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Depositional and paragenetic controls on porosity development, upper Red River Formation, North Dakota

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DEPOSITIONAL AND PARAGENETIC CONTROLS ON POROSITY
DEVELOPMENT, UPPER RED RIVER FORMATION, NORTH DAKOTA

by

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This thesis submitted by W. Kipp Carroll in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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ABSTRACT

The upper Red River Formation in North Dakota comprises a subtidal/intertidal facies overlain by three evaporitic sequences of four lithologic units each, labeled "P," "R," and "F" in stratigraphic order. Four porosity zones are recognized in the upper Red River: the subtidal/intertidal facies forms one porosity zone, and each evaporitic sequence contains another. Each unit in a sequence, as well as the sequence itself, is thinner and less widespread than its preceding counterpart. All strata are laterally continuous across the main part of the Williston basin in North Dakota, but, the porosity zones eventually disappear to the east as they approach the basin margin. Porosity within any given zone varies from one part of the basin to another, often within relatively short distances.

The "D" porosity zone consists of two primary lithologic facies: a shallow subtidal burrowed mudstone and skeletal wackestone, and an impermeable, often laminated, black organic skeletal wackestone and packstone deposited in an intertidal or supratidal barred pond environment. Porosity in the subtidal burrowed facies is due to syndepositional dolomitization and later calcite solution and microfracturing. Maximum porosity values related to dolomitization and calcite dissolution occur in the burrowed horizons immediately above the impermeable organic units, which acted as barriers to interstitial fluid movement. Poor development of the organic units near the center of the basin perhaps accounts for sporadic porosity development in that area.

The basal unit of each of the sequences overlying the "D" zone consists of open shelf bioturbated skeletal wackestone of characteristically low porosity. Porous, fine-grained, primary supratidal dolomite overlies the subtidal facies, and these units form the "C," "B," and "A" porosity zones. A very thin argillaceous marker bed of non-calcareous shale completes each sequence.

Porosity in the supratidal dolomite stems from intercrystalline voids and pinpoint porosity due to solution. Porosity in the upper three zones varies across the basin and is directly related to degree of exposure of the sediment in the supratidal environment, during which dolomitization occurred.

INTRODUCTION

The Red River Formation (Upper Ordovician) is present throughout the Williston basin (Figure 1). Maximum thickness of slightly over 700 feet occurs in the central part of the basin in Dunn County, North Dakota. Most of the original thickness of the formation is preserved in the basin center in North Dakota and along the western periphery in Montana, but has been thinned by erosion to a feather edge at the eastern periphery of the basin in eastern North Dakota. The Red River Formation is recognized Manitoba, Saskatchewan, and North Dakota. Equivalent strata in Montana and Wyoming form the lower portion of the Bighorn Group. In Kansas, Oklahoma, and Nebraska the Viola and Fernvale Formations are correlative units (Fuller, 1961). In South Dakota the Whitewood dolomite comprises the lower part of the Red River.

Various stratigraphic subdivisions of the Red River Formation have been proposed. The most widely used is the upper/lower terminology (Sinclair, 1959; Fuller, 1961; Ballard, 1963; Friestad, 1969), which is used in this report.

The Red River Formation consists predominantly of limestone and dolomitic limestone. Red River carbonates rest conformably on clastics of the Middle Ordovician Winnipeg Formation. Throughout most of the basin a series of argillaceous layers, the Hecla beds (Fuller, 1961), occur as a ten to forty feet thick transition at the base of the Red River. Contact with shale of the overlying Stony Mountain Formation is abrupt but conformable. In the central portion of the Williston

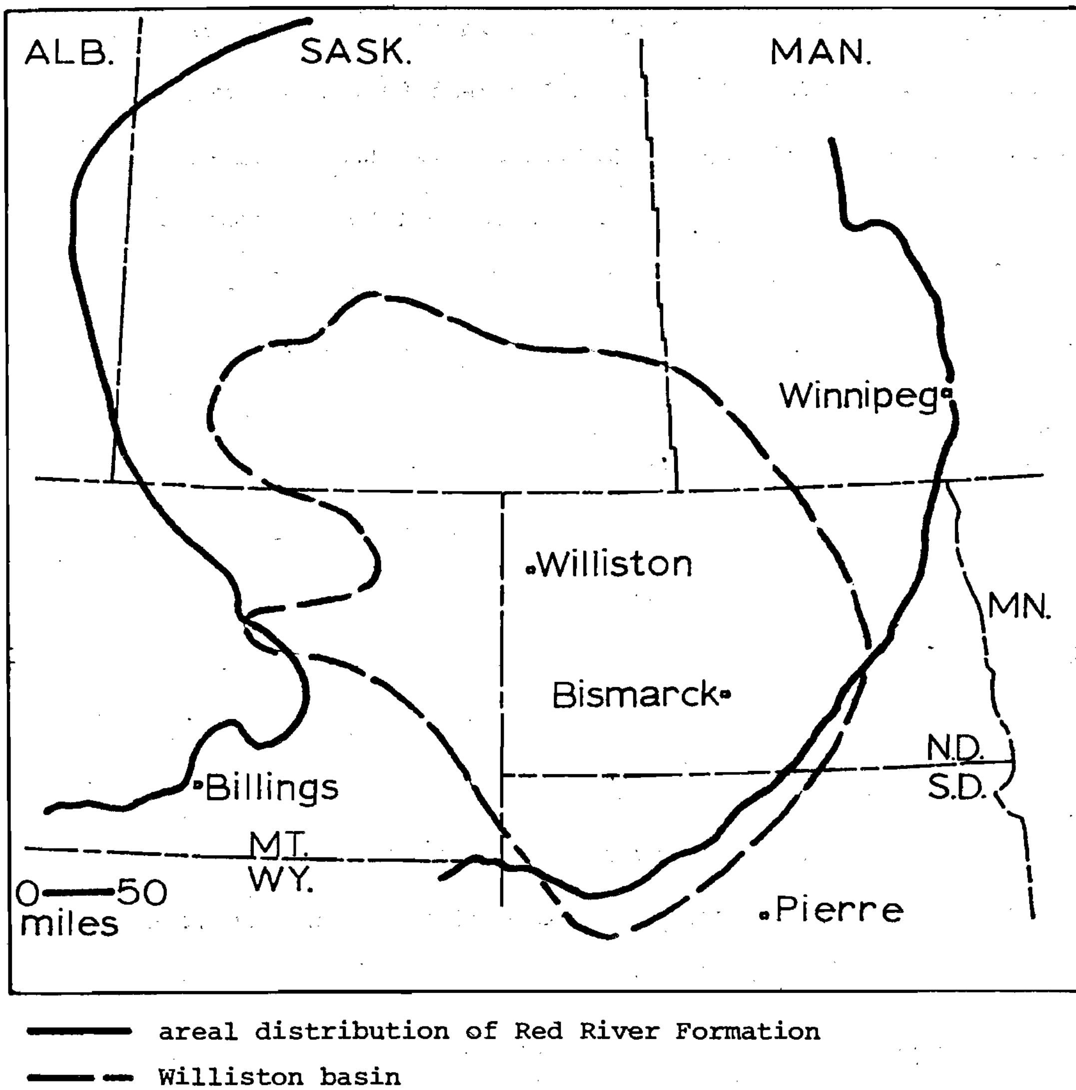

Fig. 1-- Outline of main part of Williston basin, and areal distribution of the Red River Formation (Modified from Carlson and Anderson, 1965; and Mallory, 1972).

basin the Stony Mountain shale, the lowest member of the Stony Mountain Formation, is absent and the top of the Red River is defined as a thin argillaceous layer five to twenty feet above the uppermost evaporite bed (Fuller, 1961).

The lower Red River comprises at least two-thirds of the formation, ranging from 400 to 550 feet thick. In the central basin, the basal part of the lower Red River consists of fossiliferous, bioturbated wackestone characterized by a mottled texture due to selective dolomitization. Toward the margin of the basin this unit becomes less fossiliferous and less mottled and grades into dense microgranular brown dolomites with occasional vugs. The upper part of the lower Red River consists of porous, fossiliferous, medium to fine-grained dolomitic wackestone that grades into dense, microgranular and lithographic dolomite near the margin of the basin (Porter and Fuller, 1959).

Maximum upper Red River thickness of 275 feet occurs in the basin center in Dunn County. The section includes four porosity zones, labeled "D" through "A" in stratigraphic order, separated by impermeable units of skeletal wacke-packstone and anhydrite (Figure 2). The "D" zone consists of variably dolomitized, stylolitic, burrowed,* skeletal mudstone and wackestone (terminology of Dunham, 1962). Non-porous, fossiliferous organic packstone units are interbedded with porous strata of the "D" zone.

Above the "D" zone, an ordered sequence of four lithologic units is repeated three times in vertical section. In stratigraphic order

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*In this paper, a distinction is made between "burrowed" and "bioturbated." Burrowed refers to primary fabrics in which the sediment has not been homogenized by biologic activity and individual, discrete burrows can be identified. Bioturbated refers to primary fabrics in which no individual burrows can be discerned, but biologic activity has completely reworked and homogenized the sediment.

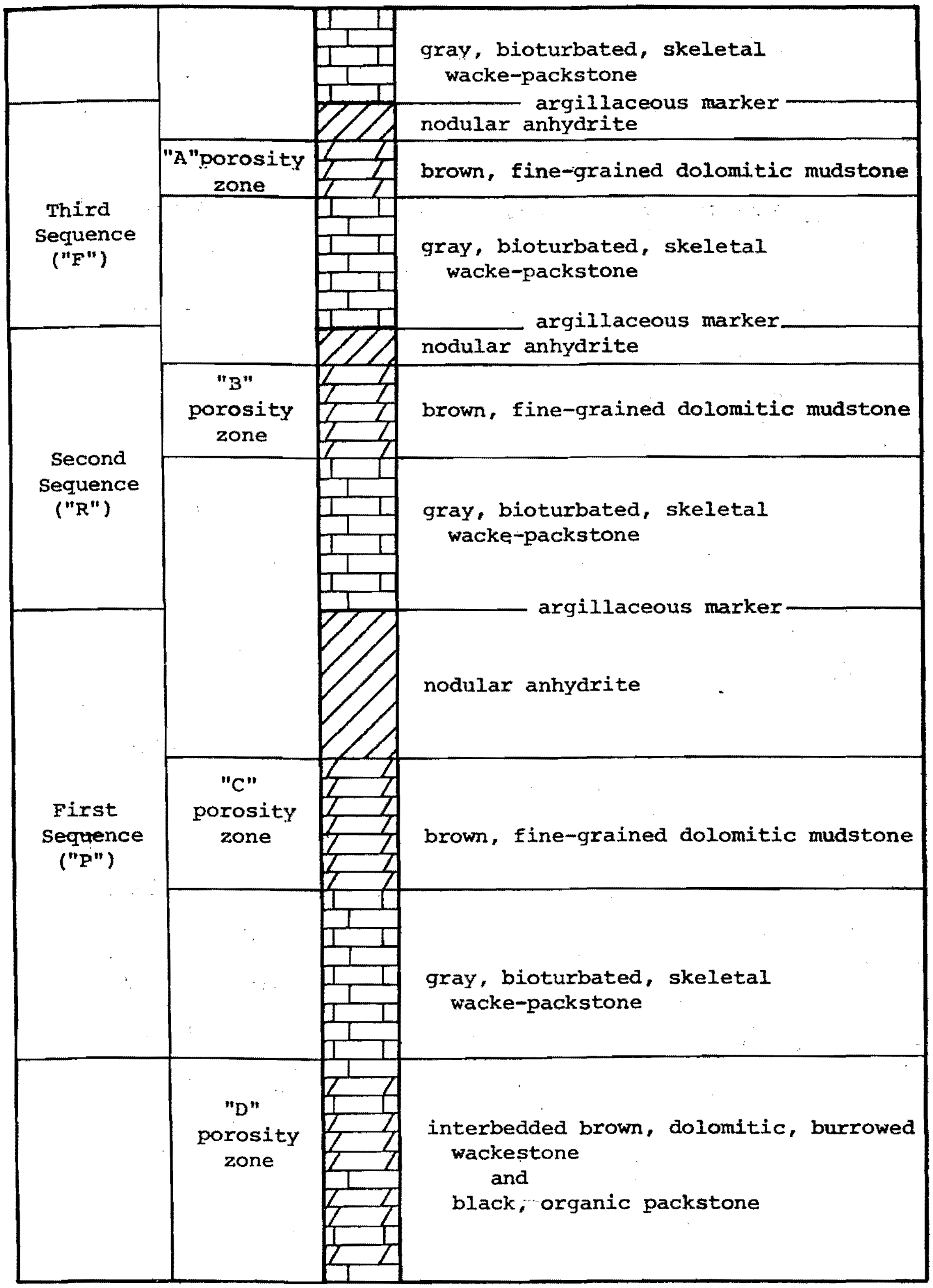


Fig. 2-- Upper Red River stratigraphic column.

each sequence consists of (1) impermeable, mottled, slightly dolomitic, bioturbated fossiliferous wackestone, (2) porous, laminated, fine-grained brown dolomitic mudstone, often containing small euhedral anhydrite crystals, (3) impermeable nodular anhydrite, and (4) a thin argillaceous bed that corresponds to a gamma ray log characteristic traceable throughout the basin.

A final unit of mottled, dolomitic, bioturbated skeletal wackestone, resembling the basal unit of each sequence, overlies the uppermost argillaceous marker and comprises the remainder of the upper Red River. In most wells studied, each sequence and each unit within a sequence is thinner than its preceding counterpart. In addition, the anhydrite units become progressively less widespread in each successive sequence. All three anhydrite units, however, are present in the basin center. The argillaceous marker at the top of the lowest sequence persists across the basin, but the upper two markers are less persistent and usually cannot be discerned on logs toward the periphery of the basin.

Previous Work

Foerste (1929) first applied the name "Red River Formation" to the carbonate sequence between the Winnipeg and Stony Mountain Formations, and divided it into the Dog Head, Cat Head, and Selkirk members (Figure 3). Porter and Fuller (1959) divided the formation into a lower unit of fossiliferous, dolomitic limestone, and an upper unit of cyclically deposited evaporites and carbonates; each cycle was subdivided into basal limestone, fine-grained dolomite, and anhydrite as described earlier in this paper. Baillie (1952) noted that the Dog Head, Cat

Sequence	System	Group or Formation
Absaroka	Permian	Spearfish
		Minnekahta
		Opeche
	Pennsylvanian	Minnelusa
		Amsden
Kaskaskia	Mississippian	Big Snowy Group
		Madison
		Bakken
	Devonian	Three Forks
		Birdbear
		Duperow
		Souris River
		Dawson Bay
		Prairie
		Winnipegosis
Tippecanoe	Silurian	Interlake
		Stonewall
	Ordovician	Stony Mountain
		Red River
		Winnipeg
Sauk	Cambrian	Deadwood

Fig. 3--North Dakota Paleozoic stratigraphic column.

Head, and Selkirk divisions that Foerste (1929) described in Lake Winnipeg outcrops are not traceable as such into the subsurface. Andrichuk (1959) formulated subsurface divisions that include a basal limestone, an intermediate dolomitic limestone and secondary dolomite, and an upper dolomite. Fuller (1961) and the Canadian Geological Survey (Sinclair, 1959) proposed a two unit division: a lower, variably dolomitized, marine fossiliferous limestone that includes about five-sixths of the thickness of the formation, and an upper section restricted to the basin interior that is evaporitic, thinly bedded, and of uniform thickness. Subsequent reports (Ballard, 1963; Friestad, 1969) support this two unit division.

Early investigators assigned both Richmondian (Bassler, 1915; Foerste, 1928; Hussey, 1926); and Trentonian (Dowling, 1900; Flower, 1952; Kay, 1935; Whiteaves, 1897) ages to the Red River Formation on the basis of fossil evidence. More recent work restricts the Red River to Richmondian age (Macauley and Leith, 1951; Ross, 1957; Twenhofel, 1954).

Tectonic Setting and History

The Williston basin is an intracratonic basin that forms the major structural feature in North Dakota and large parts of Saskatchewan, Manitoba, and South Dakota (Figure 1). Basin subsidence began in the Middle Ordovician (Sandberg, 1964), resulting in a shallow depression in which sand and shale of the Winnipeg Formation were deposited. Rate of subsidence increased and at the time of Red River sedimentation the basin was connected with the open ocean to the west (Figure 4). During lower Red River deposition the basin's center, as

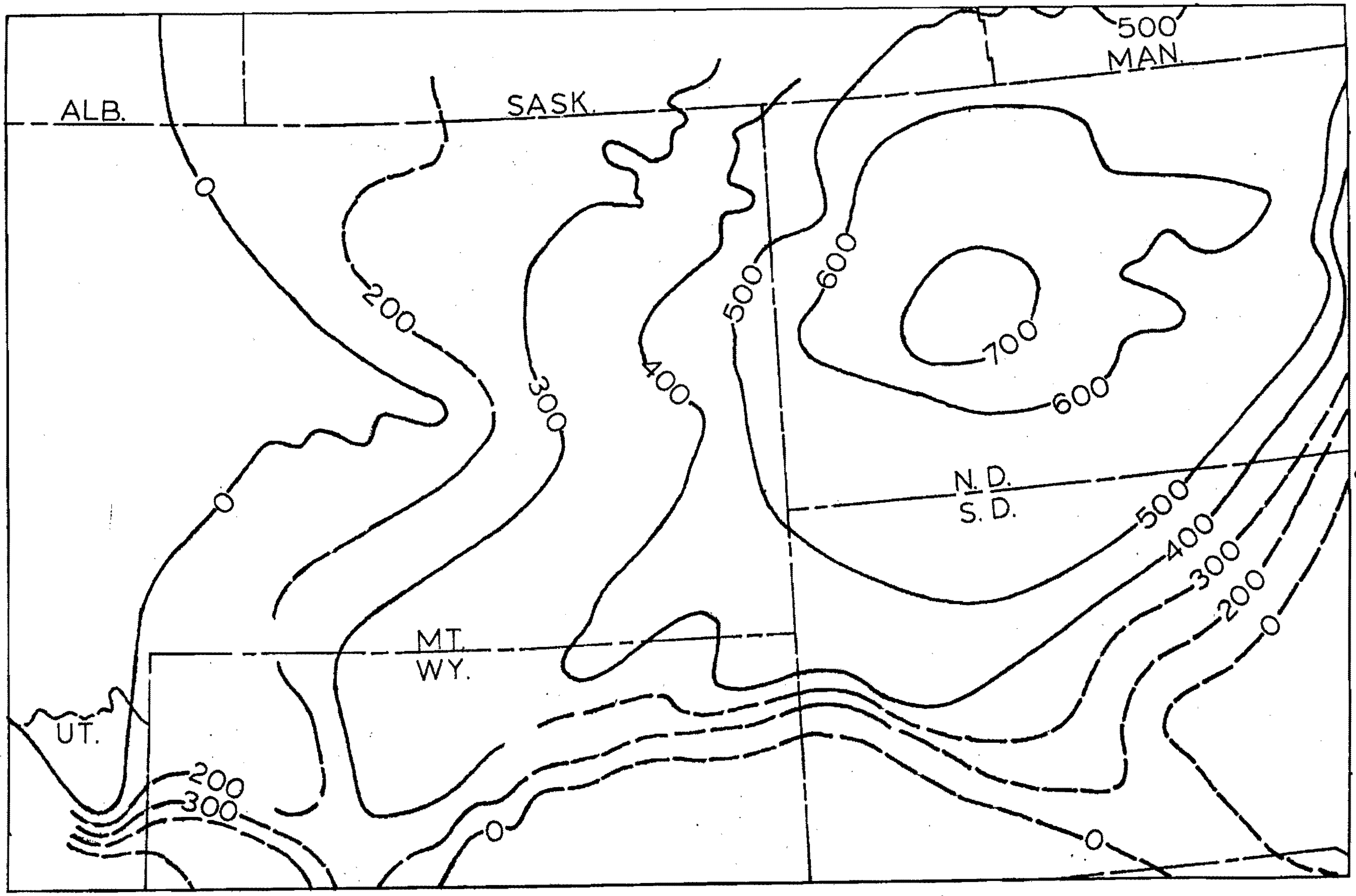
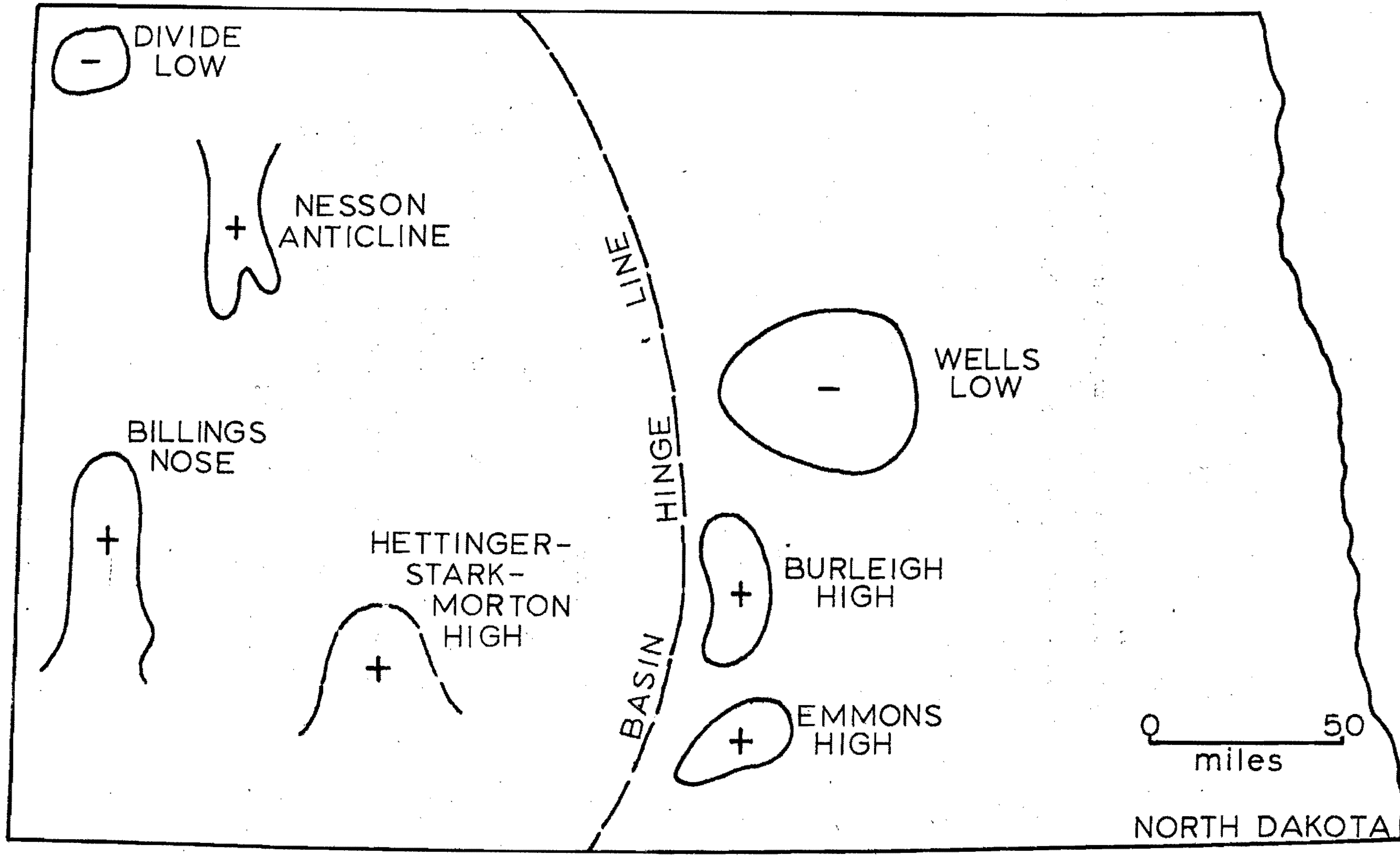


Fig. 4 -- Regional isopach of Red River Formation (Modified from Mallory, 1972, p.82).

indicated by maximum stratigraphic thickness, was in Oliver County in west-central North Dakota. The depositional center subsequently migrated northwest and during upper Red River sedimentation was in northeastern Dunn County. At present, the structural center of the basin is a few miles east of Williston, North Dakota.

Several structural or topographic features affected Red River sediment distribution as evidenced by thinning and thickening of Red River strata over the positive and negative relief areas respectively (Figure 5). A break in basin slope, sometimes referred to as the basin hinge line (Ballard, 1963), also produced a significant effect of sedimentation. This feature strikes north-south along 101° W. longitude and is concave toward the main part of the basin to the west. The hinge line marks a pronounced change from gently westward dipping strata on the basin's eastern flank to more steeply dipping strata in the basin proper. In addition, all Red River strata thin rapidly as they approach the hinge line from the west (Ballard, 1963). The lowest of the three anhydrite beds is present east of the hinge line and the depositional limits of the upper two lie at or west of the hinge line. The porous, fine-grained dolomites of the upper two evaporite sequences ("A" and "B") merge approximately at the hinge line, but the "C" dolomite may be traced separately for some distance farther east.

The north-south trending Nesson anticline in northwestern North Dakota was a prominent positive structural and topographic feature throughout the Paleozoic. Red River strata thin over the anticline forming combined structural and stratigraphic traps.



(+) positive elements (-) negative elements

Fig. 5 -- Approximate locations of structures affecting upper Red River sedimentation.

In Bowman County the Cedar Creek anticline existed as a topographic high, but except for small structural highs on the anticline itself, the feature was apparently inactive during the late Ordovician. Upper Red River strata maintain relatively constant thickness across the anticline.

Local thickness changes shown by an isopach map of the formation (Plate 1), indicate a number of minor structures that had less pronounced effects on Red River sedimentation. The Billings nose forms a prominent north-south trending structure in Billings County. The Divide low is a shallow depression in Divide County. The Emmons and Stutsman highs, in counties of the same name, are sub-circular structures of 20 to 30 feet maximum relief. The Burleigh high is a low relief structure elongate in a north-south direction. A relatively large high may exist in the Hettinger-Stark-Morton County area, but insufficient well control precludes defining it. Ballard (1963) suggests highs in Mercer, Ward, and Foster Counties similar to the Emmons and Stutsman highs. Upper Red River strata are unusually thick in Wells County, indicating a low area.

Comparison of isopach (Plate 1) and structure contour maps (Plate 2) indicates that topographic expression of most of the above features was eliminated by Red River sedimentation. Therefore, with exception of the Nesson anticline and perhaps the Billings nose, the structures were inactive during and after Red River deposition.

Purpose

The purpose of this study is to (1) reconstruct depositional environments through microfacies and regional lithofacies analysis,

(2) describe the types and origins of porosity within the upper Red River, and (3) explain the causes of localization of porosity development within the upper Red River. Depositional environment of the sediments and subsequent paragenesis constitute the two major elements investigated as factors responsible for porosity development.

Methods

This study concentrates primarily on examination of well cores and logs held by the North Dakota Geological Survey. As most cores are from wells in western North Dakota, it was necessary to rely on logs for stratigraphic correlation and facies interpretation in the central and eastern areas. Data analysis and interpretation are based on 213 well logs, 28 cores, and more than 500 petrographic thin sections.

Description of regional stratigraphy and major lithofacies of the upper Red River was accomplished by reconnaissance core study. Selected slabs, thin sections, and acetate peels were examined for constituent particles, mineralogy, and primary and secondary fabrics. These analyses, combined with lateral and vertical facies relationships, permitted reconstruction of paleo-depositional environments. Diagenetic history of all units was investigated, with emphasis on the known porosity zones. In addition to petrography, other techniques utilized for detailed study of the paragenesis included insoluble residue analysis, staining, X-ray diffraction, and cathodoluminescence.

"D" ZONE

Facies and Stratigraphy

The base of the "D" zone is chosen as the base of the upper Red River. The zone ranges from 50 feet thick, where identifiable near the edge of the basin, to a maximum of about 70 feet in the basin depocenter in Dunn County. It is continuous across the main part of the basin in North Dakota, and can be traced for varying distances onto the flank (Plate 3).

In Bowman County, the "D" zone is comprised of a sequence of two regularly interbedded primary facies (Figure 6). Units ranging from 5 to 23 feet thick of partially dolomitized, porous, burrowed brown mudstone and skeletal wackestone (Figure 7) are overlain by units 2 to 5 feet thick of impermeable, often laminated, slightly argillaceous, black organic skeletal wackestone and packstone (Figure 8). Abundant black organic material, occuring as dense laminations approximately 1 mm thick and as small dispersed flecks, characterizes these later units. Some of this organic material may have a kerogen-like character as suggested by Kendall (1974). White grainstone layers one to three inches thick occur intermittently within the organic beds and are sharply contrasted to the normally dark color of the units. Beds of dolomitic mudstone (Figure 9) one to four feet thick occur in addition to the two dominant "D" zone facies, either immediately above or below an organic unit.

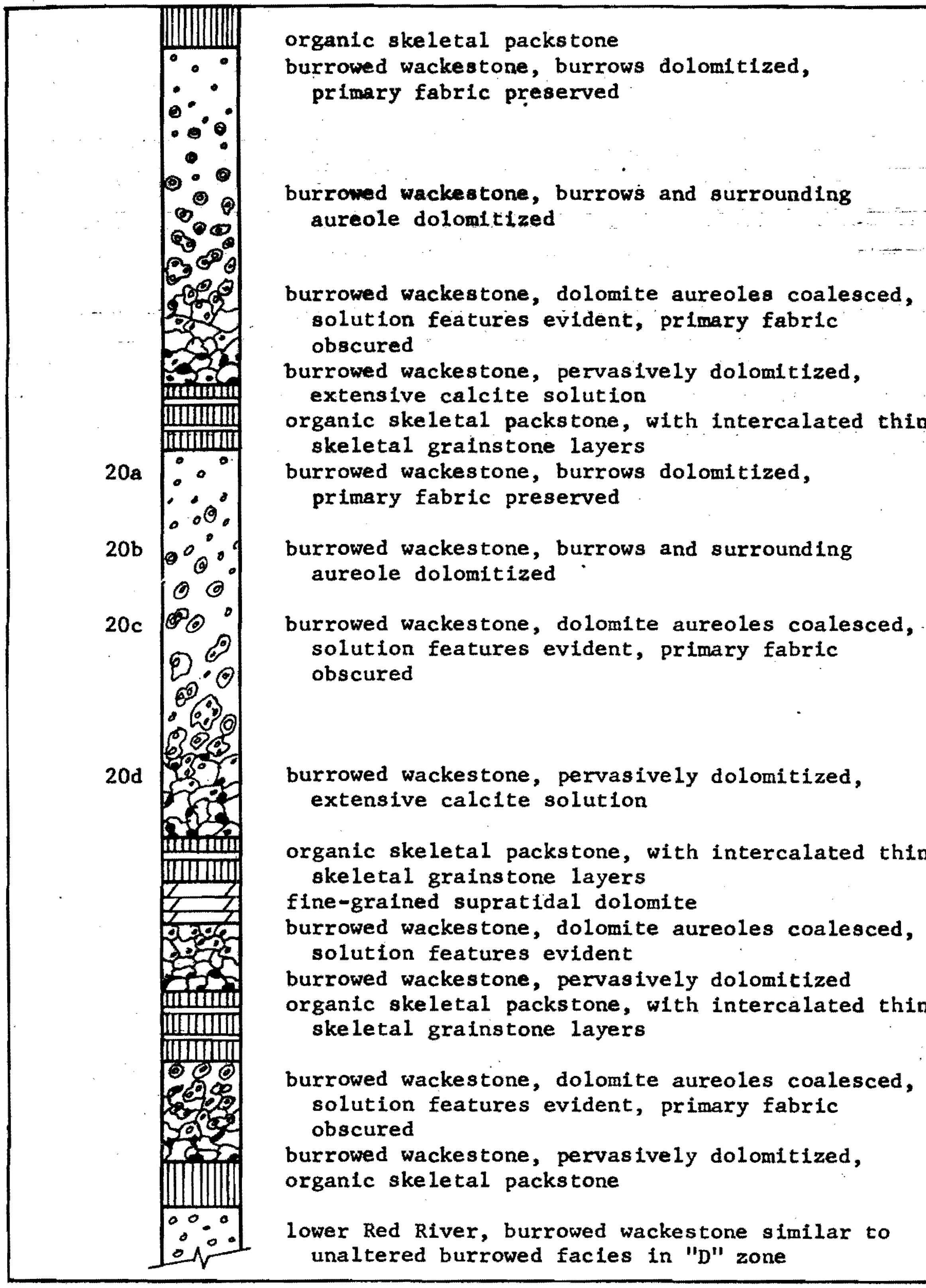


Fig. 6 --Idealized "D" zone stratigraphic column. Numbers to left of column correspond to figure of the same number.

Fig. 7 --Core slab of "D" zone burrowed facies, with minimum diagenetic alteration.

Fig. 8 --Core slab of "D" zone organic facies, showing typical laminated character. Note the light colored grainstone layers near the top of the photo.

Fig. 9 --Core slab of wispy laminated dolomitic mudstone that occasionally occurs interbedded with the two major "D" zone facies.

Fig. 7

Fig. 8

Fig. 9

The regular succession of the two "D" zone facies as diagramed in Figure 6 can be identified in cores and on logs along most of the margin of the main basin in North Dakota (Figure 10), but lack of cores prevents determination of exact lateral limits of its development. The succession is poorly developed in the center and deepest part of the basin, and is not present east of the basin hinge line. The zone is thickest at the center of the basin, and is comprised predominantly of the burrowed facies. Although present, units of the impermeable organic facies are not well developed nor as numerous in the basin center as toward the edge of the basin proper where five distinct units are recognized. The fine-grained dolomitic mudstone is present in the center of the basin in only one well.

Kendall (1974, p. 132) photographically illustrated "D" zone cores from southern Saskatchewan that bear a remarkable resemblance to cores of the same zone from Bowman County, North Dakota. Although he does not describe in detail the stratigraphic succession in that area, his photographs demonstrate that both the burrowed and organic facies are developed in the shallow part of the Williston basin to the north.

Environmental Interpretation

The burrowed wackestone fabric represents very shallow subtidal to low intertidal deposition. Infrequent desiccation fractures (Figure 11) indicate occasional subaerial exposure, probably of short duration. These units differ from underlying lower Red River strata and the basal unit of the overlying sequence in that individual discrete burrows, elongate and semi-circular in cross-section, are prominent in the "D" zone. By contrast, in the units above and below the "D" zone,

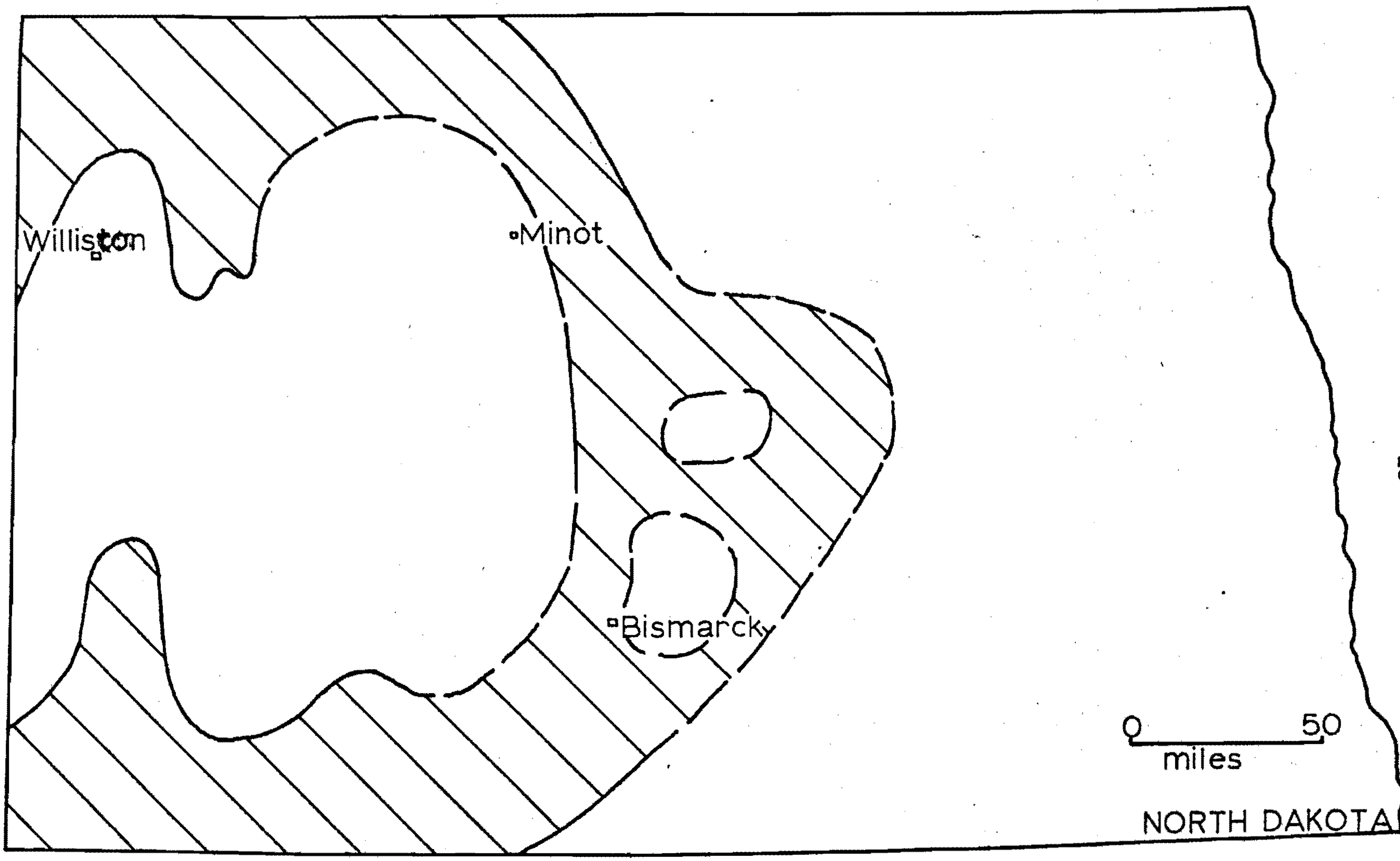


Fig. 10 -- Approximate area in which well logs indicate the presence of at least some alternating succession of "D" zone facies.

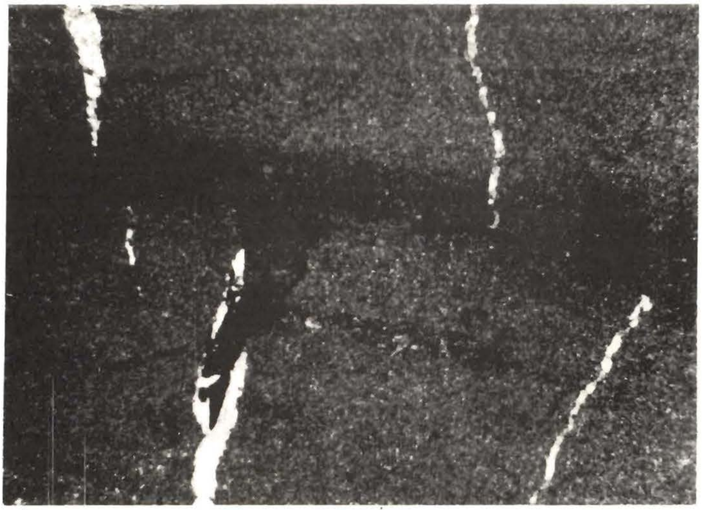
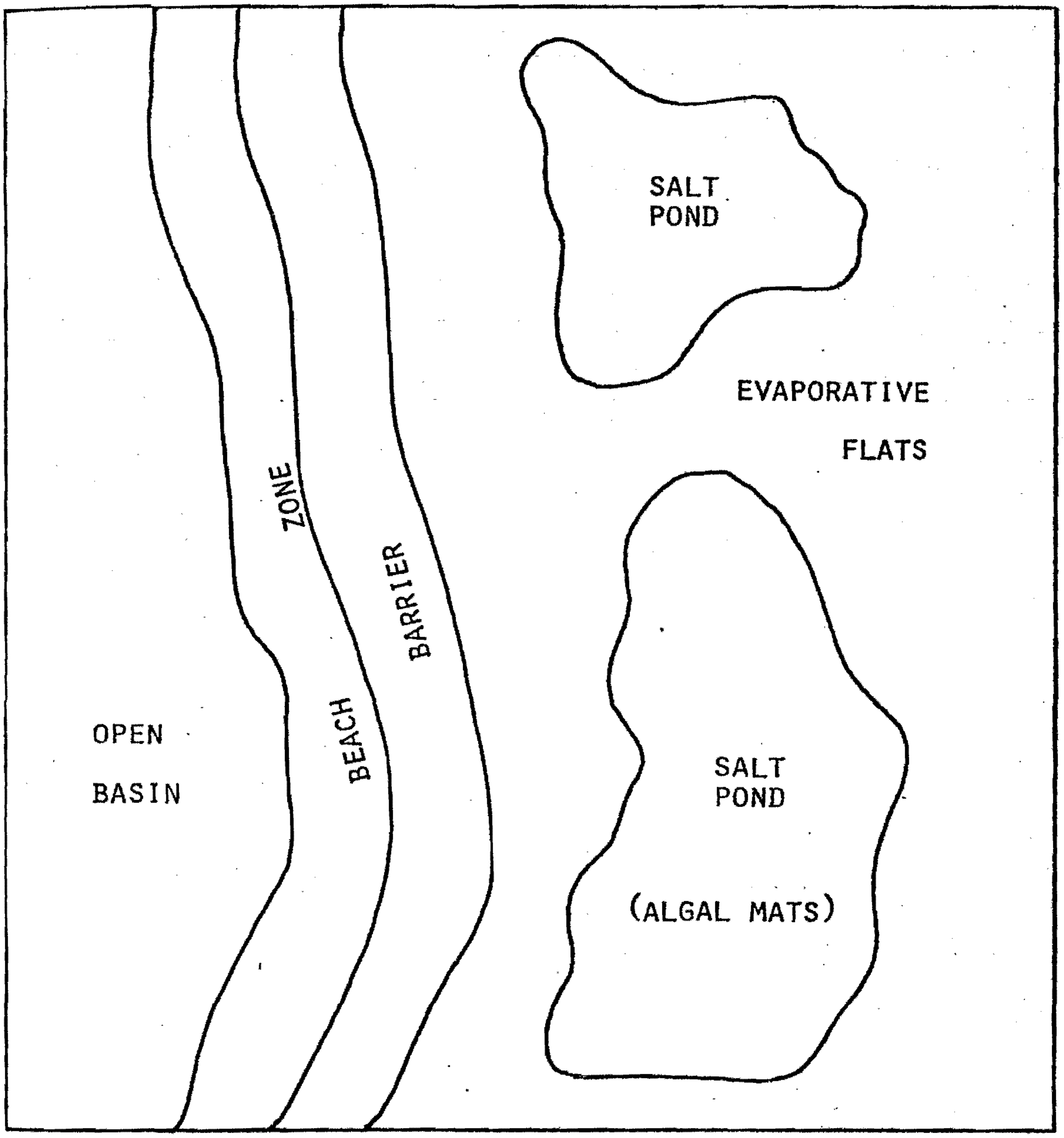


Fig. 11 --Photomicrograph of desiccation fractures in the "D" zone burrowed facies (plane polarized light).

bioturbation has completely homogenized the sediment and no individual burrows are discernible. Also in the "D" zone burrowed facies, fossil fragments are less abundant (mudstone to wackestone fabric) than in the overlying and underlying strata (generally wackestone to packstone fabric).

The differential degree of sediment reworking (burrowed versus bioturbated character) of the "D" zone burrowed facies relative to overlying and underlying strata may be a response to some change in biologic activity or physical conditions. The discrete burrows of the "D" zone may have been produced by a different assemblage of organisms that existed in the more thoroughly reworked strata. Alternatively, fewer and more discrete burrows may reflect a reduced biologic density relative to that in the subajacent and suprajacent strata. Higher salinity, shallower water, reduced circulation, or a combination of these factors may be the parameters that controlled the organisms or their activities responsible for the different fabrics.

Preservation of abundant organic detritus in the organic skeletal packstone units indicates some restriction of circulation. Sulfide minerals are not found in these units, therefore, while circulation may have been restricted, reducing conditions did not prevail. Deposition in a barred, intertidal to supratidal saline pond and evaporite flat environment is proposed for these beds (Figure 12). The area behind the bar probably was restricted from circulation with the open ocean and periodically inundated with sea water. Evaporation increased salinity in this broad pond or flat and a restricted fauna, principally algae and infaunal grazers, resulted in limited reworking of the



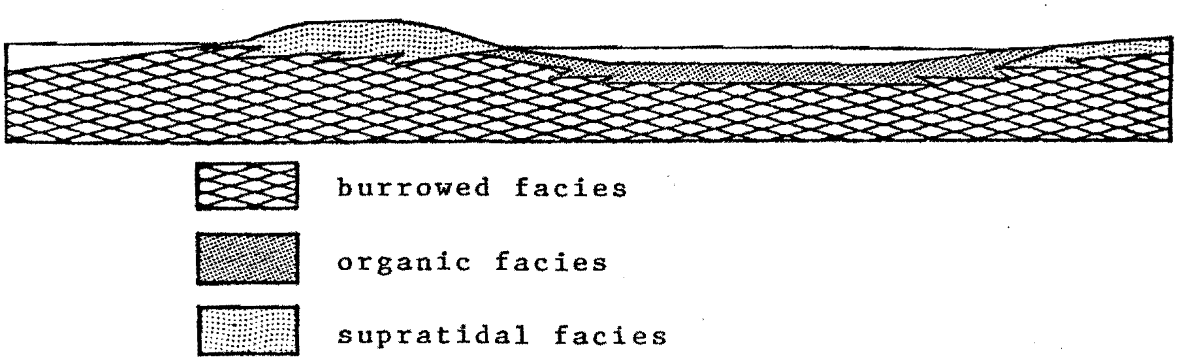


Fig. 12 --Interpreted depositional setting of "D" zone, based upon possible contemporary analog, Laguna Mormona, Baja, Mexico.

sediment. Although algal mat filaments are not preserved, abundant organic detritus and laminated sediment suggests prolific development of algal mats on the sediment surface of the shallow pond. Occasional storms or high spring tides breached the barriers and reflooded the ponds with sea water, carrying in abundant normal marine shells and fragments and orienting them preferentially to the flow. Periodic storms or high tides also explain the grainstone layers within the organic units.

A modern analog of this inferred deposition setting may exist at Laguna Mormona, Baja, Mexico (Horodyski, Bloeser and Vonder Haar, 1977; Horodyski and Vonder Haar, 1975) or the salt ponds on St. Croix, U.S.V.I. (personal observation, 1975). These ponds are approximately at sea level, are completely restricted from the open ocean by subaerially exposed dunes or bars, and are periodically flooded during storms when the barriers are breached. A very limited fauna inhabits these ponds due to high salinity and temperature, but algal mats proliferate. Shallow coring in Laguna Mormona demonstrates that discrete algal mats are not preserved greater than 10 cm below the sediment surface, but the sediment is highly organic and faintly laminated.

The fine-grained dolomitic mudstone that is sometimes present in the "D" zone is a supratidal deposit similar to the porous rocks comprising the overlying "A," "B," and "C" zones. These mudstones may represent an evaporitic flat landward of the ponds that was generally not preserved.

In Bowman County, five repetitions of the subtidal burrowed facies overlain by the intertidal, barred pond organic facies can be demonstrated in at least five cores. The base of the "D" zone, and thus the base of the upper Red River, is usually picked on logs at the lowest organic unit because porosity in the underlying burrowed facies is poorly developed due to factors considered in the following discussion. This lowest burrowed facies is gradational with the underlying lower Red River.

The laterally extensive and continuous nature of the subtidal burrowed facies indicates that the North Dakota part of the Williston basin was normally covered by very shallow water. Depositional environments were uniform from the center of the basin to the margins, where the character of the sediment changed from the subtidal burrowed facies to the barred intertidal pond organic facies. No rocks indicative of deeper water deposition are found, even at the center of the basin. As a result of the extremely low depositional slope, extensive lateral migration of one facies over another occurred commonly in response to minor sea level fluctuations, variations in rates of sediment accumulation, or both. Differential rates of sediment accumulation could be a result of storm deposition, current activity, or varying rates of physicochemical and biologic production of carbonate.

Diagenetic Fabrics

Several stages of diagenesis are recognized in the "D" zone, the chronology of which was determined by cross-cutting relationships (Figure 13). Each stage resulted in different recognizable characteristics, some of which caused porosity enhancement and others porosity occlusion.

The primary fabric of the burrowed facies was modified by three essentially syndepositional diagenetic processes. Dolomitization replaced the original micrite filling the burrows and, in many instances,

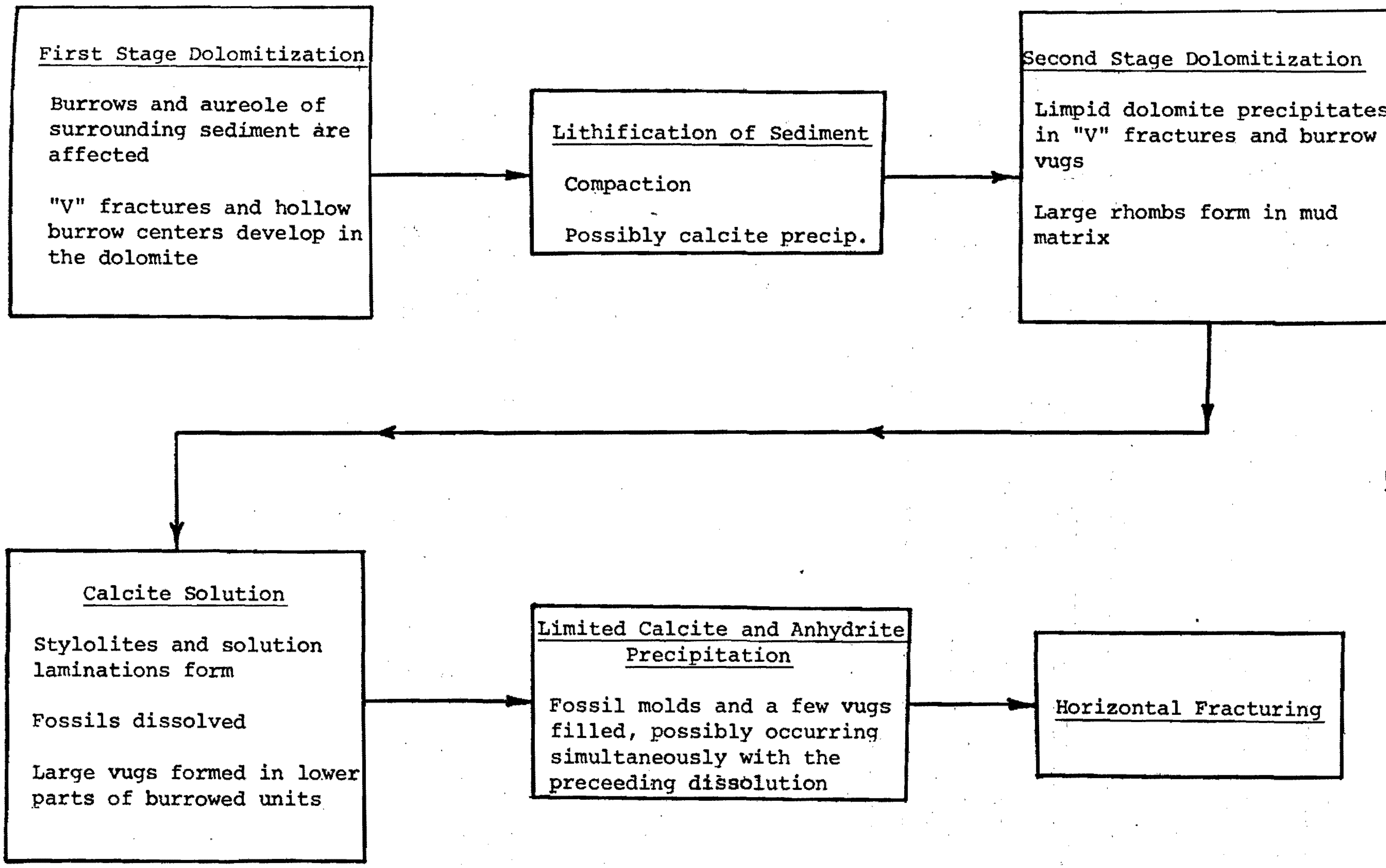


Fig. 13 -- Flow diagram of paragenesis in the "D" zone burrowed facies.

an aureole of sediment surrounding them. "V"-shaped fractures developed radially from the centers of the dolomitized burrows (Figure 14). The open ends of these fractures terminate at the edge of the dolomite, indicating that they developed prior to lithification of the enclosing sediment. In addition to the "V" fractures, a circular vug often formed in the dolomite at the center of a burrow. Where dolomite aureoles are developed, the entire burrow is sometimes hollow (Figure 15). Following these alterations, the main body of sediment was lithified.

A second post-lithification stage of dolomitization ensued, forming larger, clearer (limpid) crystals than produced by the first stage dolomitization. This second stage dolomite partially or completely fills the "V" fractures and voids at the centers of burrows (Figure 16). Large euhedral dolomite rhombs occur "floating" in the micrite matrix of the burrowed facies (Figure 17). These rhombs have an irregular distribution, though perhaps are more prolific near the base of each burrowed unit. These crystals are neither as cloudy as the first stage nor as clear as the second stage dolomite. Correspondence in size with the second stage dolomite suggests coeval formation.

Post-lithification and post-dolomitization solution of a substantial percentage of the skeletal fragments created fossil-moldic porosity. Abundant stylolites and solution laminations were also formed. These latter two features often outline dolomitized burrows or their aureoles, and in some instances truncate second stage dolomite (Figure 18).

Precipitation of calcite spar and minor quantities of anhydrite in many of the remaining burrow vugs, fossil molds, and "V" fractures resulted in approximately 20 to 50% porosity occlusion. Both minerals

Fig. 14 --Photomicrograph of dolomitized burrows, showing "V" fractures (plane polarized light).

Fig. 15 --Photomicrograph of dolomitized burrows, showing coalesced dolomite aureoles and hollow burrow centers (plane polarized light).

Fig. 16 --Photomicrograph of second stage dolomite partially filling cavity in the center of a dolomitized burrow (plane polarized light).

Fig. 17 --Photomicrograph of large dolomite rhombs "floating" in the mud matrix. Also note the mud that "dripped" into the "V" fractures before the mud was lithified, and the second stage dolomite that partially fills the "V" fractures (plane polarized light).

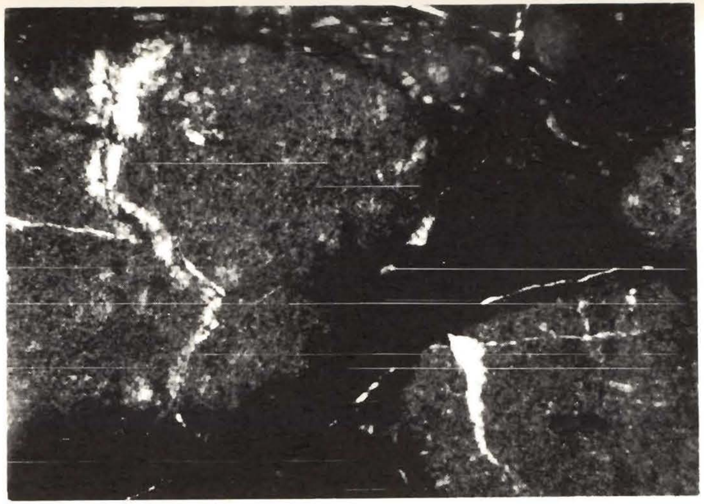
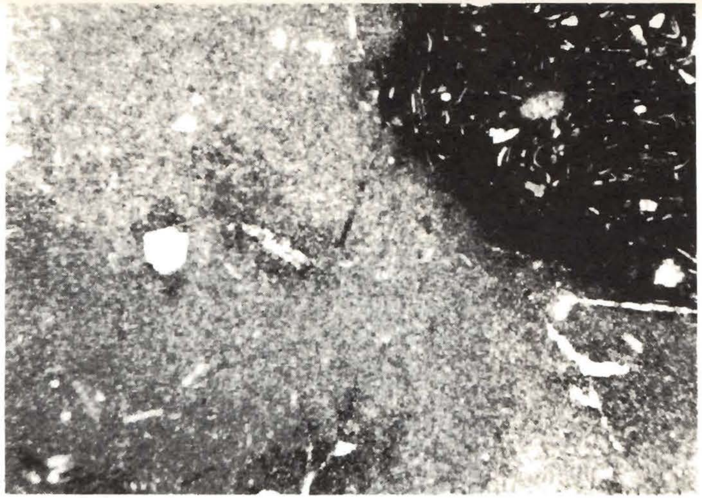


Fig. 14



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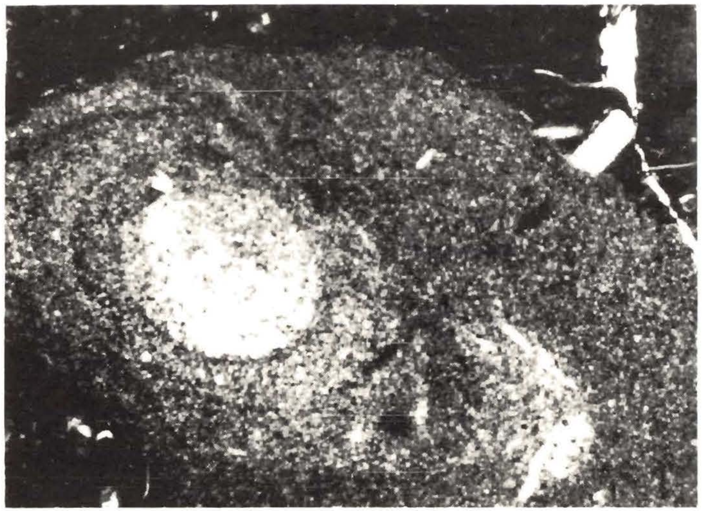

Fig. 16

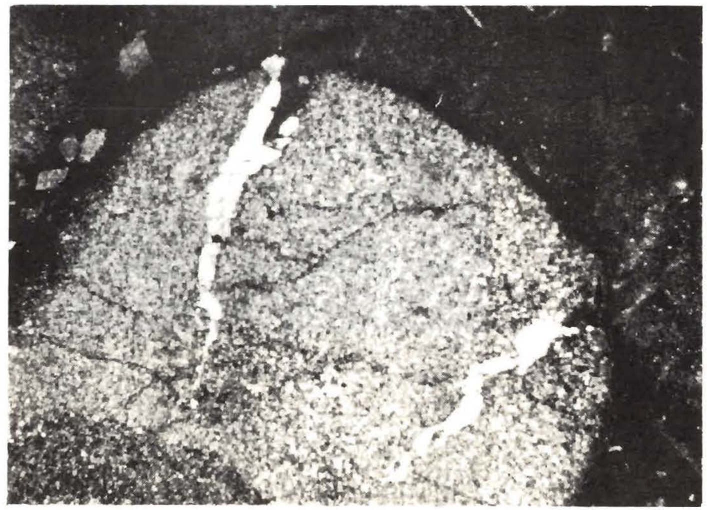

Fig. 17

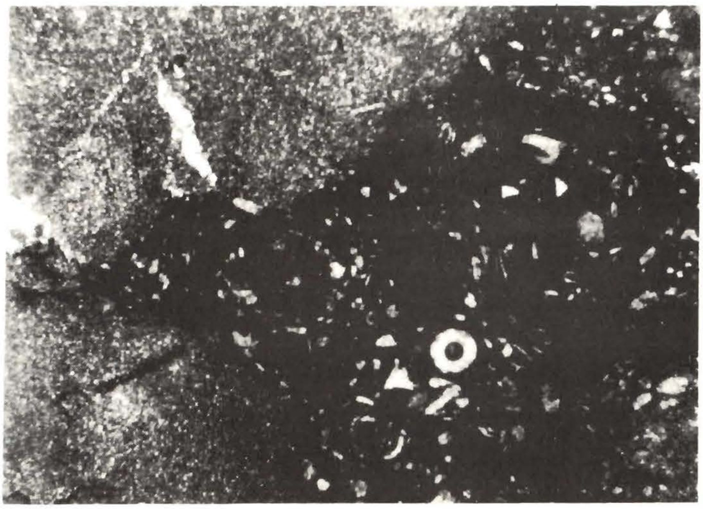

Fig. 18 --Photomicrograph of stylolites outlining dolomitized burrows (plane polarized light).

occur in single thin sections, however it has not been possible to ascertain the order of precipitation. Spar and anhydrite precipitation probably was penecontemporaneous with stylolitization.

Horizontal fracturing is the final stage of diagenesis, as these fractures cut across all other features. All such fractures observed are open, though in some cases minor quantities of microspar line the fracture walls. This fracturing is assumed to have occurred much later in the history of the rock, after stylolitization.

Diagenetic processes had considerably less effect on the organic units of the "D" zone than on the burrowed strata. In all cases, the primary fabric of the organic beds is easily discerned. Solution of many fossil fragments is the most apparent alteration, resulting in molds that have been refilled with spar or microspar (Figure 19). Stylolites occur in these beds, but are not as abundant as in the burrowed facies. This stylolitization, dissolution, and precipitation in vugs is considered to be a result of the same process responsible for similar features in the burrowed facies. Dolomitization in the organic beds is limited, and usually is associated with organic laminations. This may be a result of high initial Mg content in the organic matter (Gebelein and Hoffman, 1973). The organic units probably became impermeable shortly after deposition and initial burial due to compaction, oriented (flat-lying) fossils, organic laminations, high organic content, and presence of argillaceous material.

Increased diagenetic alteration and progressively greater porosity downsection can be demonstrated in each of the four burrowed facies in the "D" zone (Figure 6). Progressive increase in amount of first

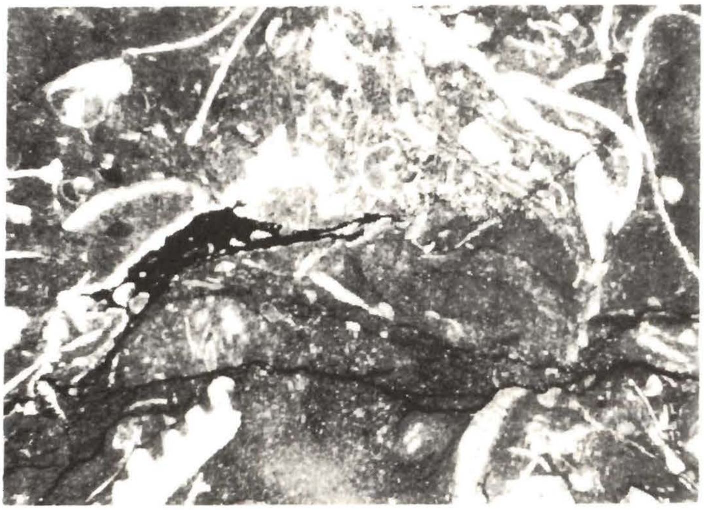

Fig. 19 --Photomicrograph of fossils in organic units that have been dissolved and replaced with microspar. Also note the organic laminations (plane polarized light).

stage dolomitization and more thorough dissolution of calcite toward the base of each unit occurs in all cases studied, and is most apparent in the thicker units. Near the top of a burrowed unit the primary rock fabric is preserved; usually only the burrows are dolomitized (Figure 20a). The main body of sediment was unaffected, presumably a result of preferential flow of intrastratal fluids through the burrows due to their greater primary porosity. First stage dolomitization increases downsection to include: (1) aureoles of dolomitized sediment immediately surrounding burrows (Figure 20b), (2) coalesence of aureoles (Figure 20c), and (3) immediately above the underlying organic bed, pervasive dolomitization which completely obscures the primary rock fabric (Figure 20d). Virtually no calcite solution occurs near the top of a burrowed unit, whereas at the base, elongate or irregularly shaped vugs up to 1 cm in diameter and 5 cm in length are present. In many instances calcite solution at the base of a burrowed unit is so complete that only uncemented first and second stage dolomite crystals remain (Figure 21).

Diagenetic Mechanisms

First stage dolomitization occurred by mixing of fresh and sea water in the phreatic zone of the intertidal environment (Figure 22). Astronomic tides and minor sea level fluctuations induced by barometric pressures and wind stress (Illing, Wells and Taylor, 1965; Kerr and Thomson, 1963) caused extensive ebb and flow across broad tidal flats. When the flats were flooded, sea water percolated into the sediment preferentially through the more porous burrows and mixed with the continental fresh water lens. As noted by Badiozamani (1973), fresh water

Fig. 20 --Sequence of core slab photographs top to bottom in a burrowed unit of the "D" zone, showing progressive dolomitization and calcite solution down-section.

(a) burrows dolomitized, some dolomite aureoles developed, low porosity, primary fabric essentially intact.

(b) dolomite aureoles coalesced, some solution laminations that outline dolomitized areas, limited porosity.

(c) more thorough dolomitization than in (b), solution laminations, porous, primary fabric obscured.

(d) pervasive dolomitization, solution vugs and laminations, primary fabric completely obscured, excellent porosity.

(a)

(b)

(c)

(d)

Fig. 20

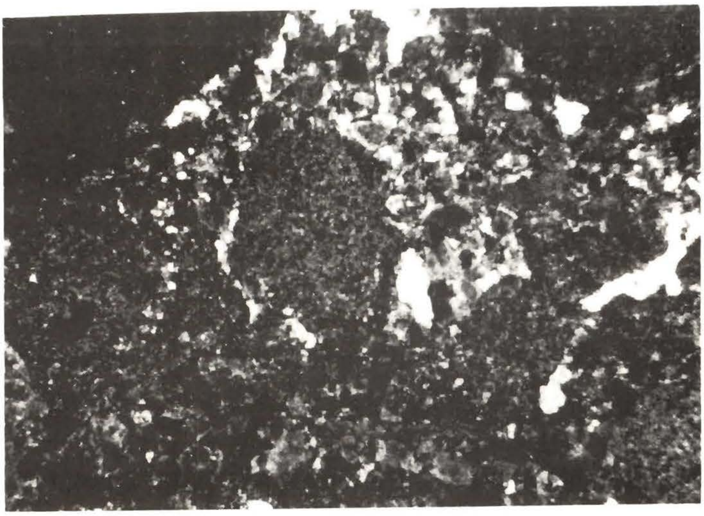

Fig. 21 --Photomicrograph of lowest horizon of a burrowed unit in the "D" zone, showing the remaining first and second stage dolomite after pervasive calcite solution. White areas are voids (plane polarized light).

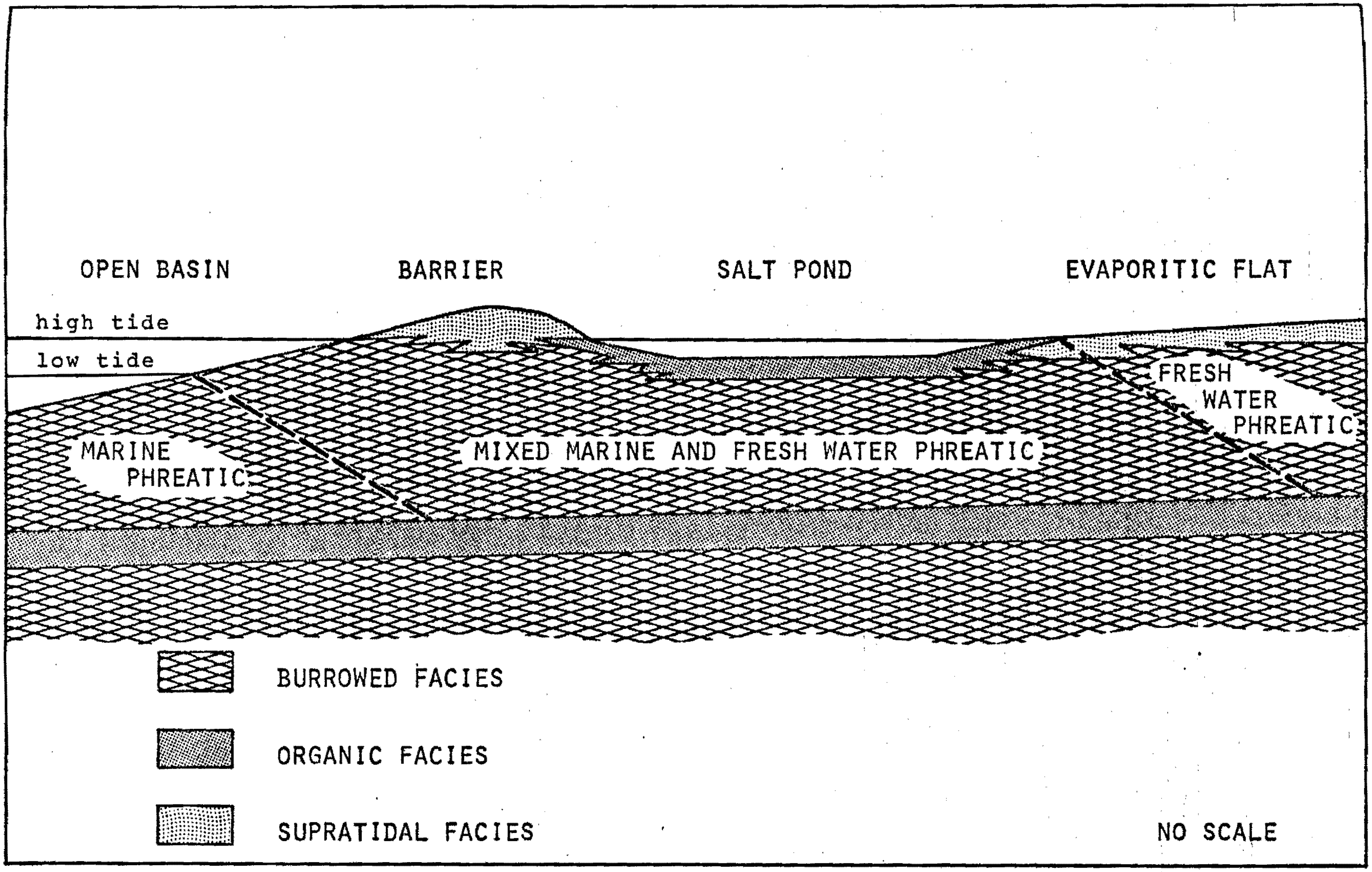

Fig. 22 --Interpreted lateral and vertical relationships of dolomitizing solutions and sedimentary facies in the "D" zone.

dilution of marine water reduces salinity and raises the Mg/Ca ratio; dolomite precipitates when Mg/Ca approaches a 1:1 ratio providing there is a concommitant reduction of salinity (Folk and Land, 1975). It is proposed that first stage dolomitization of near surface sediments occurred penecontemporaneously with sedimentation in the intertidal or very shallow subtidal zone as a consequence of periodic mixing of fresh and marine waters. First stage dolomitization was limited to the sediment above the underlying organic unit, due to the impermeability of that unit. Thus, the zone of mixed fresh and marine phreatic waters was effectively perched. The most extensive mixing, and therefore the most dolomitization, occurred immediately above this organic bed where variable surface conditions had the least affect. More dolomitization also occurs at the base of a burrowed unit due to greater residence time of the well-mixed fresh and sea waters. The sediment-water interface was the upper edge of the mixing zone, but the sediment at the surface was alternately flushed with sea water and fresh water, resulting in very little mixing and reduced dolomitization.

Interstitial movement of dolomitizing fluids also seems to enhance dolomitization (Deffeyes, Lucia and Weyl, 1965; Folk and Land, 1975; Hanshaw, Back and Deike, 1971). Two mechanisms may have acted to move these solutions. Rising tide caused sea water to infiltrate the sediment and raise the water table, and the hydrostatic head of this higher water table forced the fresh water lens and the mixing zone landward. As the tide ebbed, the fresh water hydrostatic head pushed the mixing zone seaward. Depending upon the magnitude of the tides or sea level fluctuations induced by barometric pressure and wind stresses, and permeability of the sediment, lateral movement of the mixing zone could have been considerable over the broad, low relief tidal flats. Movement of the mixing zone was also controlled by the size of the fresh water lens. As the size and thereby the hydrostatic pressure of the fresh water lens increased, the mixed water was forced seaward. Movement of the mixing zone as a result of this mechanism was probably a seasonal phenomenon.

First stage dolomitization of a burrowed unit was terminated by deposition of the overlying organic bed, which due to its low permeability, reduced or cut off the supply of dolomitizing fluids. Termination of first stage dolomitization in a particular burrowed unit was therefore essentially simultaneous with cessation of deposition of that unit. The mixing zone was now perched on the overlying organic unit, and began dolomitizing sediments in the next overlying burrowed unit as they were deposited.

Replacement of calcite by dolomite can result in a 12 to 13% volume reduction (Landes, 1946; Murray, 1960; Weyl, 1960). The "V" fractures probably formed during first stage dolomitization as shrinkage fractures resulting from this volume reduction. The small vugs at the centers of dolomitized areas are also attributed to the dolomitization process; whereas the path of greatest flow of the dolomitizing fluid was the burrow, and sediment surrounding this path was dolomitized, sediment within the burrow itself was dissolved. No positive proof of this mechanism can be demonstrated, however, a similar phenomenon has been observed on a larger scale in Bermuda (F. T. MacKenzie, personal communication, 1978). An alternative explanation is that dolomite in the burrows was dissolved after "D" zone deposition and dolomitization was complete and normal sea water again flooded the area.

Lithification of the main body of sediment followed first stage dolomitization probably as a result of compaction and calcite cementation.

Second stage dolomitization is post-lithification and probably occurred after deposition of the overlying evaporites ("C" zone and its associated anhydrite). Fresh continental water percolated downward and seaward through the underlying "D" zone strata and mixed with the normal marine intrastratal water in "D" zone vugs and fractures. Limpid dolomite precipitated in these voids, in a process similar to the mixed sea water-fresh water (Dorag) mechanism of Badiozamani (1973). The large euhedral rhombs floating in the mud matrix also formed at this time. It has not been possible to establish rhomb development in a chronological relationship with other features in the rocks, other than that they are probably post-lithification and pre-stylolitization. Folk and Land (1975) have suggested that large, relatively clear (limpid) crystals of dolomite form slowly. Inasmuch as formation of fine-grained dolomite is inferred as a relatively rapid, syndepositional process, second stage dolomitization is considered to be responsible for the euhedral, limpid rhombs. Apparent increase in the number of rhombs toward the base of some of the burrowed units is probably due to later solution of calcite, causing the dolomite rhombs to become more closely packed together.

Subsequent calcite dissolution which created stylolites, fossil molds, and vugs probably resulted from subaerial exposure of the basin following each period of evaporite deposition, as well as during later, more prolonged periods of subaerial exposure such as at the end of the Silurian. During these exposures, fresh water percolating through the rocks dissolved calcite mud matrix and fossil fragments. Intrastratal flow in the "D" zone was intensified in the lower parts of the burrowed units immediately above each impermeable organic bed, and therefore maximum dissolution occurred at these horizons. As the solution became saturated, calcite precipitated in molds and vugs within the burrowed wackestone until the solution was again undersaturated with respect to calcite. This process probably recurred with each exposure of the basin. Probably during the times of calcite precipitation, anomolous conditions related to the solutions or the enclosing strata caused minor quantities of anhydrite to precipitate.

Horizontal fracturing occurred at a later but undetermined time. In Bowman County, any of several later movements along the Cedar Creek anticline may be responsible. The cause of fractures elsewhere in the basin is unknown.

Porosity Development

Porosity in the burrowed facies developed due to diagenetic changes in the primary rock fabric. The paragenesis outlined indicates at least five instances of porosity enhancement; first stage dolomitization, "V" fracturing and formation of vugs in burrows, formation of fossil molds and vugs through calcite dissolution, and horizontal fracturing. Partial porosity occlusion resulted from precipitation of second stage dolomite in "V" fractures and vugs, and calcite and anhydrite precipitation within secondary solution vugs and fossil molds. The intercrystalline porosity that developed during first stage dolomitization and later vugs developed during calcite solution of the matrix, particularly near the base of each burrowed unit, account for most remaining porosity.

Porosity development in many cases is controlled by small topographic highs over pre-existing structures approximately 2 to 5 miles wide and 3 to 10 miles long that exist throughout the basin. These local highs are reflected by depositional thins that form many productive structural-stratigraphic traps in North Dakota. These features are most apparent in Bowman County where well control is best, but limited well control in McKenzie and Dunn Counties suggest similar features. Porosity in the "D" zone is best developed on the flanks of these positive elements, while the tops of the structures often lack adequate porosity for hydrocarbon production. One explanation for this situation is that as the mixing zone oscillated, dolomitizing solutions followed the easiest path of flow, going around rather than over the highs. The same deflection of flow occurred with vug-forming solutions. As a result, crests of topographic highs are neither as intensely dolomitized nor as thoroughly dissolved as the adjacent strata along their flanks.

In the center of the basin, "D" zone porosity is frequently poor and erratic in occurrence. This may be explained by the sporadic occurrence of organic-rich impermeable beds in the basin center; in absence of laterally continuous impermeable barriers, intrastratal solutions were not vertically confined to horizontal planes of flow and, instead, flow was more diffuse throughout the "D" zone. Lack of an impermeable barrier beneath the lowest burrowed unit, generally considered to be below the "D" zone, also accounts for its poorly developed porosity despite a primary fabric identical to the overlying porous units.

"A," "B," AND "C" ZONES

Facies and Stratigraphy

The "A," "B," and "C" porosity zones of the upper Red River resulted from three similar depositional episodes, labeled "P," "R," and "F" from oldest to youngest (Ballard, 1963), and are treated together in this paper. A succession of three distinct lithologic facies comprise each of the three depositional episodes: basal wacke-packstone overlain by dolomitic mudstone, capped by nodular anhydrite (Figure 2).

The basal unit of each sequence is a light to dark gray, slightly dolomitic, bioturbated, sparse skeletal wackestone to packstone (Figure 23). Groups of brown to black, sub-parallel and sub-horizontal, wavy laminations of organic detritus are abundant throughout these units. Brachiopods, echinoderms (predominantly crinoids), bryozoans, trilobites, and occasional corals (predominantly rugose) characterize the fossil assemblage. As a rule, these strata are impermeable, though small solution vugs are occasionally present. Near the top of many of the wacke-packstone units, clear microspar rather than micrite constitutes a large percentage of the matrix material (Figure 24). Such beds usually have packstone rather than wackestone fabrics, contain abundant mudstone intraclasts, and are gradational with the underlying wackestone. Thin horizons of sparry packstone also occasionally occur throughout the wackestone.

Fig. 23 --Core slab of basal wacke-packstone. Note wavy organic laminations.

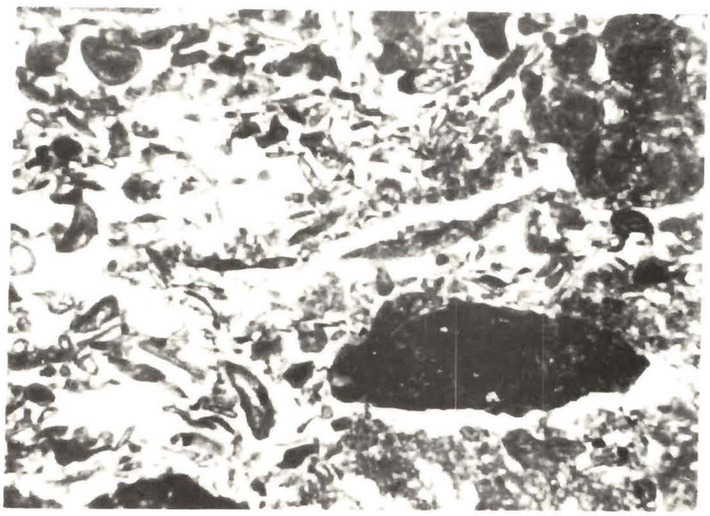

Fig. 24 --Photomicrograph of intraclastic, skeletal, sparry packstone. White areas are microspar (plane polarized light).

Fine-grained, dolomitized brown mudstone with good intercrystalline porosity overlies the basal wacke-packstone (Figure 25). These porous dolomitic mudstones form the actual "A," "B," and "C" zone reservoirs. These units contain desiccation features (Figure 26), abundant individual and massed acicular anhydrite crystals (Figure 27), subaerial laminated crust (Figure 28), pelletal fabrics (Figure 29), and erosional surfaces with associated intraclasts (Figure 30). Although these strata consist principally of fine-grained dolomite, primary sedimentary fabrics, for example the fine laminations in Figure 26, are clearly preserved. Interbedded with the fine-grained dolomitic mudstone are occasional horizons of undolomitized micrite (Figure 31) showing the same primary mudstone fabric as is preserved in dolomitized horizons. Both dolomitized and undolomitized strata vary from wispy laminated and almost featureless rocks (Figure 32), to densely laminated horizons which may be algal mats (Figures 33, 34). Infrequent burrows usually are more thoroughly dolomitized and contain slightly larger dolomite crystals than the enclosing sediment. Gastropods and brachiopods are the most common constituents of the very sparse fossil assemblage. Near the base of the units, fossil content often increases and the rocks are predominantly wackestones. In three cores studied, the Depco, Inc.--13-27 Hughes in Bowman County, the Lion Oil Co.--Erickson #1 in Bottineau County and the Pure Oil Co.--J. M. Carr #1 in Foster County, the "B" zone is represented by a white, sometimes vuggy and poorly cemented, very fine-grained chalky dolomite (Figure 35).

Impermeable nodular anhydrite and interlaminated anhydrite and dolomite overlie the fine-grained dolomitic mudstones and comprise the

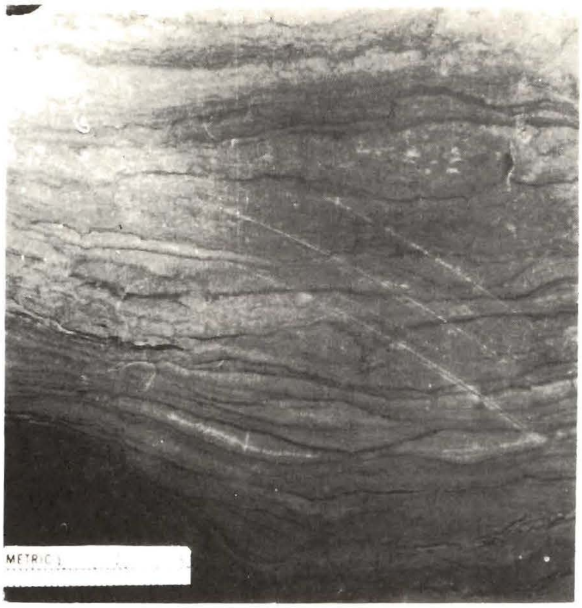

Fig. 25 --Core slab of wispy laminated, porous dolomitic mudstone. Note desiccation features along right-hand side.

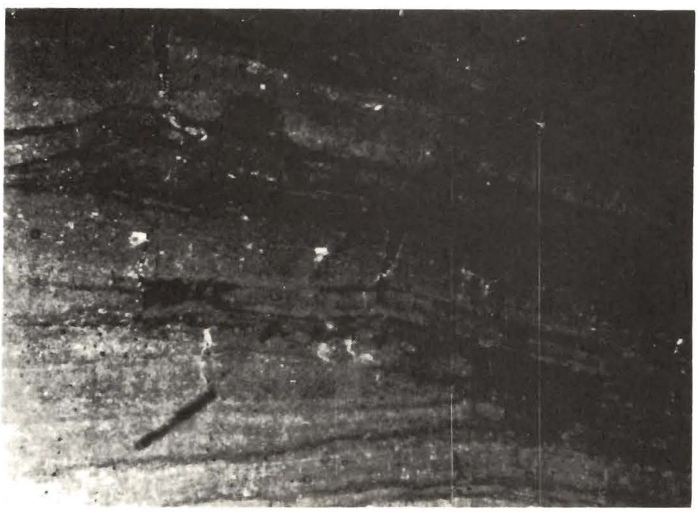

Fig. 26 --Photomicrograph of desiccation fractures. Rock is greater than 50% dolomite. Note oil stain right of center that follows primary fabric (plane polarized light).

Fig. 27 --Photomicrograph of acicular anhydrite crystals in dolomitic mudstone (plane polarized light).

Fig. 28 --Photomicrograph of subaerial laminated crust in dolomitic mudstone. White areas are voids (plane polarized light).

Fig. 29 -- Photomicrograph of pelletal packstone fabric in dolomitic mudstone. Pellets are calcite, clear cement is dolomite (plane polarized light).

Fig. 30 --Photomicrograph of cut and fill structure with associated intraclasts in dolomitic mudstone (plane polarized light).

Fig. 27

Fig. 28

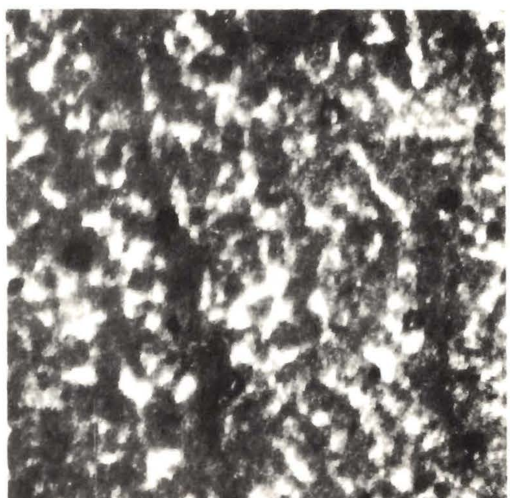

Fig. 29

Fig. 30

Fig. 31 --Core slab of undolomitized mudstone.

Fig. 32 --Core slab of thinly bedded dolomitic mudstone.

Fig. 33 --Core slab of possible algal mats in dolomitic mudstone.

Fig. 34 --Photomicrograph of possible algal mats in dolomitic mudstone. Most white areas are microspar (plane polarized light).

Fig. 31

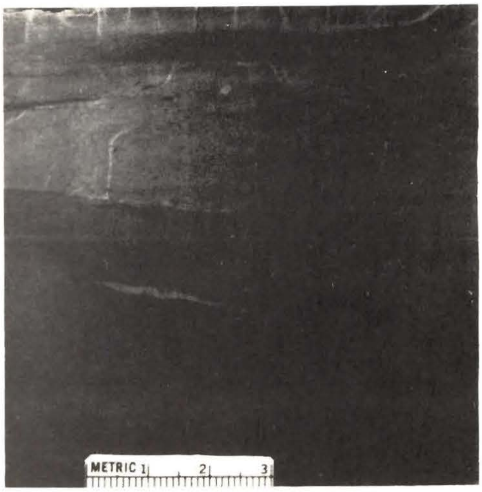

Fig. 32

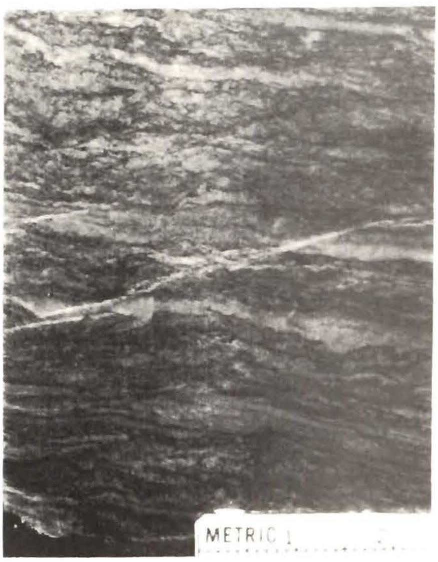

Fig. 33

Fig. 34

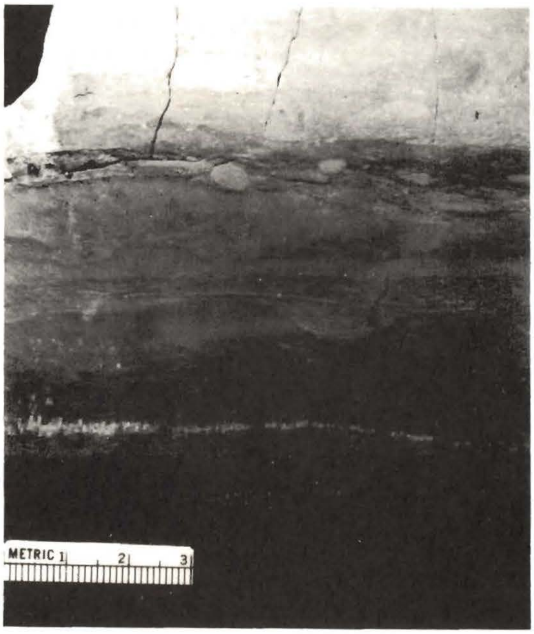

Fig. 35 --White, very fine-grained, chalky dolomitic mudstone

third unit of each sequence (Figures 36, 37). In a number of wells in Bowman County, including the well containing the chalky white dolomite, the dolomitic mudstones do not have anhydrite caps.

An argillaceous marker bed immediately on top of each anhydrite can be traced across the basin as a positive gamma ray log characteristic. In cores, this marker is a non-calcareous, dark gray fissile shale approximately one inch thick. The first one or two feet of wacke-packstone above this shale often contain intraclasts of fine-grained dolomite and may be slightly argillaceous fine-grained dolomitic mudstones similar to those below the anhydrite units. This occurrence is most frequent in the "R" and "F" sequences.

Overlying the third and uppermost argillaceous marker, another bed of wacke-packstone, variably dolomitized and sometimes slightly argillaceous, comprises the remainder of the upper Red River. The Red River--Stony Mountain contact is marked by a pronounced increase in argillaceous material.

Each of the three sequences is of fairly uniform thickness throughout the basin, but become progressively thinner toward their respective depositional limits (Plate 3). The stratigraphically lowest or "P" sequence ranges from 45 to 75 feet thick; the porous "C" zone within it is 25 to 60 feet thick with an average of 30 to 40 feet in the central basin. The thickest "C" zone strata in North Dakota occur just east of the basin hinge line, along the eastern edge of the central basin, where the entire sequence consists of porous dolomite capped by a thin anhydrite bed. The "R" depositional sequence ranges from 30 to 70 feet thick and averages around 60 feet thick in the

Fig. 36

Fig. 37

Fig. 36 --Core slab of nodular anhydrite.

Fig. 37 --Core slab of nodular anhydrite and thinly bedded anhydrite. Note soft sediment deformation structure at top of photo.

central basin. From the central part of the basin, the "R" sequence thins to the east and eventually coalesces with the overlying "F" sequence. The "B" zone within the "R" sequence averages only 12 to 14 feet thick. The uppermost or "F" sequence is 25 to 30 feet thick, with the porous "A" dolomite 2 to 6 feet thick.

The minimum areal distribution of each sequence is approximated by the limits of their respective anhydrite units (Figure 38). The capping anhydrites in each sequence are more laterally restricted than the underlying wackestone and dolomitic mudstone facies. The "A" zone of the uppermost "F" sequence is the least widespread of the three porosity zones, and in North Dakota disappears along a line west of but parallel to the basin hinge line. The wacke-packstone unit above the "F" sequence is approximately 40 feet thick near the basin center, but thins to the east and is non-existent in eastern North Dakota.

Environmental Interpretation

During deposition of each of the three sequences of the upper Red River, the Williston basin was inundated with shallow, normal salinity, open marine water. The basin was bordered by broad intertidal and supratidal flats, probably similar to sabkha environments of the Persian Gulf (Illing, Wells and Taylor, 1965; Kinsman, 1969), on which evaporitic conditions prevailed. Present day basin slopes are approximately 45 feet per mile on the basin flank and 75 feet per mile in the central basin as determined from structure contours, and paleoslopes are inferred to have been even lower. As the basin filled with sediment, sabkha conditions prograded over the normal marine subtidal environment, and eventually a continuous sheet of supratidal deposits formed to the

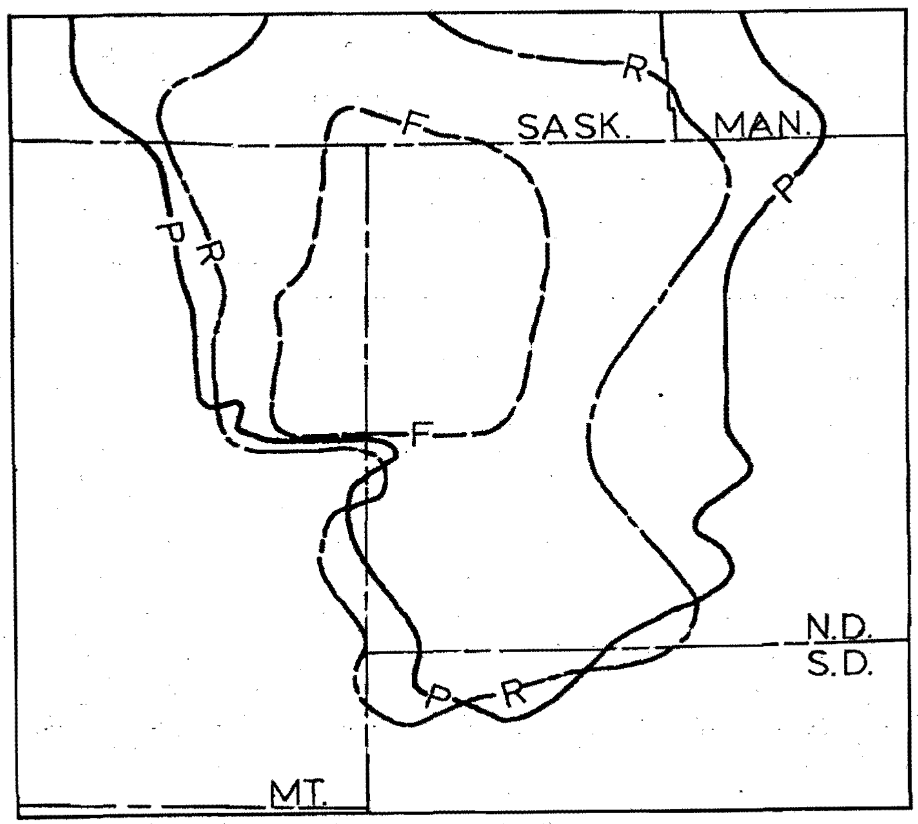

Fig. 38 -- Areal distribution of "P," "R," and "F" anhydrite units (Modified from Mallory, 1972, p.82).

center of the basin. An extensive, very thin layer of argillaceous sediment, superimposed on the sabkha flat sediment, formed during subaerial exposure of the basin. Subsequent reflooding initiated deposition of the following sequence.

The wackestone fabric, general bioturbated character, and normal marine fossil assemblage of the basal unit in each sequence indicates shallow water, open shelf deposition. The sparry packstone fabric near the top of these units probably represents deposition in the low intertidal zone in which tidal action or wave energy winnowed the mud from the coarse skeletal sand. Scattered occurrences of sparry packstone horizons within the wackestone also suggest shallow water and indicate that the sediment substrate was occasionally and repeatedly subjected to high energy conditions. The groups of dark laminations in these strata may be a result of compaction (Shinn et al., 1977).

Several features of the fine-grained dolomite units suggest high intertidal or supratidal deposition. Most indicative are desiccation fractures, acicular anhydrite crystals, and flat pebble breccias. Gastropods, uncommon elsewhere in the section, perhaps also indicate supratidal conditions. Organic rich laminations in this facies are regarded as poorly preserved algal structures, and pelletal packstones are common. Pelletal fabrics associated with organic-rich algal laminations have been reported as characteristic of supratidal and high intertidal environments (for example, Illing et al., 1965; Shinn et al, 1965). Fine-grained dolomite may itself be characteristic of the supratidal environment (Fisher and Rodda, 1969; Gerhard, 1972; Goodell and Garman, 1969; LaPorte, 1967; and Milliman, 1974). The chalky white dolomite present in at least three wells represents extreme conditions of subaerial exposure above the supratidal zone, during which fresh water dissolved aragonite and high Mg calcite (Bathurst, 1976; Gerhard et al., 1978).

Nodular anhydrite and the associated interlaminated anhydrite and dolomite are characteristic sabkha deposits in high supratidal evaporitic environments (Kinsman, 1969; Shearman, 1966).

The argillaceous marker beds, though volumetrically insignificant, are important in that they represent a time of subaerial exposure and non-deposition or erosion. A diastem is inferred from the uniformly thin, widespread character of the markers, as well as the abrupt facies change across them, from high supratidal anhydrite to subtidal wackestone.

Diagenetic Fabrics

Strata of the three depositional sequences show fewer diagenetic steps than the "D" zone. In the subtidal wacke-packstones, diagenetic modification is secondary and not directly related to the depositional environment or the primary fabric. Stylolites proliferate in this facies and some of the grouped, wavy laminations also may be solution features that lack a sutured character. Secondary dolomite rhombs are intimately associated with stylolites and laminations. A large percentage of fossil grains have been either recrystallized or dissolved and filled by microspar and spar, though occasional small vugs probably represent fossil molds that have been enlarged by solution. Crystalline masses of white anhydrite up to one inch across are scattered throughout the wacke-packstone. Notwithstanding these alterations, the primary fabric of wacke-packstones remains essentially intact.

The supratidal sediment was dolomitized penecontemporaneously with deposition. The sediment was initially carbonate mud, probably high Mg calcite and aragonite, as inferred by comparison with mineralogy and texture of sediment in modern analogs (for example, Folk and Land, 1975). The dolomite is not a direct precipitate, as indicated by well-preserved primary fabrics (Figures 25, 26, 31, 32), residual patches of undolomitized micrite, and some horizons in which the mud was completely unaffected by dolomitization (Figure 30). Dolomitization of the carbonate mud occurred while the sediment was exposed in the supratidal zone, a phenomenon recorded in a number of studies of modern environments (Curtis et al., 1963, Deffeyes et al., 1965; Shinn et al., 1965; and others) and the situation is inferred to be directly analogous to the sabkha environments of the Persian Gulf studied by Illing et al. (1965) and Kinsman (1969). The resulting rocks are considered in this paper to be primary supratidal dolomite. In some cases, micritic pellets form a packstone fabric in which primary dolomite cements the pellets, though the pellets themselves are not dolomitized (Figure 28), a situation similar to that noted by Deffeyes et al. (1965) in supratidal deposits in Bonaire. The pellets probably originated in the intertidal zone (Illing et al., 1965), and may have been carried into the supratidal zone (Shinn et al., 1965).

Limited solution during or slightly after dolomitization resulted in pinpoint porosity with some larger "vugs." The pores only occur where the sediment has been at least partially dolomitized, and are usually surrounded by primary dolomite (Figure 39). Acicular anhydrite and

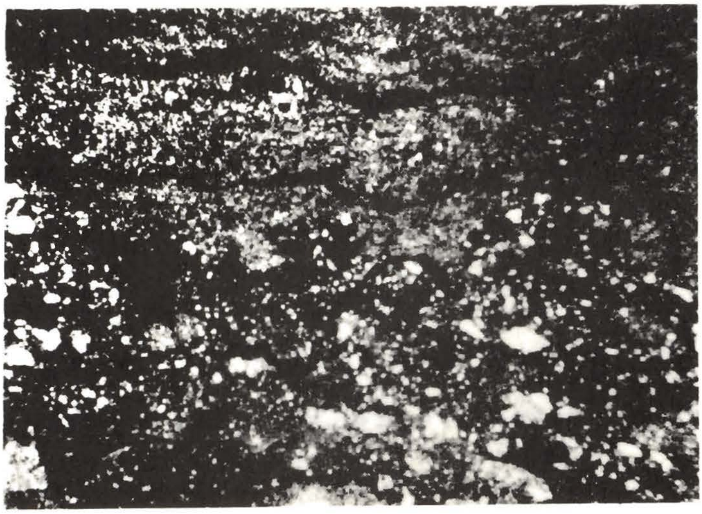

Fig. 39 --Photomicrograph of pinpoint porosity in dolomitic mudstone. White areas are voids (plane polarized light).

small aggregates of anhydrite frequently precipitated within the dolomitized areas, probably penecontemporaneously with dolomitization.

Minor secondary dolomite in the primary dolomitic mudstone occurs as coarser, clear (limpid) rhombs lining larger vugs (Figure 40). This dolomitization probably occurred much later in the history of the rocks, sometime after burial, since a much slower crystallization rate is thought to be necessary to form limpid dolomite (Folk and Land, 1975).

Stylolites are less abundant in the fine-grained dolomite than in the wacke-packstones, but dark brown wispy laminations are common throughout the "A," "B," and "C" zones (Figures 25, 26, 31, 32, 39). Some of these laminations may be secondary solution features, but most appear to be primary, perhaps a result of oxidation during subaerial exposure. No analysis was made of their chemical or mineralogical composition.

The impermeable anhydrite units formed by precipitation of anhydrite within carbonate sediment. The anhydrite formed nodules, which displaced the uncompacted carbonate mud as they grew (Kerr and Thomson, 1963; Shearman, 1966). The anhydrite units are therefore a post-depositional, pre-lithification phenomenon. Little or no alteration subsequent to their formation is evident, though infrequent small scale loading and flame structures occur, which probably formed during precipitation of the anhydrite (Figure 37). No stylolites or other solution features are seen or expected due to the impermeability of these units, and in any case, evidence of solution would probably be eradicated by subsequent pressure deformation of the anhydrite.

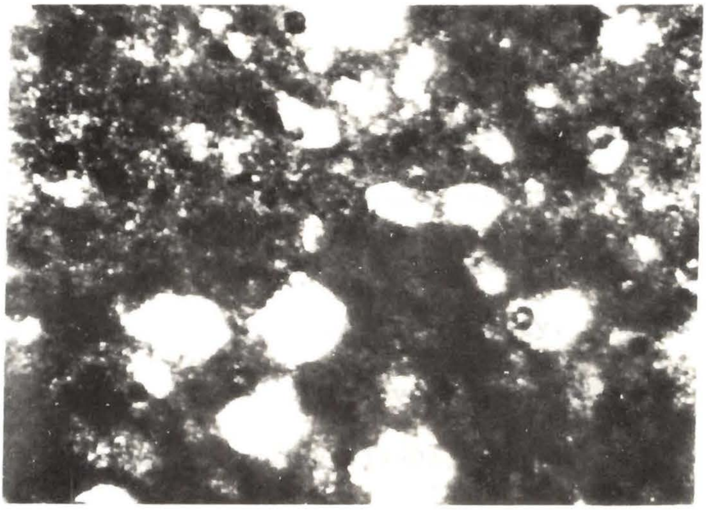

Fig. 40 --Photomicrograph of secondary dolomite lining vugs in dolomitic mudstone (plane polarized light).

Diagenetic Mechanisms

The diagenetic processes responsible for porosity development in the "A," "B," and "C" zones are more straightforward than those responsible for "D" zone paragenesis (Figure 41). In the upper 3 porosity zones, dolomitization of pre-existing carbonate sediment occurred in the low supratidal zone, seaward of the area of nodular anhydrite precipitation. This dolomitization was a result of interstitial vadose solutions from which anhydrite had precipitated, leaving the solutions with a high Mg/Ca ratio but low overall salinity. Movement of these dolomitizing solutions was caused by evaporative pumping similar to the mechanisms of Adams and Rhodes (1960), Hsu and Siegenthaler (1969), Illing et al. (1965), and Newell et al. (1953), combined with a lateral component of flow induced by evaporation and an oscillating water table controlled by tidal action.

At flood tide, the water table in the supratidal or sabkha flat rose and phreatic marine water was drawn up by evaporative pumping into the vadose zone (Figure 41a). This interstitial water became highly saline due to evaporation, and anhydrite precipitated in the high supratidal area. The lower limit of this anhydrite precipitation was probably the water table or the capillary zone immediately above it (Goodell and Garman, 1969; Shearman, 1966). As the tide ebbed and the water table fell (Figure 41b), evaporation was less effective in drawing water upward from the phreatic zone, and anhydrite precipitation was reduced. It is suggested that the interstitial water remaining in the anhydrite area (high supratidal) was no longer buoyed up by the water table and gravity began to draw it downward, but high evaporation in

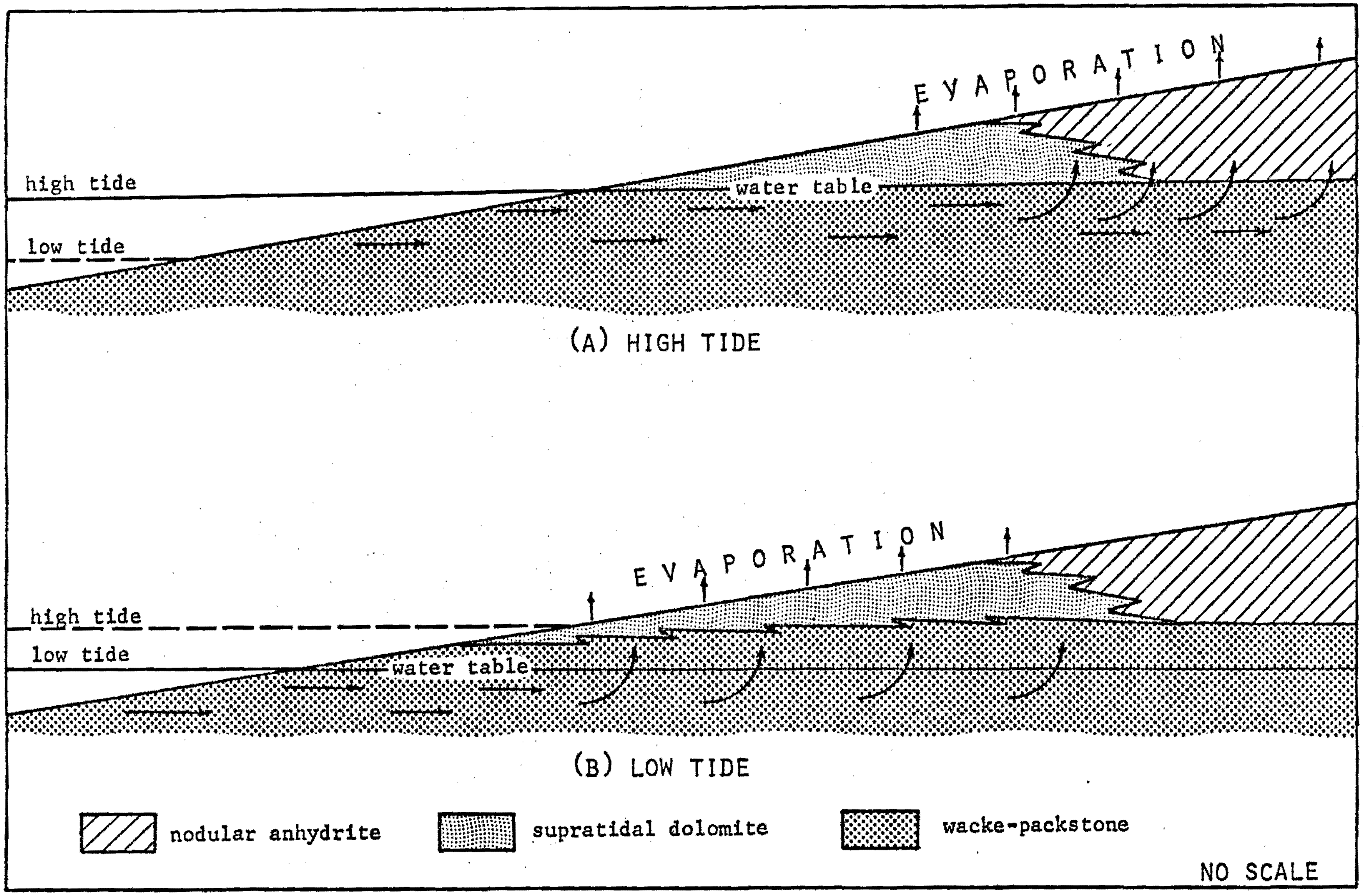

Fig. 41 --Circulation pattern of dolomitizing solutions in the "A," "B," and "C" porosity zones.

the lower supratidal zone tended to move it laterally. This movement was in the downdip, seaward direction, which may also have aided movement (Deffeyes et al., 1965). Dolomitization of carbonate mud in the low supratidal area occurred as a result of this influx of interstitial water from which anhydrite had precipitated. Anhydrite precipitation from highly saline water raises the Mg/Ca ratio appreciably by selective removal of calcium, and reduces the overall salinity of the solution. A high Mg/Ca ratio and low overall salinity are ideal dolomitizing conditions (Folk and Land, 1975). In addition to the lateral influx of interstitial water into the low supratidal zone, water was probably also drawn into the vadose zone from the marine water table by evaporation, The low-tide water table in the low supratidal zone remained close enough to the surface for evaporation to be effective. Mixing of this slightly concentrated saline water from the phreatic zone with high Mg/Ca--low salinity water percolating laterally from the high supratidal area raised the overall salinity of the latter water mass, but the Mg/Ca ratio remained proportionately much larger than if sea water had simply evaporated, and dolomitization probably was not inhibited. The Mg/Ca ratio was rapidly reduced by dolomitization, and intertidal or low intertidal sediment was not often affected.

Successive tides and changes in marine phreatic water table beneath the supratidal environments repeatedly dissolved anhydrite in the low supratidal zone and in the sediment of the high supratidal zone that was below the normal high tide water table. Large quantities of anhydrite probably were not precipitated in low supratidal zone at high or low tide because normal marine water was continuously drawn from the near surface marine phreatic zone and solutions were not supersaturated with respect to anhydrite. With exception of intermittent storm input, mixing of fresh and marine water masses probably was not an important mechanism of dolomitization as was the case in the "D" zone.

Microscopic vugs in the primary dolomite probably result from intermittent periods of fresh water influx (Goodell and Garman, 1969) during which the remaining calcite or aragonite mud was dissolved. Secondary dolomitization, which formed crystals that line some of these vugs, probably occurred after the rocks were buried, possibly a result of fresh and marine water mixing during times of subaerial exposure of the basin, as is suggested for second stage dolomitization in the "D" zone.

Porosity Development

Intercrystalline, solution, and fracture porosity characterize the "A," "B," and "C" zones. Best porosity was produced during primary dolomitization in the depositional environment, during which dolomitization of the carbonate mud on a molecule for molecule basis resulted in intercrystalline porosity (Landes, 1946; Murray, 1960; Weyl, 1960). Additional porosity is due to microscopic solution vugs in the dolomite, and open horizontal fractures of unknown origin that probably occurred much later in the history of the rock. As in the "D" zone, secondary dolomitization did not increase porosity, and may have actually reduced it by partially filling pre-existing vugs and interstices.

DISCUSSION

Deposition of the upper Red River in the Williston basin is shown diagrammatically in Figure 42. On the horizontal axis, the basin center is in the middle and the periphery of the basin is at the left and right edges of the diagram. The vertical axis represents time, therefore any horizontal line across the diagram is an isochron. The reader should note that the diagram in no way represents thickness of strata or depth of water in the basin during deposition, but rather shows the lateral changes in lithofacies across the basin at any given time, as well as vertical lithofacies changes at a given location through time. Figure 42 indicates that lateral and vertical facies changes with time in the basin were as follows.

1. Lower Red River sediments were deposited throughout the basin.

2. The lower Red River facies gave way to "D" zone facies, first on the periphery of the basin and later across the entire basin, probably a result of water becoming shallower due to sediment filling the basin. In various areas along the periphery of the basin, shallow barred ponds developed and the organic packstone facies of the "D" zone was deposited.

3. Increasing water depth marked the end of "D" zone deposition, first in the center of the basin and gradually transgressing to include all of the basin proper and part of the basin flank. A minor rise in sea level is sufficient to account for this deepening of the

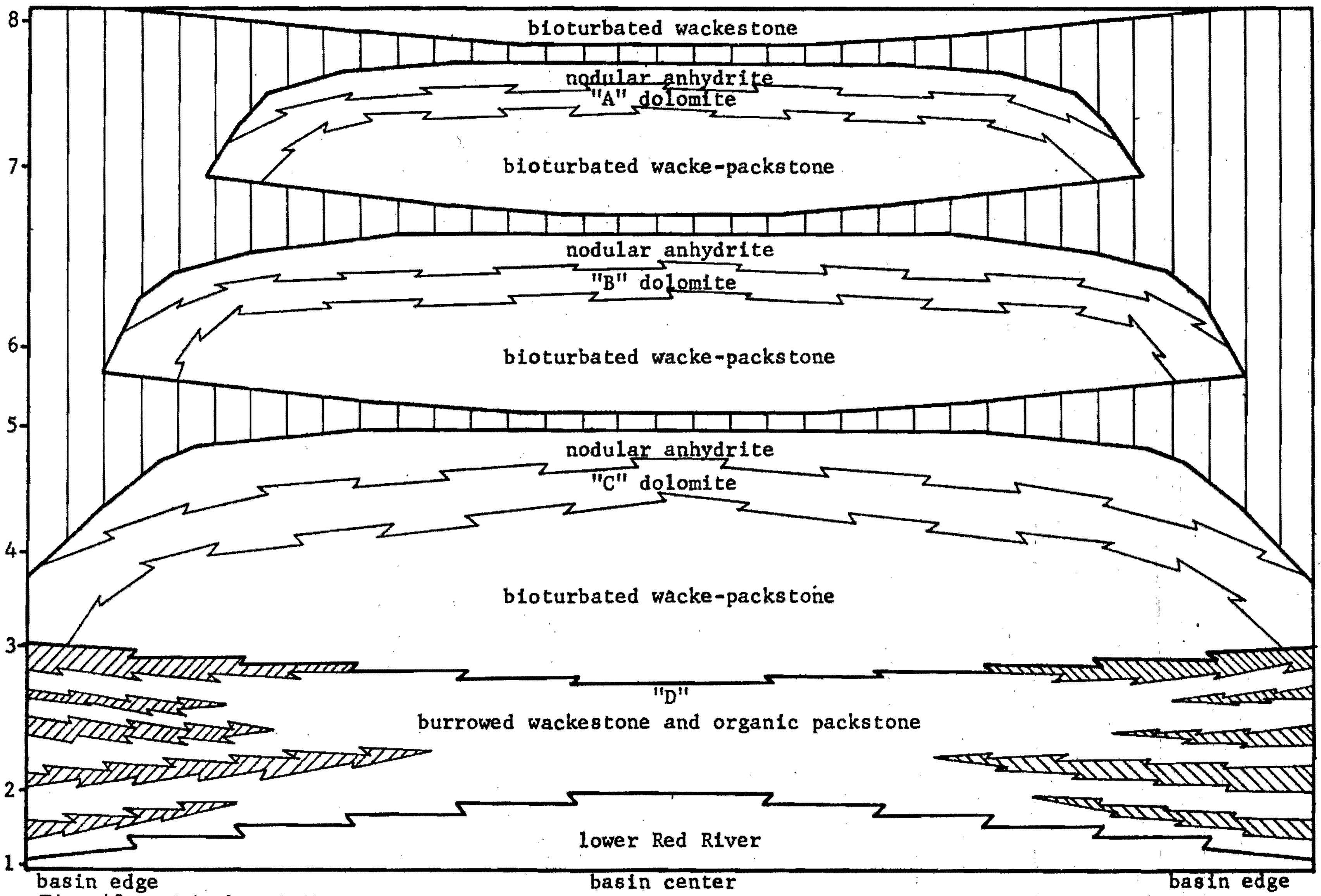

Fig. 42 -- Idealized diagram of upper Red River sedimentation through time.

basin, though downwarp of the basin is an alternative explanation. The basal wacke-packstone of the "F" sequence was deposited in the basin at this time, and maximum transgression of the sea is marked by the periphery of this unit. Landward of the periphery of this wacke-packstone, the "C" dolomite rests directly on "D" zone strata.

4. As the basin filled with sediment, the high intertidal to low supratidal dolomite facies, and the high supratidal anhydrite facies began to prograde toward the center of the basin, covering the subtidal wacke-packstone facies.

5. Sabkha conditions eventually prevailed across the entire basin, and supratidal dolomite and anhydrite formed to the center of the basin. A period of essentially non-deposition or erosion followed, during which a very thin layer of fine argillaceous material was deposited.

6. and 7. The basin was flooded twice more during upper Red River deposition, and was subsequently filled with sediment in a manner similar to that described in #3 through #5. Each of these transgressions of the sea was more restricted than the previous one, and the basin was above sea level at the end of each sequence of sedimentation.

8. Following the diastem above the uppermost or "F" sequence, the basin was again flooded and the wacke-packstone at the top of the Red River was deposited.

Porosity in the "A," "B," and "C" zones is directly related to depositional environment. Porosity in these zones is generally poorest in the deepest parts of the basin and best on the flanks due to less subaerial exposure of the basin center to dolomitizing conditions and fresh water solution.

Delineation of paleo-strandlines should be useful in ascertaining where porosity is and is not developed, since deposits in nearshore barred ponds enhance the paragenetic processes responsible for "D" zone porosity, and the porous "A," "B," and "C" zone strata are supratidal sediments. A paleo-strandline can be defined between the "D" and "C" porosity zones, where the subtidal facies separating the two zones pinches out to the east and north at the lateral limits of the flooding that followed "D" zone deposition (time 3, Figure 42). The point at which the two zones can no longer be separated is a strandline, that is, the position at which the sediment overlying the "D" zone changes facies from subtidal wackestone to supratidal dolomite. This paleo-strandline represents maximum transgression and is mapped on Plate 4. Two lines are plotted on this map, one indicating where the "C" and "D" zones definitely can be separated, the second where they cannot. Logs in the area between the lines cannot be picked with certainty, and the area may be thought of loosely as an intertidal zone. The strandline follows isopach contours closely, even around the embayment in Wells County. Major divergence from this pattern occurs just north of the embayment, at which point the strandline crosses isopachs as it continues around the north side of the basin. This may result from higher sedimentation rates in this area, or less compaction of the sediment through time, though a reason for either possibility is not apparent. Data in this area are sparse and no investigation of this apparent anomoly was attempted. On the Nesson anticline the strandline returns to the same isopach as on the east side of the basin.

With sufficient core data, a second and third strandline could be located where the subtidal deposits of the "R" and "F" sequences change facies to supratidal sediments, and thus the geometry of the basin during each successive flooding could be determined. These later strandlines occur between the "B" dolomite and "P" anhydrite, and between the "A" dolomite and "R" anhydrite. Given the thin character of all the units of the upper two sequences in the areas where the strandlines are expected, and the variability of porosity and lack of core, it has not been possible to locate the later strandlines with any certainty.

The Nesson anticline was clearly a feature of some topographic expression during upper Red River sedimentation. Units thin as they cross it, more shallow pond (organic) deposits are present in the "D" zone than in the center of the basin, and thicker "A," "B," and "C" porosity zones occur indicating more supratidal exposure. The paleo-strandline mapped on Plate 4 follows isopachs around the anticline, indicating the anticline was, if not subaerially exposed, at least a prominent high at the time.

The small structural highs referred to in various parts of this paper are also of interest, since porosity in these areas should be well-developed if the features were topographic highs during deposition. For example, in the Shell 34X-31-1 well in the Mondak field in McKenzie County, the upper Red River section is structurally higher than in other wells in the area and at least four organic units are present in the "D" zone, while other wells near the center of the basin consist predominantly of the burrowed facies. Porosity in the "D" zone in this well is well-developed. Whereas 34X-31-1 is not economical to produce, Shell's Swigart well approximately a half a mile to the west in Montana is higher on the same structure and does produce. Therefore, "D" zone porosity has developed in the center of the basin if the proper conditions existed during deposition.

The combination of topographic highs during deposition and activity of the same structures through time has resulted in adequate porosity and structural closure to form structural-stratigraphic hydrocarbon traps. Depositional thins and present structural highs can be correlated on isopach and structure contour maps in Bowman County due to good well control, and some correlation is possible in other parts of the basin, notably McKenzie County. At present, structural control of paleo-topographic features in the basin as a result of recurring activity of basement structures can only be suggested. A comprehensive study locating formational thins through the section, combined with structure contour mapping would do much to prove or disprove this hypothesis.

HYDROCARBON PRODUCTION AND POTENTIAL

Past and Current Production

Red River oil in North Dakota was first discovered in Williams County in 1957 with Amerada Petroleum Company's Iverson-Nelson Unit #1 in the Beaver Lodge Field. Subsequent Red River discoveries, all in the western part of the state, now produce throughout the entire north-south length of the state. Exploration of the Red River and subsequent production has greatly accelerated in the last ten years. In 1965, fifty-four Red River producers in four fields accounted for 3.3% of North Dakota's total oil production. By 1970 Red River production had increased to 6.1% of the state's total. In 1975, one hundred six Red River wells in nineteen fields produced 9.2% of North Dakota's oil, or 1,878,841 barrels of 20,452,498 total barrels produced in North Dakota in that year (N.D.G.S., 1965, 1970, 1975).

The largest amount of Red River production is currently from Bowman and Williams Counties. Most production in Bowman County is from the Cedar Creek Field in the western part of the county. Of five other fields in Bowman County, the largest is the Medicine Pole Hills Field. Most fields in this county are associated with small structural highs on the Cedar Creek anticline. In the northern part of the state in Williams County most Red River production is from the Beaver Lodge and Tioga Fields, both of which lie on the Nesson anticline. Additional production in this area occurs in smaller fields surrounding these two. Between the two north and south major producing areas are not less than eight recognized fields and a substantial number of additional producers in unnamed fields. Scattered production occurs in Divide, McKenzie, Dunn, Billings, Slope, and Stark Counties, with the largest amount in McKenzie County. The Buffalo Creek Field in Stark County represents the easternmost Red River production in the state. Production in the above counties in which no major structures are recognized stems from small seismic highs and facies changes that are often associated with the highs. Substantial new production from several wells in Dunn County is from what appears to be a sizeable structural high or number of highs (North Dakota Industrial Commission Order 1544).

Six porosity zones labeled "A" to "F" downhole occur in the Red River. The "E" and "F" zones are in the lower Red River and most tests are not drilled to them. The "E" zone does not produce oil anywhere in North Dakota, and only one well, the Amerada #B-1 Ives in the Tioga Field, produces from the "F" zone. A recent test in McKenzie County may also produce from the "F" horizon. The "A" through "D" zones all produce in North Dakota, however, various porosity zones are more productive in some parts of the state than in others. Production from the "A" zone occurs largely on the Cedar Creek anticline, while "B," "C," and "D" production is scattered throughout the state (Friestad, 1969).

Oil accumulation in the Red River occurs in both structural and stratigraphic traps. The Beaver Lodge and Tioga Fields on the Nesson anticline are examples of major structural traps in North Dakota. Other smaller structural highs, combined with the associated porosity development discussed previously, are responsible for production in McKenzie, Dunn, Bowman and other counties.

Potential for Production

The Billings nose and the structure in the Hettinger-Stark-Morton County area are excellent prospects for further hydrocarbon exploration. Thinning of upper Red River strata in these areas indicates depositional highs which have been shown to favorably affect porosity development. The location of these structures in the main part of the basin where the upper Red River stratigraphic succession is fully developed is also favorable.

The small highs in Burleigh and Emmons Counties, particularly the western flanks of these structures, warrant careful investigation. The two "D" zone facies should be well-developed in this area, though the potential of the upper three zones in this area may be limited by lateral termination of the anhydrite cap rocks.

The embayment in Wells County provides a particularly interesting situation. While the basinal character itself is not conducive to oil entrapment, the stratigraphic succession of the main basin is developed here, and any small structures associated with this feature should be examined carefully.

Very little is known of the basin hinge line or structures associated with it north of the Wells embayment. Also, the main basin between the hinge line and Dunn County has very few test wells drilled to the Red River, therefore it is difficult to evaluate the hydrocarbon potential of the area at this time. New production from the center of the basin in Dunn County indicates that this area from the center of the basin eastward is worthy of investigation as well.

CONCLUSIONS

1. Depositional environments, each with a characteristic lithofacies, were constant across most of the basin in North Dakota, resulting in laterally continuous units with uniform primary fabrics. Therefore, while primary fabric is important to subsequent diagenetic processes, lateral changes in the depositional environments themselves cannot be called upon to explain variable porosity within a given rock unit.

2. Diagenetic changes in the primary rock fabric are responsible for most of the porosity in all four zones. Porosity in the "A," "B," and "C" zones is due to dolomitization that was penecontemporaneous with deposition of the primary carbonate sediment. Porosity in the "D" zone also stems from syndepositional dolomitization of sediment in the burrows, as well as later calcite solution. Most porosity in these zones is therefore a result of intercrystalline voids in syndepositional (primary) dolomite.

3. The dolomitic mudstones and nodular anhydrite units of the "P," "R," and "F" sequences of the upper Red River are directly analogous to the sabkha environments of the Persian Gulf, studied by Illing et al. (1965) and Kinsman (1969). No modern analog is known for the "D" zone.

4. Dolomitization in all four porosity zones can be attributed to high Mg/Ca ratios, reduced salinity, and interstitial movement of dolomitizing fluids.

5. Small differences in primary permeability within a body of sediment are often sufficient to affect syndepositional diagenesis, which may in turn have a direct affect on porosity development. For example, preferential syndepositional dolomitization of burrows over matrix in the "D" zone has resulted in much greater porosity in the burrows, and preferential primary dolomitization of matrix over pellets in some horizons of the upper three porosity zones has affected prosity in these horizons.

6. Structural or topographic highs in the basin during upper Red River deposition resulted in thinning of the Red River strata and, perhaps more importantly, affected syndepositional diagenetic processes. In the "D" zone, depositional highs caused solutions to flow around rather than over the highs, resulting in less dolomization and less porosity on top of the highs. After burial of the strata, the structural highs adversely affected calcite solution and the associated porosity development, again by channeling solutions around the highs. Topographic highs may have favorably affected porosity development in the "A," "B," and "C" zones by exposing sediment to dolomitization in the supratidal zone, which resulted in intercrystalline porosity. During this exposure, intermittent fresh water flushing developed microscopic vugs.

7. In light of #6, exploration of the "D" zone should be concentrated "around" rather than "on" structures, and "A," "B," and "C" exploration should be concentrated "on" structure.

8. Several large areas in North Dakota show good potential for further expansion of hydrocarbon production in the upper Red River.

APPENDIX A

BASIC WELL DATA AND LOG PICKS

(This appendix includes basic well data and log picks of the tops of various units in the upper Red River. Wells are arranged alphabetically by county, and numerically by NDGS well number within a county).

ADAMS COUNTY

NDGS #6050
America Hess Corp.--Holmquist #1
SW 30-129-98
2695 K. B.

9018	Red River

BENSON COUNTY

NDGS #632
Calvert Exploration Co.--A. J. & I. John & G. Stadum #1
NWSE 31-154-70
1637 K. B.

4291	Red River
4348	P anhydrite
4470	lower Red River

BILLINGS COUNTY

NDGS #291
America Petr. Corp.--H. May #1
NWNE 9-139-100
2774 K. B.

12220	Red River
12321	P anhydrite
12460	lower Red River

NDGS #555
Stanolind Oil and Gas. Co.--N.W.I. (N.P.) #1
SESE 17-143-100
2815 K. B.

13115	Red River
13228	P anhydrite
13362	lower Red River

NDGS #2853
Shell-Northern Pacific Railway Co.--Gov't #41X-5-1
NENE 5-143-101
2572 K. B.

12774	Red River
12822	R anhydrite
12838	B zone
12858	R basal limestone
12880	P anhydrite
12906	C zone
12948	P basal limestone
12976	D zone

NDGS #3268
Amerada Petr. Corp.--Scoria #8
NESW 10-139-101
2540 K. B.

11901	Red River
11916	A zone
11930	F basal limestone
11946	R anhydrite
11952	B zone
11964	R basal limestone
12004	P anhydrite
12034	C zone
12062	P basal limestone
12071	D zone

NDGS #3746
Davis Oil Co.--Kevin Fed #1
SWSW 10-138-100
2814 K. B.

12001	Red River
12102	P anhydrite
12254	lower Red River

NDGS #4254
Pan Am. Petr. Corp.--USA A. G. Macaucey "B" #1
SENW 28-137-100
2864 K. B.

11627	Red River
11721	P anhydrite
11862	lower Red River

NDGS #5195
Lone Star Prod. Co.--A. Schwartz "B" #1
SENE 2-137-100
2786 G. L.

11694	Red River
11792	P anhydrite
11942	lower Red River

NDGS #6169
Tenneco Oil Co.--Burlington Northern #1
NWNW 25-143-101
2555 K. B.

12766	Red River
12875	P anhydrite
13004	lower Red River

NDGS #6303
Tenneco Oil Co.--Burlington Northern #1-29
NESW 29-143-100
2642 K. B.

12782	Red River
12888	P anhydrite
13018	lower Red River

BOTTINEAU COUNTY

NDGS #38
California Oil Co.--Blanche Thomson #1
SWSE 31-160-81
1526 D. F.

7239	Red River
7250	F anhydrite
7255	A zone
7265	F basal limestone
7275	R anhydrite
7285	B zone
7305	R basal limestone
7320	P anhydrite
7352	C zone
7440	lower Red River

NDGS #286
Lion Oil Co.--Erickson #1
SWNE 32-164-78
1539 K. B.

5735	Red River
5740	F anhydrite
5750	A zone
5755	R anhydrite
5760	B zone
5785	R basal limestone
5800	P anhydrite

NDGS #4655
Amerada Petr. Corp.--H. D. Lillestrand #1
SESW 31-162-78
1486 K. B.

5950	Red River
6020	P anhydrite
6128	lower Red River

BOWMAN COUNTY

NDGS #485
W. H. Hunt--Z. Brooks--State #1
NWNW 16-129-104
3212 K. B.

9156	Red River
9169	Z zone
9180	F basal limestone
9199	B zone
9212	R basal limestone
9249	P anhydrite

9273	C zone
9319	P basal limestone
9345	D zone
9404	lower Red River

NDGS #516
Western Natural Gas Co.--Truax-Traer Coal #1
NWSW 13-132-102
3074 K. B.

10397	Red River
10406	F anhydrite
10408	A zone
10420	F basal limestone
10436	R anhydrite
10440	B zone
10453	R basal limestone
10488	P anhydrite
10511	C zone
10538	P basal limestone

NDGS #1446
J. H. Snowden et al.--M. A. Morrison #1
SESW 34-130-103
3028 K. B.

9278	Red River
9286	A zone
9298	F basal limestone
9310	R anhydrite
9316	B zone
9333	R basal limestone
9365	P anhydrite
9386	C zone
9413	P basal limestone
9447	D zone
9522	lower Red River

NDGS #1575
Carter Oil Co.--L. & E. Johnson #1
NWSW 9-129-106
2953 K. B.

8198	Red River
8210	A zone
8222	F basal limestone
8235	R anhydrite
8240	B zone
8249	R basal limestone
8246	P anhydrite
8304	C zone
8440	lower Red River

NDGS #2509
Shell Oil Co.--Gov't. #41-23A
NENE 23-130-107
2979 K. B.

8151	Red River
8167	A zone
8180	F basal limestone
8190	R anhydrite
8193	B zone
8206	R basal limestone
8243	P anhydrite
8272	C zone
8289	P basal limestone
8313	D zone
8384	lower Red River

NDGS #2677
Shell Oil Co.--Gov't. #34X-3A-2
SWSE 3-130-107
3034 K. B.

8114	Red River
8131	A zone
8144	F basal limestone
8208	R anhydrite
8212	B zone
8220	R basal limestone
8257	P anhydrite
8273	C zone
8307	P basal limestone
8338	D zone
8404	lower Red River

NDGS #3150
H. W. Clarkson & E. W. Clarkson--Clarkson-White et al. #1
NESE 27-130-107
3001 K. B.

8418	Red River
8434	A zone
8455	R anhydrite
8459	B zone
8468	R basal limestone
8508	P anhydrite
8530	C zone
8561	P basal limestone
8594	D zone
8640	lower Red River

NDGS #3261
Continental Oil Co.--Fed. #1
NWNE 15-129-106
2925 K. B.

8244	Red River
8259	A zone
8271	F basal limestone
8287	R anhydrite
8291	B zone
8299	R basal limestone
8338	P anhydrite
8359	C zone
8405	P basal limestone
8424	D zone
8492	lower Red River

NDGS #3312
Houston Oil and Minerals--R. Young #33-4
NWSE 4-129-106
2865 K. B.

8194	Red River
8209	A zone
8221	F basal limestone
8234	R anhydrite
8238	B zone
8246	R basal limestone
8285	P anhydrite
8309	C zone
8326	P basal limestone
8351	D zone
8429	lower Red River

NDGS #3514
Shell Oil Co.--Gov't. #43-30C-43
NESE 30-130-106
2937 G. L.

8265	Red River
8280	A zone
8292	F basal limestone
8307	R anhydrite
8310	B zone
8316	R basal limestone
8358	P anhydrite
8371	C zone
8407	P basal limestone
8441	D zone
8493	lower Red River

NDGS #3720
Shell Oil Co.--Gov't. #31X-34B-45
NWNE 34-131-107
3018 K. B.

8314	Red River
8332	A zone
8342	F basal limestone

8357	R anhydrite
8360	B zone
8368	R basal limestone

NDGS #3798
Shell Oil Co.--Gov't. #13-32
NWSW 32-131-106
3037 K. B.

8634	Red River
8648	A zone
8660	F basal limestone
8676	R anhydrite
8679	B zone
8686	R basal limestone
8730	P anhydrite
8751	C zone
8792	P basal limestone
8809	D zone
8857	lower Red River

NDGS #4143
A. J. Hodges Inc., Inc.--C. Hestekin #1
NENE 15-130-104
3179 K. B.

9462	Red River
9472	A zone
9481	F basal limestone
9499	R anhydrite
9504	B zone
9514	R basal limestone
9550	P anhydrite
9567	C zone
9600	P basal limestone
9641	D zone
9699	lower Red River

NDGS #4158
Farmers Union Central Exchange, Inc.--F. A. Carlson #31-8
NWNE 8-129-106
2952 K. B.

8200	Red River
8219	A zone
8228	F basal limestone
8239	R anhydrite
8243	B zone
8254	R basal limestone
8296	P anhydrite
8318	C zone
8359	P basal limestone
8379	D zone
8429	lower Red River

NDGS #4248
Farmers Union Central Exchange, Inc.--Gov't. #11-5
NWNW 5-129-106
2969 K. B.

8220	Red River
8234	A zone
8240	F basal limestone
8257	R anhydrite
8260	B zone
8269	R basal limestone

NDGS #4538
A. J. Hodges Ind., Inc.--Susas-Wick #1-X
NESW 15-130-104
3145 K. B.

9340	Red River
9349	A zone
9360	F basal limestone
9379	R anhydrite
9382	B zone
9393	R basal limestone
9429	P anhydrite
9452	C zone
9480	P basal limestone
9521	D zone
9580	lower Red River

NDGS #4545
Pel-Tex Petr. Co., Inc.--J. C. Kennedy
NWNE 17-130-100
2865 K. B.

9658	Red River
9665	A zone
9675	F basal limestone
9694	R anhydrite
9696	B zone
9704	R basal limestone
9741	P anhydrite
9766	C zone
9800	P basal limestone
9823	D zone
9895	lower Red River

NDGS #4577
Golden Eagle Exploration, Ltd.--C. Holecek #1
NENE 17-129-104
3211 K. B.

9121	Red River
9132	Z zone
9141	F basal limestone
9110	B zone
9123	R basal limestone
9211	P anhydrite

9237	C zone
9276	P basal limestone
9301	D zone
9362	lower Red River

NDGS #4641
Ashland Oil and Refining Co.--A. L. Fossom #1
NENW 22-130-104
3197 K. B.

9416	Red River
9427	A zone
9438	F basal limestone
9456	R anhydrite
9459	B zone
9471	R basal limestone
9506	P anhydrite
9529	C zone
9556	P basal limestone
9599	D zone
9658	lower Red River

NDGS #4654
International Nuclear Corp.--J. M. Susa et al. #1-61
SWNE 30-130-102
2935 K. B.

9430	Red River
9438	A zone
9445	F basal limestone
9472	B zone
9478	R basal limestone
9515	C zone
9564	P basal limestone
9606	D zone
9668	lower Red River

NDGS #4662
Superior Oil Co.--Holecek #1
SESE 8-129-104
3252 K. B.

9191	Red River
9200	A zone
9211	F basal limestone
9225	R anhydrite
9227	B zone
9240	R basal limestone
9275	P anhydrite
9300	C zone
9328	P basal limestone
9345	D zone
9417	lower Red River

NDGS #4669
International Nuclear Corp.--Miller #1-62
SWNE 21-131-104
3158 K. B.

9605	Red River
9616	A zone
9628	F basal limestone
9642	R anhydrite
9647	B zone
9655	R basal limestone
9691	P anhydrite
9712	C zone
9746	P basal limestone
9776	D zone
9842	lower Red River

NDGS #4756
Calvert Drilling and Producing Co.--C. Holecek #17-4
NWSE 17-129-104
3201 K. B.

9150	Red River
9162	A zone
9168	F basal limestone
9188	R anhydrite
9194	B zone
9202	R basal limestone
9240	P anhydrite
9252	C zone
9296	P basal limestone
9327	D zone
9390	lower Red River

NDGS #4821
Amarillo Oil Co. N.D. State #1-16
NENE 16-130-104
3116 K. B.

9345	Red River
9358	A zone
9370	F basal limestone
9383	R anhydrite
9386	B zone
9396	R basal limestone
9434	P anhydrite
9457	C zone
9484	P basal limestone
9521	D zone
9585	lower Red River

NDGS #4832
Amarillo Oil Co.--A. Fossum #1-24
S NW 24-130-104
3137 K. B.

9377	Red River
9386	A zone
9399	F basal limestone
9420	B zone
9428	R basal limestone
9467	P anhydrite
9483	C zone
9512	P basal limestone
9556	D zone
9611	lower Red River

NDGS #4841
Calvert Drilling and Producing Co., et al.--Holecek-Olson #18-4
SESE 19-129-104
3246 K. B.

9148	Red River
9160	A zone
9167	F basal limestone
9184	R anhydrite
9187	B zone
9200	R basal limestone
9239	P anhydrite
9262	C zone
9296	P basal limestone
9326	D zone
9390	lower Red River

NDGS #4922
Pel-Tex, Inc.--I. & N. Landa #1
SESW 5-130-100
2944 K. B.

9779	Red River
9784	A zone
9794	F basal limestone
9814	R anhydrite
9819	B zone
9826	R basal limestone
9861	P anhydrite
9885	C zone
9904	P basal limestone
9945	D zone
10018	lower Red River

NDGS #4932
Amarillo Oil Co.--E. Fossum #1-24
NWNE 24-130-104
3160 K.B.

9426	Red River
9430	A zone

9438	F basal limestone
9453	R anhydrite
9459	B zone
9470	R basal limestone
9508	P anhydrite
9528	C zone
9558	P basal limestone
9588	D zone
9663	lower Red River

NDGS #4952
Pel-Tex, Inc.--G. R. Boor, et al. #1
SWSW 32-130-100
2958 K. B.

9570	Red River
9577	A zone
9586	F basal limestone
9606	R anhydrite
9611	B zone
9618	R basal limestone
9656	P anhydrite
9680	C zone
9708	P basal limestone
9739	D zone
9815	lower Red River

NDGS #4954
Amarillo Oil Co.--A. Fossum #2-13
NWNW 13-130-104
3160 K. B.

9428	Red River
9439	A zone
9448	F basal limestone
9470	R anhydrite
9472	B zone
9481	R basal limestone
9520	P anhydrite
9538	C zone
9577	P basal limestone
9608	D zone
9675	lower Red River

NDGS #5000
Pel-Tex, Inc.--E. Coates et al. #1
SWSW 28-131-105
2977 K. B.

8958	Red River
8970	A zone
8986	F basal limestone
9003	R anhydrite
9006	B zone
9015	R basal limestone

9055	P anhydrite
9076	C zone
9112	P basal limestone
9146	D zone
9202	lower Red River

NDGS #5045
Amarillo Oil Co.--Nelson #1-14
C NE 14-130-104
3242 K. B.

9480	Red River
9490	A zone
9496	F basal limestone
9516	R anhydrite
9519	B zone
9527	R basal limestone
9568	P anhydrite
9588	C zone
9620	P basal limestone
9656	D zone
9718	lower Red River

NDGS #5061
Amarillo Oil Co.--E. Fossum #2-13
C SE 13-130-104
3125 K. B.

9394	Red River
9404	A zone
9422	F basal limestone
9439	R anhydrite
9443	B zone
9449	R basal limestone
9487	P anhydrite
9498	C zone
9540	P basal limestone
9574	D zone
9643	lower Red River

NDGS #5070
Penneoil United, Inc.--Swanke #1
NWNW 15-131-105
2960 K. B.

9222	Red River
9236	A zone
9249	F basal limestone
9271	R anhydrite
9274	B zone
9280	R basal limestone
9318	P anhydrite
9338	C zone
9380	P basal limestone
9408	D zone
9468	lower Red River

NDGS #5089
Amarillo Oil Co.--A. Fossum #3-23
C E½SE 23-130-104
3137 K. B.

9412	Red River
9424	A zone
9431	F basal limestone
9448	R anhydrite
9452	B zone
9459	R basal limestone
9498	P anhydrite
9512	C zone
9548	P basal limestone
9590	D zone
9648	lower Red River

NDGS #5128
Pel-Tex, Inc.--F. N. Stricherz #1
SWNE 30-130-104
3089 K. B.

9122	Red River
9136	A zone
9143	F basal limestone
9154	B zone
9168	R basal limestone
9206	P anhydrite
9225	C zone
9260	P basal limestone
9297	D zone
9355	lower Red River

NDGS #5133
Amarillo Oil Co.--Anderson #1-12
C. W/2 NW 12-130-104
3258 K. B.

9579	Red River
9588	A zone
9595	F basal limestone
9611	R anhydrite
9619	B zone
9630	R basal limestone
9670	P anhydrite
9689	C zone
9727	P basal limestone
9750	D zone
9823	lower Red River

NDGS #5163
Farmers Union Central Exchange, Inc.--N.D. #15X-16
C S/2 S/2 16-131-104
3240 K. B.

9696	Red River
9706	A zone
9717	F basal limestone
9735	R anhydrite
9738	B zone
9746	R basal limestone
9784	P anhydrite
9806	C zone
9841	P basal limestone
9866	D zone
9935	lower Red River

NDGS #5200
Eason Oil Co.--C. Olson #1-13
SENWNW 13-129-105
3135 K. B.

8938	Red River
8951	A zone
8958	F basal limestone
8976	R anhydrite
8978	B zone
8990	R basal limestone
9030	P anhydrite
9052	C zone
9102	P basal limestone
9124	D zone
9185	lower Red River

NDGS #5209
Depco, Inc.--Dronen #33-20
NWSE 20-130-103
3029 K. B.

9348	Red River
9356	A zone
9365	F basal limestone
9384	R anhydrite
9389	B zone
9397	R basal limestone
9435	P anhydrite
9450	C zone
9475	P basal limestone
9500	D zone
9574	lower Red River

NDGS #5227
Depco, Inc.,--Grem #33-26
NWSE 26-129-103
2938 K. B.

8916	Red River
8922	A zone
8928	F basal limestone
8947	R anhydrite
8950	B zone

8960	R basal limestone
8997	P anhydrite
9015	C zone
9040	P basal limestone
9092	D zone
9147	lower Red River

NDGS #5256
Farmers Union Central Exchange, Inc.--H. and T. Gete #1
SESW 22-131=104
3207 K. B.

9652	Red River
9664	A zone
9672	F basal limestone
9689	R anhydrite
9644	B zone
9702	R basal limestone
9740	P anhydrite
9763	C zone
9791	P basal limestone
9828	D zone
9890	lower Red River

NDGS #5262
Depco, Inc.--Grem #22-26
SENW 26-129-103
2934 K. B.

8937	Red River
8946	A zone
8952	F basal limestone
8968	R anhydrite
8972	B zone
8983	R basal limestone
9021	P anhydrite
9042	C zone
9082	P basal limestone
9106	D zone
9171	lower Red River

NDGS #5266
Rainbow Resources, Inc.--A. Fossum #2-14
SESW 14-130-104
3207 K. B.

9497	Red River
9508	A zone
9518	F basal limestone
9536	R anhydrite
9540	B zone
9548	R basal limestone
9587	P anhydrite
9600	C zone

9628	P basal limestone
9670	D zone
9729	lower Red River

NDGS #5269
Farmers Union Central Exchange, Inc.--R. M. Miller #7X-27
C N/2 27-131-104
3185 K. B.

9616	Red River
9627	A zone
9636	F basal limestone
9651	R anhydrite
9656	B zone
9666	R basal limestone
9703	P anhydrite
9725	C zone
9758	P basal limestone
9787	D zone
9854	lower Red River

NDGS #5270
Depco, Inc.--Hughes #13-27
NWSW 27-129-103
2992 K. B.

8991	Red River
9000	A zone
9011	F basal limestone
9029	R anhydrite
9032	B zone
9039	R basal limestone
9075	C zone
9144	P basal limestone
9164	D zone
9222	lower Red River

NDGS #5278
Rainbow Resources, Inc.--Oakland BND #1-2
SWSW 2-130-104
3255 G. L.

9594	Red River
9604	A zone
9610	F basal limestone
9632	R anhydrite
9635	B zone
9645	R basal limestone
9682	P anhydrite
9696	C zone
9734	P basal limestone
9766	D zone
9838	lower Red River

NDGS #5347
Depco, Inc.--Homquist #31-8
NWNE 8-131-104
3042 K. B.

9623	Red River
9634	A zone
9644	F basal limestone
9665	R anhydrite
9669	B zone
9674	R basal limestone
9714	P anhydrite
9731	C zone
9766	P basal limestone
9796	D zone
9863	lower Red River

NDGS #5382
Eason Oil Co.--Jorgenson #21-44X
S/2 SE 21-129-104
3199 K. B.

9143	Red River
9153	A zone
9163	F basal limestone
9181	R anhydrite
9185	B zone
9197	R basal limestone
9233	P anhydrite
9254	C zone
9289	P basal limestone
9327	D zone
9382	lower Red River

NDGS #5397
Farmers Union Central Exchange, Inc.--M. Miller #4-21
NWNW 21-131-104
3091 K. B.

9555	Red River
9559	A zone
9568	F basal limestone
9592	R anhydrite
9596	B zone
9604	R basal limestone
9642	P anhydrite
9660	C zone
9693	P basal limestone
9722	D zone
9791	lower Red River

NDGS #5402
K. Luff & Hanover Planning--Jett #1-28
NENW 28-124-101
2889 K. B.

9156	Red River
9162	A zone
9172	F basal limestone
9193	R anhydrite
9196	B zone
9202	R basal limestone
9235	P anhydrite
9256	C zone
9280	P basal limestone
9325	D zone
9384	lower Red River

NDGS #5403
K. Luff & Hanover Planning--Hughes #1-27
SENW 27-129-103
2967 K. B.

8922	Red River
8930	A zone
8936	F basal limestone
8960	B zone
8966	R basal limestone
9000	C zone
9038	P basal limestone
9074	D zone
9136	lower Red River

NDGS #5421
Rainbow Resources, Inc.--C. Hesterin #2A
SWNE 15-130-104
3145 K. B.

9392	Red River
9403	A zone
9412	F basal limestone
9430	R anhydrite
9434	B zone
9444	R basal limestone
9480	P anhydrite
9502	C zone
9532	P basal limestone
9576	D zone
9631	lower Red River

NDGS #5456
Rainbow Resources, Inc.--Wallman #1-8
NESW 8-130-104
3107 K. B.

9270	Red River
9284	A zone
9289	F basal limestone

9310	R anhydrite
9312	B zone
9320	R basal limestone
9355	P anhydrite
9374	C zone
9405	P basal limestone
9448	D zone
9506	lower Red River

NDGS #5459
Depco, Inc.--Peters #14-29
SWSW 29-130-102
2916 K. B.

9440	Red River
9450	A zone
9460	F basal limestone
9484	B zone
9491	R basal limestone
9529	P anhydrite
9558	C zone
9577	P basal limestone
9624	D zone
9678	lower Red River

NDGS #5492
Eason Oil Co.--Olson #18-34X
SWSE 18-129-104
3223 G. L.

9112	Red River
9124	A zone
9132	F basal limestone
9152	B zone
9164	R basal limestone
9204	P anhydrite
9226	C zone
9264	P basal limestone
9296	D zone
9366	lower Red River

NDGS #5495
Patrick Petr. Corp.--Mann-Grem #1
SENE 4-129-103
3015 K. B.

9225	Red River
9235	A zone
9245	F basal limestone
9266	B zone
9275	R basal limestone
9310	P anhydrite
9336	C zone
9364	P basal limestone
9399	D zone
9465	lower Red River

NDGS #5567
Amax Petr. Corp.--N.D. State #1
SWSE 36-129-106
3008 K. B.

8361	Red River
8373	A zone
8382	F basal limestone
8399	R anhydrite
8401	B zone
8409	R basal limestone
8448	P anhydrite
8462	C zone
8492	P basal limestone
8536	D zone
8590	lower Red River

NDGS #5584
K. Luff & Hanover Planning--Faris et al. #1-22
SESW 22-130-102
2888 K. B.

9288	Red River
9248	A zone
9304	F basal limestone
9329	R anhydrite
9333	B zone
9340	R basal limestone
9375	P anhydrite
9396	C zone
9423	P basal limestone
9470	D zone
9523	lower Red River

NDGS #5618
K. Luff-G. Hughes #1-15
C S/2 N/2 15-129-103
2954 K. B.

9055	Red River
9065	A zone
9074	F basal limestone
9093	B zone
9098	R basal limestone
9136	P anhydrite
9151	C zone
9172	P basal limestone
9220	D zone
9273	lower Red River

NDGS #5651
Depco, Inc.--Nygaard #44-30
SESE 30-130-103
3105 K. B.

9258	Red River
9613	A zone

9626	F basal limestone
9643	R anhydrite
9647	B zone
9658	R basal limestone
9692	P anhydrite
9716	C zone
9745	P basal limestone
9780	D zone
9841	lower Red River

NDGS #5700
Petroleum, Inc.--Arithson #1
SESW 34-129-104
3052 K. B.

8920	Red River
8926	A zone
8934	F basal limestone
8952	R anhydrite
8956	B zone
8966	R basal limestone
9002	P anhydrite
9027	C zone
9042	P basal limestone
9071	D zone
9133	lower Red River

NDGS #5712
K. Luff-Richards #1-28
C E/2 28-130-102
2915 K. B.

9388	Red River
9396	A zone
9405	F basal limestone
9422	R anhydrite
9429	B zone
9437	R basal limestone
9473	P anhydrite
9488	C zone
9526	P basal limestone
9572	D zone
9627	lower Red River

NDGS #5733
Pennzoil Co.--Bagley #1
NESW 11-129-102
2832 K. B.

9204	Red River
9212	A zone
9217	F basal limestone
9244	R anhydrite
9247	B zone
9253	R basal limestone
9287	P anhydrite

9309	C zone
9327	P basal limestone
9378	D zone
9438	lower Red River

NDGS #5745
Farmers Union Central Exchange, Inc.--Miller #6-23
SENW 23-131-104
3244 K. B.

9784	Red River
9796	A zone
9804	F basal limestone
9823	R anhydrite
9828 B zone	
9837	R basal limestone
9876	P anhydrite
9898	C zone
9931	P basal limestone
9962	D zone
10022	lower Red River

NDGS #5772
True Oil Co.--Fisher #11-5
C NWNW 5-131-100
2892 K. B.

10053	Red River
10063	A zone
10073	F basal limestone
10092	R anhydrite
10098	B zone
10106	R basal limestone
10143	P anhydrite
10167	C zone
10193	P basal limestone
10225	D zone
10282	lower Red River

NDGS #5823
K. Luff & Hanover Planning, Inc.--Mosbrucker #1-6
NESE 6-130-102
2961 K. B.

9558	Red River
9565	A zone
9571	F basal limestone
9594	R anhydrite
9597	B zone
9601	R basal limestone
9639	C zone
9679	P basal limestone
9725	D zone
9779	lower Red River

NDGS #5829
Farmland International--Oakland Wick #1-11
C SWNW 11-130-104
3195 K. B.

9529	Red River
9538	A zone
9544	F basal limestone
9570	R anhydrite
9575	B zone
9585	R basal limestone
9622	P anhydrite
9637	C zone
9667	P basal limestone
9702	D zone
9768	lower Red River

NDGS #5865
Depco, Inc.--Fleming #14-32
C SWSW 32-130-102
2918 K. B.

9333	Red River
9340	A zone
9349	F basal limestone
9368	R anhydrite
9372	B zone
9382	R basal limestone
9420	P anhydrite
9442	C zone
9466	P basal limestone
9514	D zone
9570	lower Red River

NDGS #5882
Farmland International--Arithson-Fed. #1-35
SESE 35-129-104
3052 K. B.

8997	Red River
9009	A zone
9016	F basal limestone
9034	R anhydrite
9038	B zone
9050	R basal limestone
9089	P anhydrite
9116	C zone
9146	P basal limestone
9170	D zone
9241	lower Red River

NDGS #5892
Farmland International--Oakland-Nelson #2-11
SESE 11-130-104
3193 K. B.

9463	Red River
9473	A zone
9482	F basal limestone
9502	R anhydrite
9505	B zone
9516	R basal limestone
9553	P anhydrite
9576	C zone
9602	P basal limestone
9636	D zone
9706	lower Red River

NDGS #5895
K. Luff & Rainbow Resources, Inc.--State #1-16
C N/2 N/2 16-130-102
2919 K. B.

9446	Red River
9454	A zone
9460	F basal limestone
9486	R anhydrite
9488	B zone
9494	R basal limestone
9535	P anhydrite
9558	C zone
9610	P basal limestone
9634	D zone
9691	lower Red River

NDGS #5904
Petroleum, Inc.--Hilton #1
C NWNE 34-131-103
3043 K. B.

9700	Red River
9713	A zone
9721	F basal limestone
9740	R anhydrite
9746	B zone
9757	R basal limestone
9798	P anhydrite
9822	C zone
9874	P basal limestone
9880	D zone
9956	lower Red River

NDGS #5709
K. Luff & Pennzoil Co.--F. Paulson #1-24
C W/2 NW 24-130-102
2921 K. B.

9437	Red River
9444	A zone
9453	F basal limestone
9478	R anhydrite
9481	B zone
9487	R basal limestone
9524	P anhydrite
9547	C zone
9573	P basal limestone
9624	D zone

NDGS #5920
K. Luff--M. L. Peters #1-20
NWNE 20-130-102
2960 K. B.

9472	Red River
9481	A zone
9488	F basal limestone
9512	B zone
9518	R basal limestone
9556	P anhydrite
9570	C zone
9612	P basal limestone
9639	D zone
9702	lower Red River

NDGS #5951
K. Luff--W. Anderson #1-3
SWNE 3-130-103
3030 K. B.

9263	Red River
9268	A zone
9278	F basal limestone
9297	R anhydrite
9300	B zone
9313	R basal limestone
9348	P anydrite
9371	C zone
9400	P basal limestone
9425	D zone
9499	lower Red River

NDGS #5967
Petroleum, Inc. et al.--Arithson #1-D
NENW 34-129-104
3039 K. B.

8928	Red River
8941	A zone

8944	F basal limestone
8969	R anhydrite
8972	B zone
8982	R basal limestone
9017	P anhydrite
9044	C zone
9064	P basal limestone
9104	D zone
9166	lower Red River

NDGS #6074
Farmland International et al.--Richards & Southland Royalty #1-2
C SESE 2-129-102
2850 G. L.

9224	Red River
9230	A zone
9239	F basal limestone
9262	R anhydrite
9266	B zone
9273	R basal limestone
9307	P anydrite
9332	C zone
9348	P basal limestone
9394	D zone
9450	lower Red River

BURLEIGH COUNTY

NDGS #155
Continental Oil Co.--Dronen #1
NENE 9-140-75
1901 G. L.

5080	Red River
5140	P argillaceous marker
5230	lower Red River

NDGS #174
Contiental Oil Co.--Dueneland #1
NWNW 3-140-77
1970 G. L.

5775	Red River
5800	A zone
5810	F basal limestone
5816	B zone
5825	R basal limestone
5838	P anhydrite
5850	C zone
5894	P basal limestone
5905	D zone
5960	lower Red River

NDGS #701
C. Hunt Trust Estate--Board of Univ. and School Lands #1
NENE 36-144-75
2023 K. B.

5400	Red River
5456	P argillaceous marker
5582	lower Red River

NDGS #723
C. Hunt Trust Estate--R. P. Schlabach #1
NENE 36-139-76
1877 D. F.

5030	Red River
5088	P argillaceous marker
5186	lower Red River

NDGS #756
C. Hunt Trust Estate--R. A. Nicholson #1
SESE 32-137-77
1890 D. F.

5313	Red River
5375	P argillaceous marker
5500	lower Red River

NDGS #763
C. Hunt Trust Estate--A. Nory #1
SESE 14-144-77
1947 K. B.

6060	Red River
6124	P anhydrite
6140	C zone
6190	P basal limestone
6244	lower Red River

NDGS #765
C. Hunt Trust Estate--Soder Investment Co. #1
SWSW 31-142-76
2027 K. B.

5876	Red River
5944	P argillaceous marker
6040	lower Red River

NDGS #772
C. Hunt Trust Estate--P. Ryberg #1
NWNW 23-140-79
2007 K. B.

6361	Red River
6386	B zone
6393	R basal limestone
6438	P anhydrite
6454	C zone
6496	P basal limestone
6566	lower Red River

DIVIDE COUNTY

NDGS #1546
Kerr McGee Oil Inc., Inc.--A. Johnson #1
NENW 34-162-101
2261 K. B.

11131	Red River
11160	A zone
11172	F basal limestone
11203	B zone
11212	R basal limestone
11250	P anhydrite
11362	lower Red River

NDGS #2010
Carter Oil Co.--D. D. Moore #1
NWNE 7-163-102
2195 K. B.

10390	Red River
10494	P anhydrite
10618	lower Red River

NDGS #4837
Miami Oil Producers, Inc. et al.--R. Hagen #1
SWNE 12-160-100
2112 K. B.

10728	Red River
10830	P anhydrite
10946	lower Red River

NDGS #5192
H. L. Hunt--A. B. Erickson #1
SWNENE 3-160-95
2373 K. B.

11182	Red River
11270	P anhydrite
11382	lower Red River

NDGS #5248
Oil Development Co. of Texas--Rogers #1
NENE 10-160-98
2242 K. B.

10880	Red River
10979	P anhydrite
11098	lower Red River

DUNN COUNTY

NDGS #505
Socony-Vacuum Oil Co., Inc.--C. Dvorak #1
SENE 6-141-94
2296 K. B.

12313	Red River
12330	A zone
12335	F basal limestone
12362	R anhydrite
12374	B zone
12380	R basal limestone
12424	P anhydrite
12442	C zone
12469	P basal limestone

NDGS #793
Socony-Vacuum Oil Co. Pegasus Division--Solomon Bird Bear et al. #F22-22-1
SENW 22-149=91
2102 K. B.

13014	Red River
13190	P anhydrite
13206	C zone
13266	P basal limestone
13284	D zone

NDGS #3044
Amerada Petr. Corp.--M. Selle T-1 #1
NENE 27-143-92
2200 K. B.

12020	Red River
12042	A zone
12049	F basal limestone
12076	R anhydrite
12092	B zone
12104	R basal limestone
12140	P anhydrite

NDGS #4220
Sinclair Oil and Gas. Co.--N. A. Knudsvig #1
SWNE 13-145-94
2210 K. B.

13014	Red River
13039	F anhydrite
13044	A zone
13051	F basal limestone
13074	R anhydrite
13087	B zone
13100	R basal limestone

13139	P anhydrite
13158	C zone
13188	P basal limestone
13222	D zone
13276	lower Red River

NDGS #4611
Hemerich & Payne, Inc.--N.D. State #1
SWSW 36-146-96
2435 K. B.

13771	Red River
13828	R anhydrite
13842	B zone
13853	R basal limestone
13891	P anhydrite
13922	C zone
13950	P basal limestone
13972	D zone
14032	lower Red River

NDGS #4725
Kathol Petr., Inc.--Noble Drilling Corp.--Little Mo #1-24
SWSE 24-148-97
2373 K. B.

14240	Red River

NDGS #4957
Miami Oil Producers, Inc.--Estate of H. Robe #1
NWNW 8-147-93
2212 K. B.

13360	Red River
13390	F anhydrite
13394	A zone
13397	F basal limestone
13429	R anhydrite
13438	B zone
13454	R basal limestone
13488	P anhydrite
13524	C zone
13544	P basal limestone
13572	D zone
13615	lower Red River

NDGS #5621
Mesa Petr. Co.--Roshav #1
NENW 23-142-97
2583 K. B.

12796	Red River
12854	R anhydrite
12859	B zone
12866	R basal limestone
12902	P anhydrite
12927	C zone

12971	P basal limestone
12990	D zone
13052	lower Red River

NDGS #5887
Alpar Resources, Inc.--McNamara #1
SWSW 8-144-92
2203 K. B.

12460	Red River
12484	F anhydrite
12487	A zone
12491	F basal limestone
12514	R anhydrite
12528	B zone
12541	R basal limestone
12575	P anhydrite
12614	C zone
12641	P basal limestone
12676	D zone

NDGS #5971
Amoco Production Co.--G. Carlson #1
C NENW 6-145-94
2360 K. B.

13324	Red River
13350	F anhydrite
13356	A zone
13367	F basal limestone
13382	R anhydrite
13398	B zone
13412	R basal limestone
13450	P anhydrite
13486	C zone
13522	P basal limestone
13540	D zone
13608	lower Red River

NDGS #6086
Amoco Production Co.--B. Selle #1
C NENE 7-145-94
2327 K. B.

13250	Red River
13276	F anhydrite
13284	A zone
13294	F basal limestone
13310	R anhydrite
13323	B zone
13337	R basal limestone
13372	P anhydrite
13406	C zone

13323	B zone
13337	R basal limestone
13372	P anhydrite
13406	C zone

EMMONS COUNTY

NDGS #16
Northern Ordinance-Franklin Investment Co.
C NWNW 35-133-75
1909 D. F.

4290	Red River
4350	P argillaceous marker
4450	lower Red River

NDGS #23
Roeser-Pendelton--J. J. Weber #1
SE 35-133-76
2012 K. B.

4470	Red River
4530	P argillaceous marker
4615	lower Red River

NDGS #43
Peak Drilling Co.--Ohlhauser #1
NESE 8-132-78
1820 K. B.

4750	Red River
4820	P anhydrite

FOSTER COUNTY

NDGS #287
Frazier-Conroy Drilling Co.--S. Dunbar #1
NWNW 13-146-63
1513 G. L.

2290	Red River
2348	P argillaceous marker
2460	lower Red River

NDGS #403
Pure Oil Co.--J. M. Carr #1
NENE 15-146-66
1547 K. B.

2818	Red River
2878	P argillaceous marker
2995	lower Red River

GOLDEN VALLEY COUNTY

NDGS #410
Gulf Oil Corp.--Dorough Fed. #1
NESW 24-143-103
2513 D. F.

12400	Red River
12505	P anhydrite
12640	lower Red River

NDGS #4130
Amerada Petr. Corp.--R. Waldron #1
SWNW 9-138-105
2867 K. B.

11032	Red River
11134	P anhydrite
11283	lower Red River

NDGS #5438
Texas Gas Expl. Corp.--G. M. Brown et al. #1
NENW 27-141-105
2710 G. L.

11558	Red River
11664	P anhydrite
11811	lower Red River

GRANT COUNTY

NDGS #3636
Cardinal-Lone STar-National Bulk Carriers, Inc.--M. Bierwagen #1
SWNE 1-133-90
2350 K. B.

8662	Red River
8666	A zone
8675	F basal limestone
8699	R anhydrite
8704	B zone
8716	R basal limestone
8762	P anhydrite
8778	C zone
8812	P basal limestone
8834	D zone

NDGS #5097
Hemerich & Payne, Inc.--Burlington Northern "J" #27-1
NENW 27-131=88
2512 G. L.

7580	Red River
7611	R anhydrite
7615	B zone

7630	R basal limestone
7673	P anhydrite
7698	C zone
7741	P basal limestone
7768	D zone
7811	lower Red River

NDGS #5118
Hemerich & Payne, Inc.--Burlington Northern "L" #23-1
NESW 23-130-88
2194 G. L.

7026	Red River
7051	R anhydrite
7054	B zone
7068	R basal limestone
7113	P anhydrite
7136	C zone
7192	D zone
7250	lower Red River

NDGS #5496
Wainoco, Inc.--Krause #22-5
SENW 5-134-90
2408 G. L.

9065	Red River
9068	A zone
9078	F basal limestone
9101	R anhydrite
9106	B zone
9117	R basal limestone
9170	P anhydrite
9200	C zone
9228	P basal limestone
9258	D zone

HETTINGER COUNTY

NDGS #511
Socony-Vacuum Oil. Co., Inc.--C. & M. Jacobs F14-24P
SWSW 24-134-96
2614 K. B.

10208	Red River
10217	F anhydrite
10221	A zone
10229	F basal limestone
10249	R anhydrite
10253	B zone
10266	R basal limestone
10301	P anhydrite
10320	C zone

NDGS #4984
Pubco Petr. Corp.--J. Haberstroh #12-2
NWNE 12-135-92
2524 K. B.

9844	Red River
9851	A zone
9860	F basal limestone
9884	R anhydrite
9890	B zone
9900	R basal limestone
9948	P anhydrite
9973	C zone
10000	P basal limestone
10030	D zone
10072	lower Red River

NDGS #5447
W. H. Hunt--V. Senn #1
C SESW 15-136-92
2430 K. B.

9974	Red River
9982	F anhydrite
9990	A zone
10010	R anhydrite
10020	B zone
10029	R basal limestone
10080	P anhydrite
10100	C zone
10122	P basal limestone
10146	D zone

KIDDER COUNTY

NDGS #24
Magnolia Petr. Co.--Dakota "A" Strat. Test
NE 36-141-73
1968 D. F.

4582	Red River
4640	P anhydrite
4650	C zone
4690	P basal limestone
4700	D zone
4766	lower Red River

NDGS #230
Carter Oil Co.--N.D. State #1
NESE 16-143-71
1890 K. B.

4235	Red River
4286	P anhydrite
4290	C zone
4424	lower Red River

NDGS #748
C. Hunt Trust Estate--E. B. Sauter #1
NWNE 32-142-74
1848 K. B.

5026	Red River
5085	P argillaceous marker
5187	lower Red River

LOGAN COUNTY

NDGS #590
C. Hunt Trust Estate--F. M. Fuller #1
SWSE 6-136-73
2011 K. B.

4312	Red River
4364	P argillaceous marker
4489	lower Red River

NDGS #5523
Wise Oil Co. #2 et al.--B. A. Weigel #1
NWNW 29-135-73
2117 K. B.

4240	Red River
4299	P argillaceous marker
4380	lower Red River

MCHENRY COUNTY

NDGS #39
Hunt Oil Co.--W. B. Shoemaker #1
NESW 3-157-78
1480 D. F.

6350	Red River
6412	P argillaceous marker
6545	lower Red River

NDGS #61
Hunt Oil Co.--P. Lennertz #1
NWSE 17-153-77
1570 D. F.

6338	Red River
6400	P argillaceous marker
6530	lower Red River

MCKENZIE COUNTY

NDGS #956
Gulf Oil Corp.--Bennie Pierre Fed. #1
NWSW 28-148-104
2339 D. F.

12763	Red River
12782	F anhydrite
12789	A zone
12798	F basal limestone
12821	R anhydrite
12834	B zone
12849	R basal limestone
12890	P anhydrite
12905	C zone
12944	P basal limestone
12956	D zone
13020	lower Red River

NDGS #2372
Amerada Petr. Corp.--Antelope "A" #1
NWNESE 1-152-95
2117 K. B.

13109	Red River
13144	F anhydrite
13148	A zone
13152	F basal limestone
13174	R anhydrite
13186	B zone
13204	R basal limestone
13240	P anhydrite
13268	C zone
13356	lower Red River

NDGS #2584
Shell Oil Co.-Northern Pacific Railway--State 32-16-1
SWNE 16-145-101
2463 K. B.

13022	Red River
13128	P anhydrite
13273	lower Red River

NDGS #2602
Texaco, Inc.--S. A. Garland #5
NE 6-153-95
1983 K. B.

12920	Red River
13040	P anhydrite
13079	C zone
13104	P basal limestone
13121	D zone
13154	lower Red River

NDGS #3645
Quintana Petroleum Corp.--U.S.A. #1
SESE 24-145-105
2379 K. B.

12184	Red River
12300	P anhydrite
12445	lower Red River

NDGS #3804
Tiger Oil Co.--R. Slaaten #1
NWSW 23-153-95
2344 K. B.

13478	Red River
13606	P anhydrite
13728	lower Red River

NDGS #4062
Shell Oil Co.--22X-28-1
NWSENW 28-148-101
2214 K. B.

13336	Red River
13450	P anhydrite
13612	lower Red River

NDGS #4305
Helmerich & Payne, Inc.--Fed. McKenzie #1 (OWDD-AFE-7607)
NENW 33-146-104
2515 K. B.

12576	Red River
12688	P anhydrite
12836	lower Red River

NDGS #4723
Consolidated Oil & Gas, Inc. & Miami Oil--Fed. Land Bank #1
SENE 23-151-101
2048 K. B.

13416	Red River
13530	P anhydrite
13702	lower Red River

NDGS #4807
Consolidated Oil & Gas, Inc.--Miami Oil--Fed. Land Bank #24-1
NW 24-151-101
2130 K. B.

13588	Red River
13705	P anhydrite
13844	lower Red River

NDGS #5002
General American Oil Co. of Texas--Burlington Northern #1-9
SENW 9-146-103
2372 K. B.

12770	Red River

12840	B zone
12880	P anhydrite
12890	C zone
12917	P basal limestone
12982	D zone

NDGS #5655
Pennzoil Co.--Fed. #25-1
C SW 25-150-104
2170 K. B.

12751	Red River
12871	P anhydrite
12894	C zone

NDGS #5821
Shell Oil Co.--Gov't. #34X-31-1
SWSE 31-149-104
2128 K. B.

12355	Red River
12470	P anhydrite
12485	C zone
12519	P basal limestone
12588	lower Red River

NDGS #5840
Tiger Oil Co.--Fed. #26-1
NESE 26-150-104
2103 K. B.

12744	Red River
12868	P anhydrite
12887	C zone

MCLEAN COUNTY

NDGS #49
Stanolind Oil & Gas Co.--McLean Co. #1
SWSW 28-150-80
2081 G. L.

7996	Red River
8034	R anhydrite
8045	B zone
8060	R basal limestone
8078	P anhydrite
8105	C zone
8250	lower Red River

MERCER COUNTY

NDGS #21
F. F. Kelly - F. Leutz #1
NWNE 28-142-89
2284 D.F.

11160	Red River

MORTON COUNTY

NDGS #1620
Pan Am. Petr. Corp.--R. Yetter #1
NESW 27-139-90
2426 K. B.

10341	Red River
10456	P anhydrite
10579	lower Red River

NDGS #3859
Amerada Petr. Corp.--J. Meyer #1
SENE 34-135-83
2124 K. B.

6920	Red River
6926	A zone
6933	F basal limestone
6951	R anhydrite
6957	B zone
6973	R basal limestone
7008	P anhydrite
7028	C zone
7140	lower Red River

NDGS #3978
Austral Oil Co. Inc.--J. J. Leingang 6524 #1
SENW 34-137-83
2281 K. B.

7048	Red River
7147	P anhydrite
7288	lower Red River

NDGS #5379
Campbell & Partners--Picha #1
C NWNE 5-138-83
1980 K. B.

6527	Red River
6610	P anhydrite
6739	lower Red River

MOUNTRAIL COUNTY

NDGS #4386
Empire State Oil Co. et al.--Vorwerk #1
SESE 28-151-90
2216 K. B.

12810	Red River
12938	P anhydrite
13066	lower Red River

NDGS #5072
Amerada Hess Corp.--A. Erickson #2X
NENE 22-158-94
2367 K. B.

11600	Red River
11689	P anhydrite
11804	lower Red River

OLIVER COUNTY

NDGS #15
Carter Oil Co.--E. L. Semling #1
C SE 18-141-81
2033 D. F.

7644	Red River
7651	F anhydrite
7656	A zone
7660	F basal limestone
7685	R anhydrite
7694	B zone
7707	R basal limestone
7732	P anhydrite
7748	C zone
7822	P basal limestone
7874	lower Red River

NDGS #95
Youngblood & Youngblood--E. Wachter #1
SESW 3-141-81
1924 D. F.

7400	Red River
7475	P anhydrite

NDGS #4940
General American Oil Co. of Texas--R. Henke #1-24
SESW 24-142-85
2231 G. L.

9307	Red River
9405	P anhydrite

PIERCE COUNTY

NDGS #435
Midwest Exploration Co.--Heckman #1
SWNE 12-158-69
1589 D. F.

3992	Red River
4055	P argillaceous marker
4150	lower Red River

NDGS #706
Shell Oil Co.--G. Marchus #1
SESE 23-157-70
1641 G. L.

4200	Red River
4260	P argillaceous marker
4365	lower Red River

NDGS #3920
A. J. Hodges Inc., Inc.--A. Martin #1
SESE 23-152-74
1596 G. L.

5123	Red River
5130	A zone
5134	F basal limestone
5149	B zone
5166	R basal limestone
5183	P argillaceous marker
5210	C zone
5242	P basal limestone
5270	D zone
5300	lower Red River

ROLETTE COUNTY

NDGS #316
T. M. Evans Production Corp.--A. J. Johnson #1
NWSW 23-160-70
1680 G. L.

4180	Red River
4248	P argillaceous marker
4345	lower Red River

SHERIDAN COUNTY

NDGS #665
Caroline Hunt Trust Estate--J. Waltz, Sr. #1
NENE 15-148-76
1793 K. B.

5954	Red River
6018	P argillaceous marker

NDGS #684
C. Hunt Trust Estate--J. R. Matz #1
NENE 1-147-75
1849 K. B.

5544	Red River
5600	P argillaceous marker
5740	lower Red River

NDGS #693
C. Hunt Trust Estate--W. E. Bauer #1
SWSW 19-146-76
1984 K. B.

6270	Red River
6334	P anhydrite
6354	C zone
6406	P basal limestone
6458	lower Red River

NDGS #735
C. Hunt Trust Estate--C. A. Pfeiffer #1
SWSW 16-146-74
1994 K. B.

5500	Red River
5552	P anhydrite
5558	C zone
5625	P basal limestone
5690	lower Red River

SIOUX COUNTY

NDGS #631
Ohio Oil Co.--Standing Rock Sioux Tribal #1
NESW 29-131-80
1730 D. F.

5050	Red River
5122	P anhydrite
5128	C zone
5190	P basal limestone
5236	lower Red River

SLOPE COUNTY

NDGS #91
Deep Rock Stanolind--J. Brusich #1
SESE 8-135-98
2801 D. F.

11046	Red River
11147	P anhydrite
11300	lower Red River

NDGS #3383
Pan Am. Petr. Corp.--L. Foreman #1
SWSE 23-133-106
2787 G. L.

9147	Red River
9158	F anhydrite
9162	A zone
9172	F basal limestone
9184	R anhydrite
9190	B zone
9203	R basal limestone
9241	P anhydrite
9266	C zone
9296	P basal limestone
9326	D zone
9370	lower Red River

NDGS #3588
Sun Oil Co.--Greer Fed. #1
SESE 21-134-105
2895 K. B.

9894	Red River
9913	A zone
9918	F basal limestone
9938	B zone
9948	R basal limestone
9985	P anhydrite
10007	C zone
10053	P basal limestone
10073	D zone
10114	lower Red River

NDGS #4075
H. L. Hunt--NPRR "A" #1
NESW 9-136-101
2777 K. B.

11241	Red River
11287	B zone
11298	R basal limestone
11338	P anhydrite
11363	C zone
11396	P basal limestone
11424	D zone
11482	lower Red River

NDGS #4124
H. L. Hunt--E. Hayden #1
NWSE 4-136-101
2729 G. L.

11273	Red River
11319	B zone
11330	R basal limestone

11369	P anhydrite
11388	C zone
11417	P basal limestone
11438	D zone
11496	lower Red River

NDGS #4241
H. L. Hunt--NPRR "A" #3
NENW 23-136-101
2868 K. B.

11325	RedRiver
11339	F anhydrite
11342	A zone
11349	F basal limestone
11367	R anhydrite
11370	B zone
11380	R basal limestone
11424	P anhydrite
11444	C zone
11475	P basal limestone
11492	D zone
11564	lower Red River

NDGS #4280
Amerada Petr. Corp.--I. Mitchell #1
NESW 18-135-103
2971 K. B.

10787	Red River
10798	A zone
10808	F basal limestone
10820	R anhydrite
10829	B zone
10838	R basal limestone
10880	P anhydrite
10902	C zone
10941	P basal limestone
10976	D zone
11010	lower Red River

NDGS #4749
States Oil Co.--J. J. Sedevie #1
SWNW 33-133-101
2976 K. B.

10443	Red River

NDGS #5210
Belco Petr. Corp.--Cannonball #3-3
NENW 3-133-100
2975 K. B.

10678	Red River
10767	P anhydrite
10914	lower Red River

NDGS #5933
J. Chambers--H. J. Burke #1
SESW 9-133-102
2897 K. B.

10341	Red River
10427	P anhydrite
10565	lower Red River

STARK COUNTY

NDGS #850
W. H. Hunt--A. Privratsky #1
NWNW 15-138-98
2650 K. B.

11894	Red River
11908	A zone
11917	F basal limestone
11948	B zone
11958	R basal limestone
11994	P anhydrite
12027	C zone
12146	lower Red River

NDGS #3515
Continental Oil Co.--C. Stoxen #1
NWNW 9-140-93
2277 K. B.

11430	Red River
11468	R anhydrite
11482	B zone
11496	R basal limestone
11529	P anhydrite
11546	C zone
11573	P basal limestone
11596	D zone
11660	lower Red River

NDGS #4134
Texaco, Inc.--A. Schrank (NCT-1) #1
NWSE 15-137-92
2341 K. B.

10165	Red River
10171	F anhydrite
10173	A zone
10176	F basal limestone
10218	B zone
10227	R basal limestone
10268	P anhydrite
10282	C zone
10310	P basal limestone
10335	D zone
10408	lower Red River

NDGS #4182
Texaco Inc.--A. Schrank (NCT-1) #2
C SW 23-137-92
2344 K. B.

10162	Red River
10168	A zone
10174	F basal limestone
10201	R anhydrite
10211	B zone
10224	R basal limestone
10265	P anhydrite
10282	C zone
10309	P basal limestone
10334	D zone
10408	lower Red River

NDGS #4311
Union Oil Co. of Calif.--V. H. Kudrna #1
NESW 20-139-97
2560 K. B.

11969	Red River
12014	R anhydrite
12022	B zone
12035	R basal limestone
12072	P anhydrite
12102	C zone
12136	P basal limestone
12160	D zone

NDGS #5142
Bridger Petr. Corp.--B. Kilzer #1
SENE 9-137-92
2326 K. B.

10260	Red River
10365	P anhydrite
10492	lower Red River

NDGS #5143
Lone Star Producing Co.--Wanner #1
NENW 9-137-97
2688 K. B.

11612	Red River
11712	P anhydrite

NDGS #5255
Continental Oil Co.--Feimer-Anger #1
NESW 22-137-95
2717 K. B.

11258	Red River
11363	P anhydrite

STUTSMAN COUNTY

NDGS #40
Barnett Drilling Inc.--John Gaier #1
NWNW 11-141-67
1857 G. L.

3220	Red River
3270	P argillaceous marker
3350	lower Red River

NDGS #134
General Atlas Carbon Co.--F. Borthel #1
SWNE 15-142-65
1551 D. F.

2540	Red River
2600	P argillaceous marker
2700	lower Red River

NDGS #668
Calvert Exploration Co.--M. Meyers #1
SESW 25-137-67
1907 K. B.

2817	Red River
2877	P argillaceous marker
2994	lower Red River

NDGS #669
Calvert Exploration Co.--C. Rav #1
SESW 35-139-68
1880 K. B.

3172	Red River
3226	P argillaceous marker
3336	lower Red River

NDGS #670
Calvert Exploration Co.--D. C. Wood #1
SESW 24-139-67
1874 K. B.

2940	Red River
2996	P argillaceous marker
3117	lower Red River

NDGS #672
Calvert Exploration Co.--V. Wanzek #1
NWNW 12-139-67
1867 K. B.

3002	Red River
3062	P argillaceous marker
3166	lower Red River

NDGS #673
Calvert Exploration Co.--F. L. Robertson #1
NENE 26-138-67
1919 K. B.

2897	Red River
2972	P argillaceous marker
3088	lower Red River

WARD COUNTY

NDGS #105
Stanolind Oil and Gas Co.--W. & I. Waswick #1
SWNE 2-153-85
2175 K. B.

10082	Red River
10105	A zone
10115	F basal limestone
10136	R anhydrite
10144	B zone
10160	R basal limestone
10190	P anhydrite
10215	C zone
10340	lower Red River

NDGS #126
Quintana Production Co.--C. W. Linnerte #1
SWSE 33-156-83
1772 D. F.

8660	Red River
8750	P anhydrite
8905	lower Red River

NDGS #588
W. H. Hunt--F. C. Neumann #1
SWSE 33-152-82
2086 D. F.

8815	Red River
8900	P anhydrite
9070	lower Red River

NDGS #4990
Anschutz Corp., Inc. et al.--R. Musch #1
NWSW 22-156-84
1788 K. B.

9034	Red River
9086	P anhydrite
9262	lower Red River

WELLS COUNTY

NDGS #207
Continental Oil Co.--Lueth #1
SESE 27-146-73
1933 K. B.

5032	Red River
5084	P anhydrite
5214	lower Red River

NDGS #609
C. Hunt Trust Estate--G. Leitner #1
SWSE 14-148-71
1601 G. L.

4220	Red River
4280	P anhydrite
4286	C zone
4330	P basal limestone
4360	D zone
4430	lower Red River

NDGS #689
C. Hunt Trust Estate--N. Thormodssard #1
NENE 31-147-71
1702 K. B.

4404	Red River
4462	P anhydrite
4602	lower Red River

NDGS #1211
Calvert Drilling Inc.--F. Zwinger #1
NENE 8-146-68
1608 K. B.

3510	Red River
3570	P argillaceous marker
3640	P basal limestone
3656	D zone
3713	lower Red River

WILLIAMS COUNTY

NDGS #999
Texaco Inc.--J. M. Donahue #1
SWNE 23-154-100
2253 K. B.

13858	Red River
13889	A zone
13902	F basal limestone
13922	R anhydrite
13928	B zone

13946	R basal limestone
13977	P anhydrite
13994	C zone

NDGS #1231
Amerada Petr. Corp.--Beaver Lodge Ord. #1
NE 2-155-96
2316 K. B.

12670	Red River
12726	R anhydrite
12732	B zone
12758	R basal limestone
12772	P anhydrite
12784	C zone
12826	P basal limestone
12847	D zone
12874	lower Red River

NDGS #1385
Amerada Petr. Corp.--N.D. "A" #9
C SW 16-156-95
2360 K. B.

13128	Red River
13248	P anhydrite
13352	lower Red River

NDGS #1403
Amerada Petr. Corp.--Beaver Lodge Dev. #B304
NESWNE 15-155-96
2165 K. B.

12658	Red River
12686	A zone
12702	F basal limestone
12720	R anhydrite
12726	B zone
12734	R basal limestone
12774	P anhydrite
12808	C zone
12832	P basal limestone
12854	D zone
12884	lower Red River

NDGS #1636
Amerada Petr. Corp.--B.L.O.V. #2
SW 17-156-95
2401 K. B.

12992	Red River
13115	P anhydrite
13204	lower Red River

NDGS #4321
Amerada Petr. Corp.--N.D. "C" "B" #9
NWSW 36-158-95
2457 K. B.

12725	Red River
12790	P anhydrite
12948	lower Red River

NDGS #4323
Amerada Petr. Corp.--Lalim-Ives #1
NESW 26-158-95
2460 K. B.

12589	Red River
12702	P anhydrite
12800	lower Red River

NDGS #4618
Amerada Petr. Corp.--N. Trosstad #1
NENW 17-156-103
2413 K. B.

12766	Red River
12883	P anhydrite
13000	lower Red River

NDGS #4916
L. Hunt--P. Haarstad #1
NESW 29-156-102
2409 K. B.

13215	Red River
13290	R anhydrite
13299	B zone
13312	R basal limestone
13338	P anhydrite
13348	C zone
13368	P basal limestone
13408	D zone

NDGS #5912
Amerada Hess Corp.--B.L.O. #6
NESW 35-156-96
2294 K. B.

12794	Red River
12906	P anhydrite
13022	lower Red River

RICHLAND COUNTY, MONTANA

Shell Oil Co.--Swigart #24X-8
8-22-60
2183 K. B.

12387	Red River
12462	R anhydrite
12474	B zone
12480	R basal limestone
12512	P anhydrite
12536	C zone
12579	D zone

APPENDIX B

CORE DESCRIPTIONS

(This appendix consists of well core descriptions arranged alphabetically by county, and numerically within counties by NDGS well number).

BILLINGS COUNTY

NDGS #1678

12025	Red River top
12178-190	brown dolomitic mudstone, parts laminated, desiccation
12190-192	gray mudstone, laminated, stylolites
12192-200	brown dolomitic mudstone, fine grained, occasional laminations
12200-205	missing
12205-208	brown dolomitic mudstone, as above
12208-216	mottled brown mudstone, dolomitic, coarse/fine grained, anhydrite vug fillings and crystals, porous, possibly burrowed
12216-233	mottled brown mudstone, as above, with heavy oil stain, vuggy porosity

BOTTINEAU COUNTY

NDGS #38

7238	Red River top
7286-7289	tan mudstone, laminated, anhydritic
7289-91	nodular anhydrite
7291-92	tan mudstone, laminated
7292-95	nodular anhydrite
7295-96	brown dolomitic mudstone, anhydritic
7296-97	nodular anhydrite
7297-98	brown dolomitic mudstone, laminated, anhydritic
7298-7301	brown mudstone, anhydritic, irregularly bedded
7301-319	dolomitic mudstone, light brown, occasional lamitations, anhydritic, parts very porous
7319-33	gray brown wacke-packstone, bioturbated, anhydritic, stylolitic, grouped laminations, low porosity
7333-36	nodular anhydrite

NDGS #286

5733	Red River top
5756-59	gray wacke-packstone, grouped laminations, possibly burrowed
5759-62	light brown mudstone, laminated, burrowed, low porosity
5763-68	missing
5768-83	very light brown dolomitic mudstone, chalky, laminated, porous
5783-98½	gray wacke-packstone, bioturbated, grouped laminations, anhydritic, some porosity
5798½-5801	argillaceous dolomitic mudstone
5801-803	nodular anhydrite

BOWMAN COUNTY

NDGS #516

10398	Red River top
10415-425	gray wacke-packstone, bioturbated, grouped laminations, anhydritic, calcite spar
10425-433	gray mudstone, laminated, anhydritic, gradational with above
10433-437	black and white nodular anhydrite, some laminations
10437-440	gray mudstone, laminated, bedded, burrows, amjudritic, possible cut and fill
10440-443	brown dolomitic mudstone, convoluted laminations, fine grained
10443-445	brown/gray porous mudstone, laminated, fine grained, no porosity

NDGS #4669

9604	Red River top
9810-811½	brown dolomitic mudstone, stylolites, possible burrows
9811½-814	brown mud-wackestone, burrowed, preferentially dolomitized, stylolites
9814-821	brown mud-wackestone, burrowed, pervasively dolomitized, porous, oil stain
9825-827	black wacke-packstone, abundant organics, parts laminated, occasional stylolites
9827-830	brown dolomitic mudstone, laminated, porous
9830-833	brown wackestone, burrowed, preferentially dolomitized, coarse crystalline matrix
9833-835	black wacke-packstone, abundant organics, parts laminated, occasional stylolites
9835-836	brown dolomitic mudstone, possible intraclasts, laminated, porous
9836-838	gray mudstone-wackestone, laminated
9838-841	brown mudstone-wackestone, burrowed, pervasively dolomitized, porous, oil stain
9841-843	black wacke-packstone, abundant organics, parts laminated
9843-863	gray wacke-packstone, dolomitized

NDGS #5070

9222	Red River top
9396-9400½	brown wackestone, burrowed, preferentially dolomitized, stylolites
9400½-402	black wacke-packstone, abundant organics, parts laminated
9402-404	brown wackestone, burrows preferentially dolomitized, porous, laminated
9404-410	brown wackestone, burrows preferentially dolomitized, porous, some anhydrite filled vugs
9410 -411	brown wacke-packstone, laminated

9411-413½	brown wackestone, burrows preferentially dolomitized, laminated
9413½-418½	brown wackestone, burrows preferentially dolomitized, porous, some anhydrite filled vugs
9418½-419	black wacke-packstone, abundant organics, occasional stylolite
9419-423½	brown wackestone, burrows preferentially dolomitized, anhydrite filled vugs
9423½-424	brown dolomitic mudstone, possibly burrowed
9424-425½	brown dolomitic mudstone, possibly burrowed, porous
9425½-426½	brown dolomitic mud-wackestone, bedded
9426½-439	brown wackestone, burrows preferentially dolomitized, anhydrite filled vugs, porous
9439-439½	black wacke-packstone, abundant organics
9439 -443	brown dolomitic mudstone, possibly burrowed, porous
9443-446	brown waekestone, burrows preferentially dolomitized, anhydrite filled vugs, porous
9446-447	dark brown dolomitic mudstone-wackestone, vague bedding
9447-449	black wacke-packstone, abundant organics, parts laminated
9449-453½	brown wackestone, burrows preferentially dolomitized, anhydrite filled vugs, porous
9453½-456	black wacke-packstone, abundant organics, laminated

NDGS #5227

8916	Red River top
9100-108	brown wackestone, burrows preferentially dolomitized, stylolites
9108-109	black wacke-packstone, abundant organics, parts laminated
9109½-114	brown wackestone, burrows preferentially dolomitized, stylolites
9114-114½	black wackestone, abundant organics
9114½-122	brown wackestone, burrows preferentially dolomitized, stylolites
9122-132½	brown mudstone-wackestone, pervasively dolomitized, porous, large vugs, oil stain
9132½-136	black wacke-packstone, abundant organics, parts laminated
9136½-138	brown dolomitic mudstone, possibly burrowed
9138-141	brown wackestone, burrows preferentially dolomitized, stylolites
9141-146	black wacke-packstone, abundant organics, parts laminated
9146-150½	brown wackestone, pervasively dolomitized, porous, large vugs, oil stain
9150½-152	black wacke-packstone, abundant organics, parts laminated
9152-155	brown wackestone, burrows preferentially dolomitized, stylolites

9155-155½	black wackestone, abundant organics
9155½-159	brown wackestone, burrows preferentially dolomitized, stylolites

NDGS #5262

8937	Red River top
9113-116	brown wackestone, burrows preferentially dolomitized, calcite filled vugs
9116-118½	black wacke-packstone, abundant organics, laminated, parts burrowed
9118½-122	brown wackestone, burrows preferentially dolomitized, calcite filled vugs, oil stain
9122-126	brown mudstone-wackestone, pervasively dolomitized, anhydrite, porous
9126-127	brown wackestone, burrows preferentially dolomitized, calcite filled vugs
9127-130	brown mudstone-wackestone, pervasively dolomitized, anhydrite, porous
9130-131½	black wackestone, abundant organics
9131½-143	brown wackestone, burrows preferentially dolomitized, parts laminated
9143-154	brown mudstone-wackestone, pervasively dolomitized, oil stain
9154-159	brown dolomitic mudstone, few burrows, porous, occasional stylolites
9159-162	brown mudstone-wackestone, pervasively dolomitized, oil stain
9162-163	brown dolomitic mudstone, porous, occasional stylolites
9163-165½	black wacke-packstone, abundant organics, parts laminated
9165½-171	brown mudstone-wackestone, pervasively dolomitized, oil stain
9171-173	black wacke-packstone, abundant organics, parts laminated

NDGS #5270

9350½-352	brown mudstone-wackestone, burrows preferentially dolomitized, stylolites
9352-53	black wackestone, abundant organics, parts laminated
9353-366	brown mudstone, burrows preferentially dolomitized, stylolites
9366-374	brown wackestone, pervasively dolomitized, porous, oil stain
9374-375	black wacke-packstone, abundant organics, parts laminated
9375-80	brown/gray mudstone-wackestone, limited dolomitization
9380-382½	brown mudstone, burrows preferentially dolomitized, stylolites
9382½-383½	brown/gray mudstone-wackestone, pervasively dolomitized, porous

9383 -386	black wacke-packstone, abundant organics, parts laminated
9386-393½	brown wackestone, pervasively dolomitized, porous
9393½-9410	brown mudstone-wackestone, burrows preferentially dolomitized

DIVIDE COUNTY

NDGS #1546

11131	Red River top
11131-143	gray wacke-packstone, grouped laminations

FOSTER COUNTY

NDGS #403

2818	Red River top
2825-833	pink mudstone, very fine grained, pelletal, stylolitic, scattered fossils, possible desiccation
2833-841	pink dolomite mudstone, very fine grained, very porous, possibly intraclasts
2841-883	no core
2883-888	pink to white dolomitic mudstone, very porous, some small vugs, intraclasts, possible desiccation
2888-890	white dolomitic mudstone, chalky, poorly cemented
2890-898	same as 2883-888

HETTINGER COUNTY

NDGS #511

10208	Red River top
10257-260	brown dolomitic mudstone, laminated, anhydrite up upper 6", possible desiccation, porous, scattered fossil fragments
10260-263	gray packstone, bioturbated, grouped laminations, pelletal, stylolitic, anhydritic, calcite spar
10263-270	no core
10270-276	gray packstone, as above
10276-300	no core
10300-312	nodular anhydrite

MCKENZIE COUNTY

NDGS #956

12763	Red River top

12795-797	gray mudstone-wackestone, fossils concentrated in burrows, grouped laminations, pyrite, stylolites
12797-800	brown dolomitic mudstone, laminated, very fine grained
12800-819	gray mudstone to wackestone, bioturbated, intraclasts, grouped laminations, anhydritic, pyrite, stylolites
12819-822	gray/brown mudstone, laminated, anhydritic, low porosity
12822-836	nodular anhydrite
12836-849	brown dolomitic mudstone, fine grained, convoluted laminations, anhydritic, stylolites, desiccated, parts burrowed
12849-852	brown dolomitic mudstone-wackestone, fine grained, few laminations, burrowed, possibly desiccated.
12852-858	gray wackestone, bioturbated, stylolitic, sparry calcite vug fillings
12858-860	brown dolomitic mudstone, no laminations
12860-893	gray wacke-packstone, bioturbated, grouped laminations, spar vug fillings, anhydrite, some pellets
12893-894	brown dolomitic mudstone, anhydrite, no porosity
12894-901	nodular anhydrite, thin dolomite interbeds
12901-905	nodular anhydrite

NDGS #2373

13110	Red River top
13110-111	mottled gray wackestone
13111-125	missing
13125-131	gray wacke-packstone, intraclasts, grouped laminations, anhydrite
13131-135½	bedded anhydrite
13135½-139	brown dolomitic mudstone, vague bedding
13138-145	dark gray mudstone, bioturbated, laminated, anhydrite
13145-156	dark gray wacke-packstone, bioturbated, pelletal, laminated, some spar, scattered porosity
13156-165	nodular anhydrite, dolomitic
13165	shale, non-calcareous, approx. 1 inch thick
13165-168	nodular anhydrite
13168-178	brown dolomitic mudstone, parts laminated, parts with anhydrite
13178-186	brown dolomitic mudstone, parts laminated, anhydrite, possibly desiccated
13186-225	dark gray wacke-packstone, blocky, grouped laminations, anhydrite, pelletal areas, intraclasts, desiccated, parts burrowed, cut and fill
13225-239	nodular anhydrite, dolomitic
13239-244	nodular anhydrite
13244-249	brown dolomitic mudstone, anhydrite, occasional laminations
13249-251½	nodular anhydrite, dolomitic
13251½-261	brown dolomitic mudstone, anhydrite, laminated

NDGS #2602

12927	Red River top
12996-13001	brown dolomitic mudstone, fine grained, laminated, desiccated, occasional burrows, anhydrite, parts pelletal, oil stain
13001-038	gray wacke-packstone, grouped laminations, spar and anhydrite vug fillings, scattered open vugs
13138-041	dark bedded anhydrite, dolomitic, dolomite intraclasts

NDGS #5821

12425-432	nodular anhydrite
12432-447	brown dolomitic mudstone, laminated, anhydrite near top, pyrite
12447-479	gray wacke-packstone, bioturbated
12479-482	bedded anhydrite, dolomitic
12482-484½	brown dolomitic mudstone, laminated, heavy oil stain
12484½-491	nodular anhydrite
12491-523	brown dolomitic mudstone, part laminated, part oil stained, stylolites, anhydritic
12523-528	brown/black dolomitic mudstone, oil stain
12528-550	gray wacke-packstone, bioturbated, stylolites
12550-552	black wacke-packstone, abundant organics, laminated
12552-553	brown mudstone, burrowed, limited dolomitization
12553-555	brown mudstone-wackestone, burrows preferentially dolomitized
12555-556½	brown mudstone-wackestone, pervasively dolomitized, porous, vugs, oil stain
12556½-557½	brown mudstone-wackestone, burrows preferentially dolomitized, oil stain in burrows
12557½-563	brown dolomitic mudstone, laminated, burrowed
12563-576	brown mudstone-wackestone, burrowed, limited dolomitized
12576-576½	black wacke-packstone, abundant organics, laminated
12576½-582	brown wackestone, burrowed, limited dolomitization, stylolites
12582-583	black wacke-packstone, abundant organics, parts laminated
12583-587	brown wackestone, burrowed, limited dolomitization, stylolites
12587-588½	black wackestone, abundant organics, laminated
12588½-592	brown wackestone, burrowed, limited dolomitization
12592-593	black wackestone, abundant organics

MCLEAN COUNTY

NDGS #49

7996	Red River top
8066-70	gray wacke-packstone, bioturbated, anhydritic, grouped laminations, low porosity

SLOPE COUNTY

NDGS #3588

9894	Red River top
9989-9991	brown dolomitic packstone, anhydrite, porous
9991-9992	brown mudstone, intraclasts, bioturbated, anhydrite, laminated, some pellets
9992-9993	brown dolomitic mudstone, anhydrite, porous
9993-9995	bedded/nodular anhydrite
9995-9999	brown dolomitic mudstone, laminated, anhydrite, some burrows, possibly desiccated

NDGS #4241

11325	Red River top
11436-443	brown dolomitic mudstone, irregular laminations, anhydrite
11443-446	bedded/nodular anhydrite

STARK COUNTY

NDGS #4182

10160	Red River top
10160-162	gray/brown packstone, grouped laminations, bioturbated
10162-165	brown dolomitic mudstone, laminated, intraclasts, desiccated
10165-174	gray/brown mudstone, laminated, anhydrite, parts bioturbated, stylolites
10174-191	gray wackestone, grouped laminations, bioturbated, anhydrite, stylolites
10191-202	nodular anhydrite
10202-205	brown dolomitic mudstone, porous, no laminations
10205-214	brown mudstone, laminated, anhydrite, microspar, scattered porosity
10214-230	gray wacke-packstone, grouped laminations, stylolites, microspar fossil replacement

NDGS #4311

11969	Red River top
12020-031½	brown dolomitic mudstone, laminated, anhydrite, porous
12031½-035	dark gray packstone, bioturbated, stylolites, calcite vug fillings, pelletal areas
12035-037	gray wacke-packstone, grouped laminations, bioturbated, microspar, stylolites
12095-096	brown dolomitic mudstone, intraclasts, porous
12096-097	dark gray mud-wackestone, bioturbated, laminated, intraclasts, anhydrite vug fillings

12097-100	bedded/nodular anhydrite
12100-102	brown dolomitic mudstone, laminated, anhydrite
12102-105	nodular anhydrite
12105-115	brown dolomitic mudstone, laminated, anhydrite, intraclasts, pellets
12115-123	brown mud-wackestone, laminated, anhydrite, sparry, porous, possible desiccation
12123-130½	gray packstone, bioturbated, stylolites, microspar, laminations
12130½-132	brown mudstone, desiccated, laminated, stylolites
12132-136	brown dolomitic mudstone, few laminations

WARD COUNTY

NDGS #105

10082	Red River top
10157-74	light brown mudstone, laminated, anhydritic, some pellets, no porosity
10174-88	gray wacke-packstone, anhydritic, possible desiccation in upper part
10188-89	shale, anhydritic, non-calcareous, approximately 1 inch thick
10189-202	dolomitic nodular anhydrite, dolomite laminations, occasional burrows
10202-204	light brown dolomitic mudstone, fine grained, faintly bedded
10204-208	nodular anhydrite
10208-210	light brown mudstone, laminated, anhydritic, stylolitic, possible desiccation, no porosity
10210-220	nodular anhydrite, parts dolomitic
10220-223	brown to gray mudstone, dolomitic, anhydritic
10223-227	light brown mudstone, laminated, anhydritic

WILLIAMS COUNTY

NDGS #1231

12670	Red River top
12676-701	mottled gray wackestone, dolomitic, grouped laminations, burrowed
12701-703	brown dolomitic mudstone, bedded, anhydrite near bottom
12703-705	nodular anhydrite, dolomitic
12705-708	brown dolomitic mudstone, occasional laminations, possible desiccation
12708-721	mottled dark gray wackestone, blocky, anhydrite vug fillings, pyrite, occasional stylolites
12721-730	white to black nodular anhydrite, parts dolomitic
12730-737	brown dolomitic mudstone, occasional laminations, few stylolites

12737-741	brown dolomitic mudstone, laminated, anhydrite, rare pyrite
12741-745	brown dolomitic mudstone, convoluted laminations, anhydrite
12745-748	brown dolomitic mudstone, few laminations, occasional stylolites, possibly anhydrite·
12748-754½	dark gray wackestone, blocky, anhydrite vug fillings
12754½-758	brown dolomitic mudstone, intraclasts, convoluted laminations
12758½-770	gray wacke-packstone, parts blocky, anhydrite
12770-771	brown dolomitic mudstone, laminated and convoluted laminations
12771-777½	nodular anhydrite, dolomitic at upper and lower contacts
12777½-778	brown dolomitic mudstone
12778-779	dark nodular anhydrite, dolomitic
12779-780	brown dolomitic mudstone
12780-782	dark nodular anhydrite, dolomitic
12782-785	dark brown dolomitic mudstone, laminated, intraclasts, anhydrite
12785-798	brown dolomitic mudstone, laminated, anhydrite
12798-804	brown dolomitic mudstone, convoluted laminations, some porosity
12804-815	brown dolomitic mudstone, laminated
12815-826	brown dolomitic mudstone, convoluted laminations
12826-836	dark mottled dolomitic wackestone, carbonaceous
12836-844	mudstone-wackestone, pervasively dolomitized, burrowed, oil stain
12844-850	gray wacke-packstone, grouped laminations
12850-858	mudstone-wackestone, pervasively dolomitized, burrowed, oil stain
12858-860	gray wacke-packstone, grouped laminations
12860-870	mudstone-wackestone, pervasively dolomitized, burrowed, oil stain
12870-872	gray wacke-packstone, grouped laminations
12872-873	mudstone-wackestone, pervasively dolomitized, burrowed, oil stain
12873-890	gray wacke-packstone, grouped laminations

NDGS #1403

12659	Red River top
12659-691½	mottled gray wackestone, dolomitic
12691½-692½	brown dolomitic mudstone, fine grained
12692½-694½	missing
12694½-695½	nodular anhydrite
12695½-697½	brown dolomitic mudstone, laminated, some convoluted laminations
12697½-716	missing
12716-725	nodular anhydrite, dolomitic
12725-727	gray mudstone, fine grained, porous
12727-746	brown dolomitic mudstone, fine grained, some parts laminated, porous

12746-769½	gray wacke-packstone, bioturbated, grouped laminations, intraclasts, anhydrite vug fillings
12769½-776½	nodular anhydrite, dolomite laminations
12776½-779	brown dolomitic mudstone, laminated, convoluted laminations at lower contact
12779-784½	nodular anhydrite, parts dolomitic
12784½-797	brown dolomitic mudstone, parts laminated, porous
12797-798	nodular anhydrite, dolomitic mudstone intraclasts
12798-805	brown dolomitic mudstone, parts laminated, intraclasts
12805-810	missing
12810-814	brown dolomitic mudstone, as above
12814-825	missing
12825-832	dark brown dolomitic mudstone, convoluted laminations, wackestone intraclasts
12832-853	gray wacke-packstone, bioturbated, grouped laminations
12853-877	mottled dark brown wacke-packstone, pervasively dolomitized, anhydrite vug fillings, some scattered open vugs
12877-13000	gray wacke-packstone, grouped laminations

NDGS #4916

13215	Red River top
13250-254	mottled gray wackestone
13254-255	brown dolomitic mudstone, intraclasts
13255-255½	bedded/nodular anhydrite
13255½-259½	brown dolomitic mudstone, parts laminated
13259½-281	gray/brown wacke-packstone, parts laminated, parts with high organic content
13281-291	bedded/nodular anhydrite, dolomitic
13291-295½	brown dolomitic mudstone, abundant large individual anhydrite nodules
13259½-304½	brown dolomitic mudstone, parts laminated
13304½-310	brown dolomitic mudstone, occasional laminations, more organics than above, some oil stain

RICHLAND COUNTY, MONTANA

SHELL OIL CO.-Swigart #24X-8

12455-462	gray/brown mudstone, parts laminated, anhydritic
12462-465½	brown/black dolomitic mudstone, interlaminated anhydrite, flame structures
12465½-477	nodular anhydrite
12477-493	brown dolomitic mudstone, parts laminated, desiccated, stylolites, anhydrite
12493-498	light gray mudstone, parts laminated, anhydrite possible burrows
12498-502	brown dolomitic mudstone, laminated, anhydrite

12502-523	light gray mudstone, parts laminated, anhydrite possible burrows
12523-531½	brown dolomitic mudstone, laminated, anhydrite
12531½-540	nodular anhydrite
12540-553	light brown dolomitic mudstone, parts laminated
12553-559	dark brown dolomitic mudstone, laminated
12559-562	light brown dolomitic mudstone, laminated
12562-570	brown dolomitic mudstone, parts laminated
12570-575	brown/black dolomitic mudstone, oil stain

APPENDIX C

DESCRIPTION OF PRIMARY AND DIAGENETIC FEATURES OF THE MAJOR LITHOFACIES UNITS IN THE UPPER RED RIVER

DESCRIPTION OF PRIMARY AND DIAGENETIC FEATURES OF THE MAJOR LITHOFACIES UNITS IN THE UPPER RED RIVER

"D" Zone

In cores of the burrowed facies of the "D" zone, the following features are visible:

- primary fabrics that range from sparsely fossiliferous mudstone to skeletal wackestone
- light to dark brown color
- individual, discrete burrows with sub-circular cross sections 3 to 5 mm in diameter
- rare desiccation fractures
- a fossil assemblage that includes brachiopods, echinoderms, infrequent corals
- variable amounts of dolomite, often confined to burrows or an aureole of sediment surrounding the burrows, though in some instances more than 75% of the rock is dolomite
- common stylolites and solution laminations, which often outline the dolomite areas
- elongate solution vugs up to 1 cm in diameter and 5 cm long, or of irregular shape occur, usually in the pervasively dolomitized horizons
- varies from very low to very good permeability

In thin section, the following features are also visible:

- euhedral dolomite rhombs "floating" in the mud matrix
- "V" shaped fractures in some of the dolomitized burrows, that radiate from the center of the burrow and terminate at the edge of the dolomite
- limpid dolomite filling the "V" fractures and small vugs at the centers of burrows
- a large percentage of the fossil content that has been dissolved and replaced by microspar or spar.

Typical thin sections of these units are: 1403-D4, 5070-D3, 5070-D4, 5070-D6, 5070-D11, 5262-D2, 5262-D4, 5402-D3, 5042-D4, 5402-D5, 5402-14

In cores of the organic facies of the "D" zone, the following features are visible:

- primary fabrics that range from skeletal wackestone to packstone
- very dark gray to black color
- infrequent burrows
- a fossil assemblage that includes brachiopods, echinoderms, trilobites and occasional bryozoans
- abundant organic detritus, occurring concentrated in dense black laminations as dark flecks scattered throughout the rock
- limited development of stylolites

low permeability
white, fossiliferous grainstone layers 1 to 7 cm thick, cemented with microspar, containing little or no organic detritus, and having well-defined contacts with the enclosing organic fabric

In thin section, the following features are also visible:

restricted dolomitization, usually associated with the black laminations or stylolites
a large percentage of the fossil content that has been dissolved and replaced by microspar or spar

Typical thin sections of these units are: 5402-D12

"P", "R," and "F" Sequences

In cores of the basal facies of each sequence, the following features are visible:

primary fabrics that range from fossiliferous mudstone, through skeletal wackestone, to sparry skeletal packstone
light to dark gray color
thorough bioturbation resulting in a homogenous fabric at any given horizon
a fossil assemblage that includes brachiopods, echinoderms, trilobites, bryozoans, and occasional rugose corals
some horizons, notably the sparry packstones, are sometimes composed predominantly of bryozoans
black to brown, sub-horizontal, sub-parallel, fine laminations of organic detritus that usually occur grouped together, with the groups scattered throughout the units
abundant stylolites
occasional masses of white anhydrite
low permeability

In thin section, the following features are also visible:

dissolution and replacement with microspar or spar of some of the fossils
limited dolomitization usually associated with stylolites

Typical thin sections of these units are: 105-7, 511-4, 2373-9, 4182-1, 4311-6, SWIG-18

In cores of the "A," "B," and "C" porosity zones the following features are visible:

primary fabrics that range from fine-grained mudstone to dolomitic wackestone
very light brown to dark brown color
rare ghosts of burrows

- frequent desiccation fractures
- frequent anhydrite crystals
- a very sparse fossil assemblage that includes gastropods and brachiopods
- occasional stylolites and solution laminations
- horizons with abundant brown, wispy laminations
- horizons of sub-parallel, organic-rich laminations of possible algal origin
- mineralogy varying from 100% calcite to greater than 90% fine-grain dolomite
- negligible porosity in the undolomitized horizons, ranging to very good porosity in the pervasively dolomitized horizons

In thin sections, the following features are also visible:

- pelletal packstone fabrics, in which the pellets are cemented by dolomite but are not dolomite themselves
- horizons of intraclasts
- cut and fill structures
- fine-grained, rhombic dolomite crystals
- pinpoint porosity
- intercrystalline porosity
- individual acicular anhydrite crystals, and masses of anhydrite

Typical thin sections of these units are: 505-2, 511-2, 2602-1, 4182-5A, 4182-6, 4182-10, 4812-12, 4311-1, 4311-2, 4311-10, 4311-11, 4311-17, SWIG-2, SWIG-7

In cores of the capping anhydrite units of each sequence, the following features are visible:

- nodular to thinly laminated anhydrite, often with interlaminations of dolomite
- white, very light brown, to black color
- impermeable
- soft sediment deformation features
- occasional thin dolomite interbeds

Typical thin sections of these units are: 2373-4, SWIG-4

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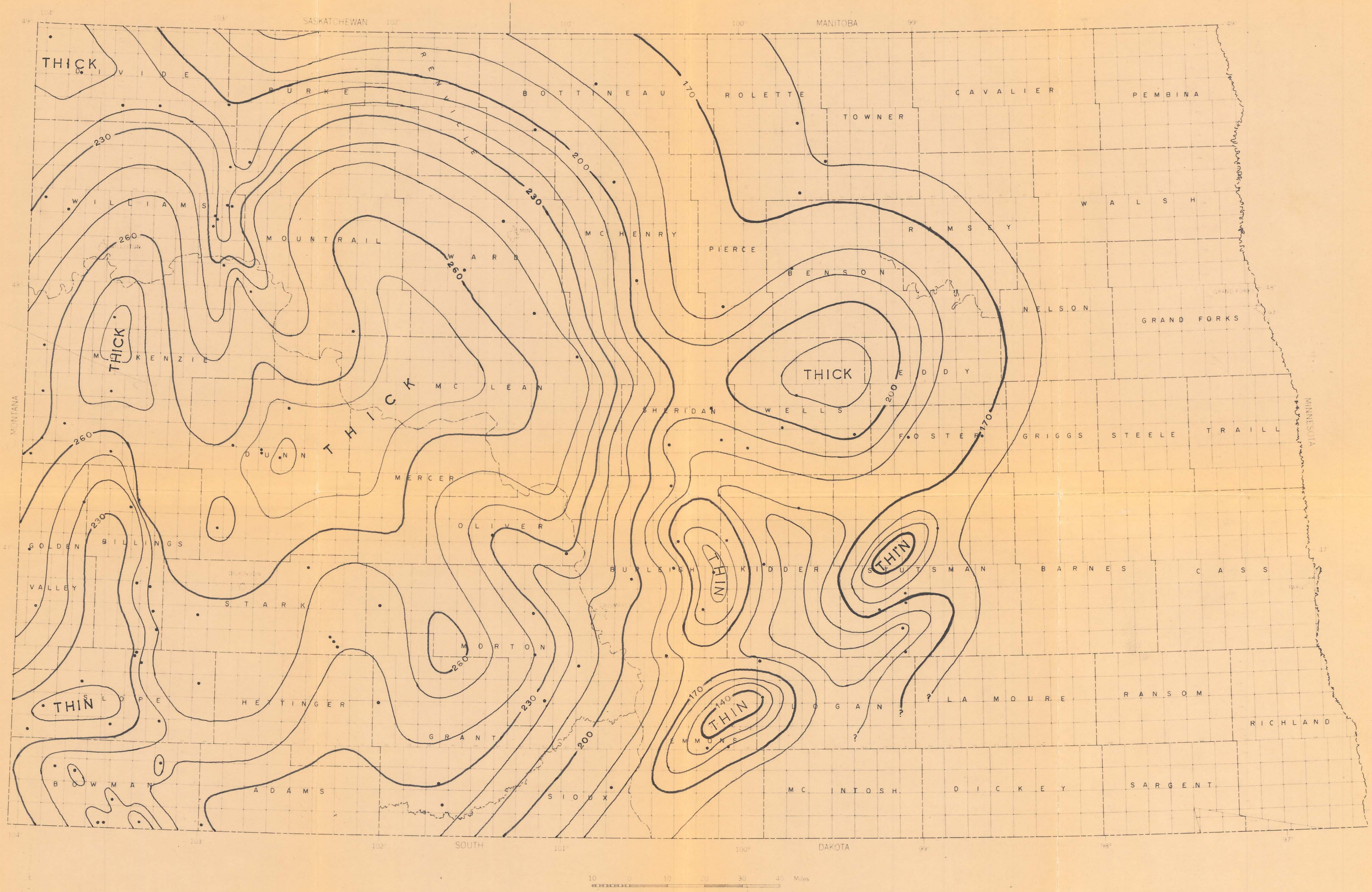
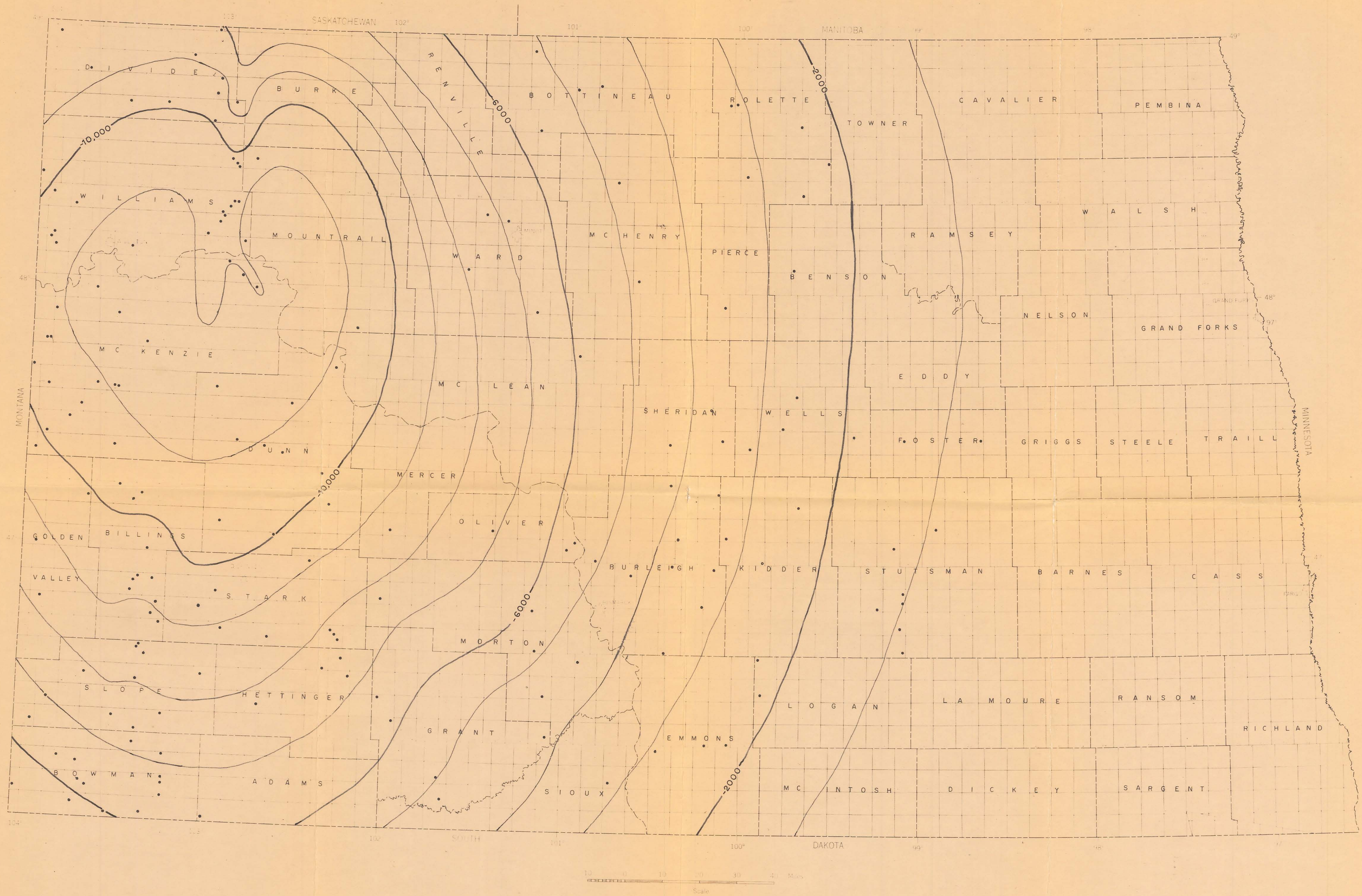


ISOPACH -- UPPER RED RIVER

CONTOUR INTERVAL: 10.0 FEET

PLATE 1

W. K. CARROLL



STRUCTURE CONTOUR -- RED RIVER TOP

CONTOUR INTERVAL: 1000.0 FEET

PLATE 2

W. K. CARROLL

PLATE 3
W. K. CARROLL

ISOPACH -- UPPER RED RIVER:

"D" ZONE THROUGH "P" ANHYDRITE

CONTOUR INTERVAL: 10.0 FEET

PLATE 4

W. K. CARROLL