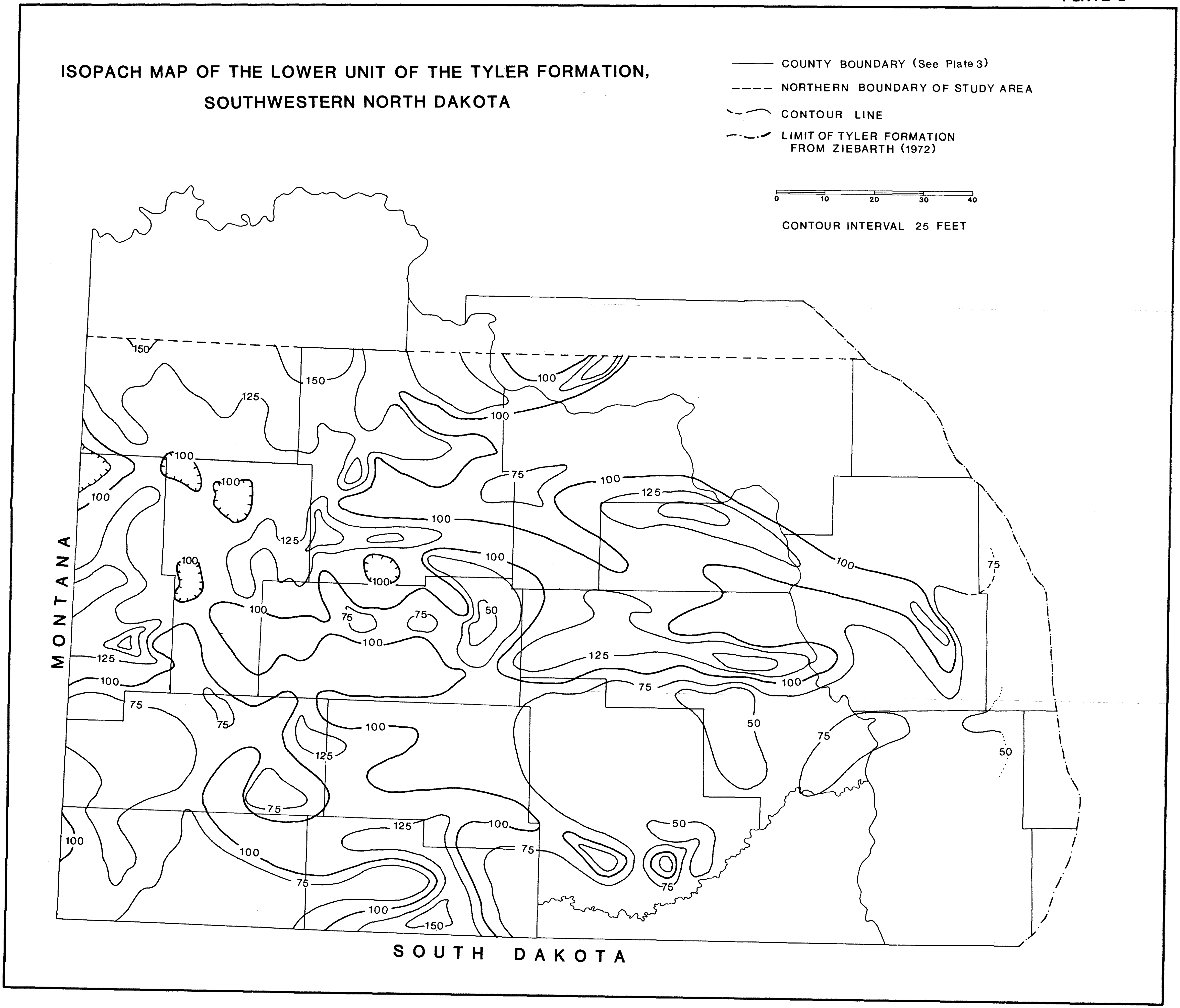
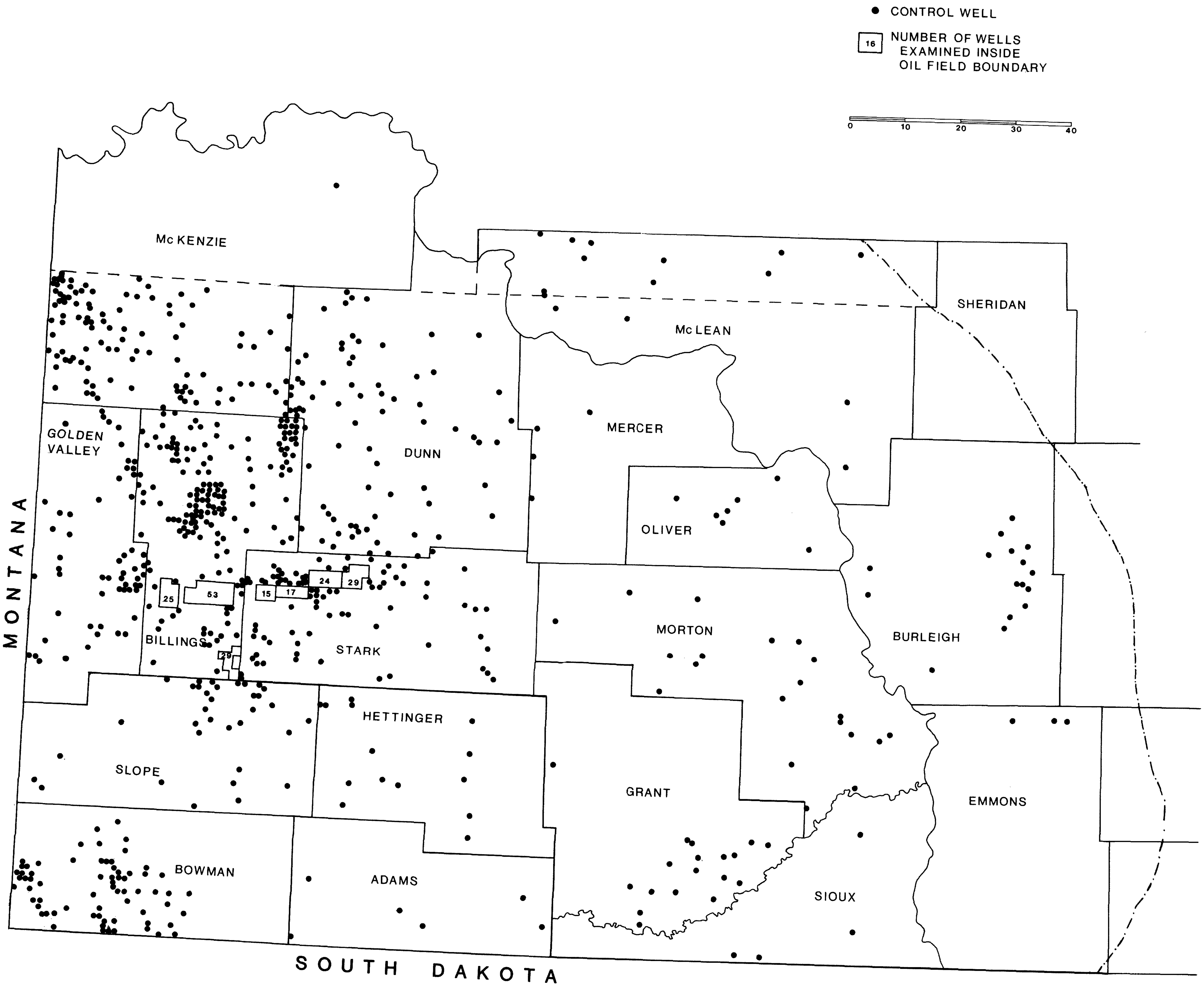

ISOPACH MAP OF THE TYLER FORMATION, SOUTHWESTERN NORTH DAKOTA
COUNTY BOUNDARY (See Plate 3)
NORTHERN BOUNDARY OF STUDY AREA
CONTOUR LINE
LIMIT OF TYLER FORMATION FROM ZIEBARTH (1972)
0 10 20 30 40
CONTOUR INTERVAL 25 FEET
MONTANA
SOUTH DAKOTA
200
175
150
125
100
75
50
25

PLATE 2


ISOPACH MAP OF THE LOWER UNIT OF THE TYLER FORMATION, SOUTHWESTERN NORTH DAKOTA
COUNTY BOUNDARY (See Plate 3)
NORTHERN BOUNDARY OF STUDY AREA
CONTOUR LINE
LIMIT OF TYLER FORMATION FROM ZIEBARTH (1972)
0 10 20 30 40
CONTOUR INTERVAL 25 FEET
MONTANA
SOUTH DAKOTA
150
125
100
75
50

INDEX MAP OF CONTROL WELLS



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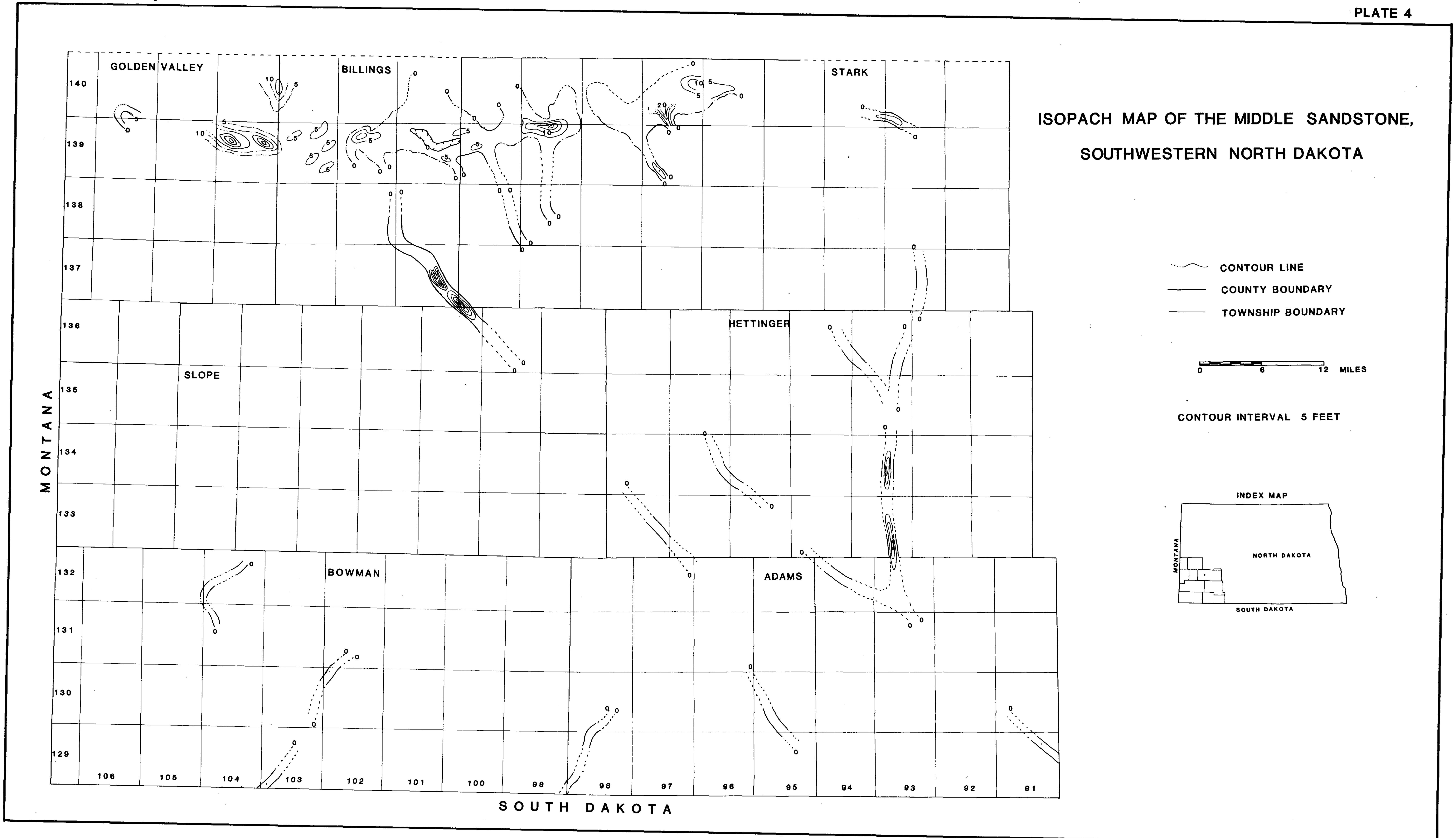
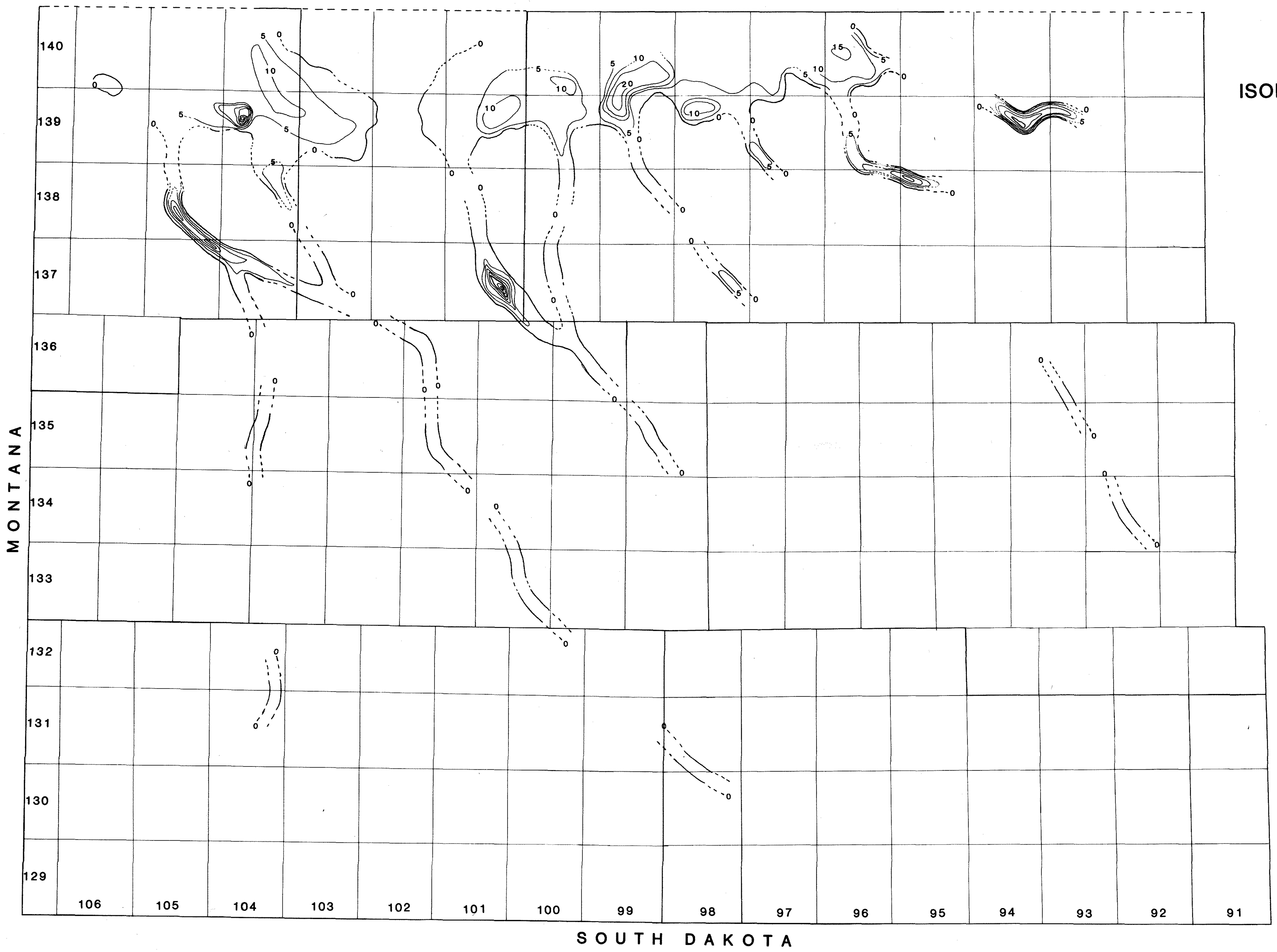


PLATE 5



ISOPACH MAP OF THE BASAL SANDSTONE, SOUTHWESTERN NORTH DAKOTA

CONTOUR LINE

COUNTY BOUNDARY

TOWNSHIP BOUNDARY

0 6 12 MILES

CONTOUR INTERVAL 5 FEET

INDEX MAP

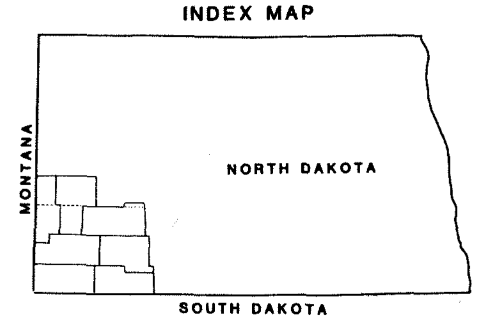


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PLATE 6