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Little Knife Field

Robert F. Lindsay and Christopher G. St. C. Kendall

RESERVOIR SUMMARY

Location & Geologic Setting	Billings, Dunn and McKenzie Co.'s (T144 & 145N, R97 & 98W, Williston Basin, North Dakota, USA
Tectonics	Linear block and wrench-fault tectonics, recurrent basement movement
Regional Paleosetting	SE shelf of cratonic Williston Basin
Nature of Trap	Structural/stratigraphic
Reservoir Rocks	
Age	Mississippian
Stratigraphic Units(s)	Mission Canyon Formation
Lithology(s)	Dolomite and calcareous dolomite
Diagenesis/Porosity	Transitional open-restricted marine and restricted marine, shoaling upward, cyclically repeated
Productive Facies	Dolomitized skeletal wackestone and pellet wackestone-packstone
Entrapping Facies	Anhydrite, intertidal packstone-grainstone, and subtidal dense packstone
Diagenesis/Porosity	Partial replacement by anhydrite, followed by dolomitization, then dissolution of anhydrite.
Petrophysics	
Pore Type(s)	Moldic and intercrystal
Porosity	8.5–27% avg 14% dolomite
Permeability	01.0–167 md range, 30 md avg
Fractures	Common but widely spaced, closed to hairline vertical
Source Rocks	
Age	Late Devonian to Early Mississippian
Lithology(s)	Bakken Shale, organically rich (Lodgepole limestone secondary source)
Migration Time	Cretaceous
Reservoir Dimensions	
Depth	9800 ft avg (~3000 m)
Thickness	Max 109 ft (33 m) net, avg 24 ft (7.3 m) net, B–D zones
Areal Dimensions	12 × 2.5–6.0 mi (19.2 × 4–10 km)
Productive Area	~24,000 acres (96 km^2)
Fluid Data	
Saturations	$S_o = 60\%$, $S_w = 40\%$ (averages)
API Gravity	41°
Gas-Oil Ratio	1250:1
Other	C_1-$C_3 = 51.7\%$, C_4–$C_6 = 10\%$, $C_6 = 27\%$, $H_2S = 8\%$, other 3.3%
Production Data	
Oil and/or Gas in Place	195 million BO
Ultimate Recovery	NA
Cumulative Production	28 million BO through November 1982

Remarks: IP 480 BOPD flowing from 8 ft (2.4 m) of perforated casing. IP mechanism solution-gas (depletion) drive with limited water drive. Discovered 1977.

Carbonate Petroleum Reservoirs (Roehl & Choquette), Springer-Verlag New York, Inc.

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Depositional Facies, Diagenesis, and Reservoir Character of Mississippian Cyclic Carbonates in the Mission Canyon Formation, Little Knife Field, Williston Basin, North Dakota

Robert F. Lindsay and Christopher G. St. C. Kendall

Location and Discovery

Little Knife Field is located near the structural center of the Williston Basin in west central North Dakota, south of the Nesson Anticline, in parts of Billings, Dunn, and McKenzie Counties, T144-145N, R97-98W (Fig. 10-1). Production is from the Mission Canyon Formation (lower Mississippian). The Mission Canyon lies between the Lodgepole Limestone below and the Charles Formation above, and all three combine to form the Madison Group. At this location, the Mission Canyon is 465 feet thick (142 m) and contains several porous hydrocarbon-bearing zones. The field lies within the Little Knife Anticline, a broad, low, northward-plunging anticlinal nose with less than 1 degree of structural relief (Fig. 10-2). The top of the Mission Canyon at the crest of the structure lies at a depth of 9600 to 9700 feet (≈3 km). The field is approximately 12 miles (19.2 km) long and 2.5 to 6 miles wide (4–9.3 km).

Little Knife was discovered in January 1977 by the Gulf 1-18 State wildcat well, which flowed 480 barrels of oil per day of undersaturated sour crude (API 43° gravity) from 8 feet (2.4 m) of perforations. As of June 1984, the field included 179 wells drilled on 160-acre spacing and had produced 31 million barrels of oil. The primary reservoir drive mechanism is solution gas drive (depletion drive).

Forty-one Mission Canyon wells were cored inside the field boundaries, and seven outside the field boundaries (Fig. 10-2), yielding 5490 feet (1674 m) of core.

Major Zone Lithologies

Key beds were identified on the basis of open-hole well logs, which permitted subdivision of the section into six informal zones designated as A, B, C, D, E, and F (Fig. 10-3). Facies of the complete Mission Canyon section were studied using several overlapping cores to construct a composite section. Lithologies of these zones, within the Mission Canyon Formation at Little Knife Field, are summarized in this section. Net pay thickness distributions are shown in Figure 10-4.

Zone F, the lowest log/lithology zone in the Mission Canyon, is 170 feet (52 m) thick and composed of alternating medium to thick beds of undolomitized (to slightly dolomitized) lime mudstone interbedded with skeletal packstone/grainstone. The basal 10 to 15 feet (3-5 m) are slightly argillaceous, interlaminated skeletal lime packstones and pelletal lime packstones, forming a transition into the underlying Lodgepole Limestone. Zone F is non-hydrocarbon bearing.

Zone E, 50 feet (15 m) thick, is composed of thick-bedded, slightly to completely dolomitized

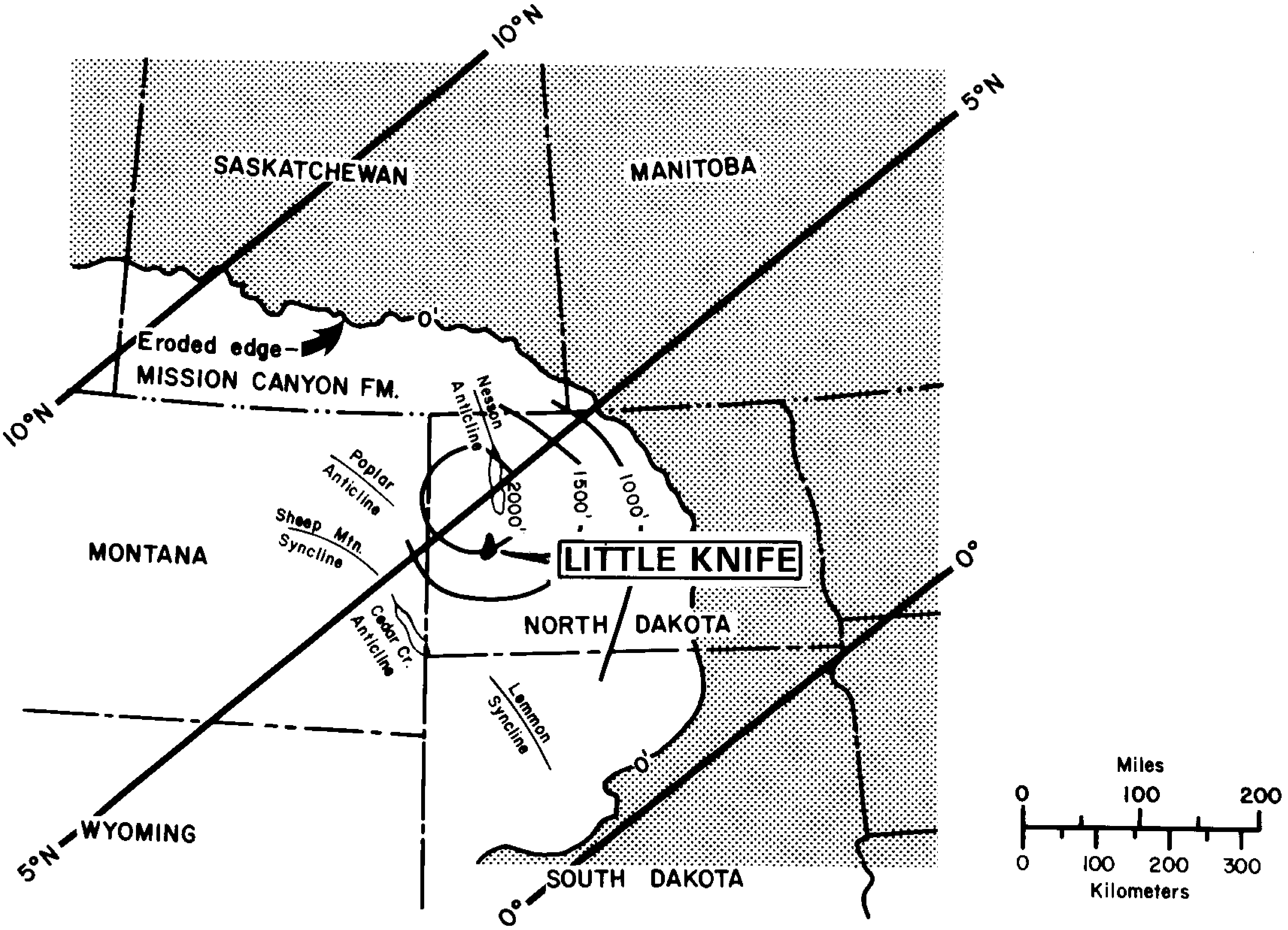


Fig. 10-1. Index map of Williston Basin, showing: eroded edge of Mission Canyon Formation (Proctor and Macauley, 1968); major surface and subsurface structural features (Willstrom and Hagemeier, 1978, 1979); isopach thickness of Madison Group (Carlson and Anderson, 1965); and generalized Carboniferous paleolatitude lines (Habicht, 1979).*

skeletal mudstone/wackestone with irregularly shaped incipient siliceous nodules. Porous beds in this zone also are non-hydrocarbon bearing.

Zone D, 50 feet (16 m) thick, constitutes the lowermost interval of the reservoir itself at Little Knife. It is medium to thick-bedded, partially to completely dolomitized, burrowed, mudstone and skeletal wackestone, which exhibits local replacement by anhydrite that was later leached.

Zone C, 65 feet (20 m) thick, also forms a portion of the porous reservoir interval. It is medium to thick-bedded, becoming mostly nonporous in its mid- to upper portions. Dolomitized skeletal wackestone beds, containing some replacement anhydrite, grade upward into variable dolomitized pelletal wackestone/packstones. Nonporous beds have small amounts of chert occluding intercrystal pores. Upper portions of the zone have rare quartz-silt laminations in dense microcrystal dolostone beneath porous reservoir beds.

Zone B, 70 feet (21 m) thick, forms the uppermost interval of the reservoir. It is subdivided into upper and lower portions:

1. The *mid-lower* portion consists of beds of dolomitized, burrowed, sparsely skeletal, pelletal wackestone/packstones. These were partially replaced by anhydrite and later leached, producing moldic pores in intercrystalline dolostone porosity. This facies thins southward.

*Figures 10-1, 2, 3 modified from and 10-5, 6, 7, 10 from Lindsay and Kendall, 1980. Published by permission, Society of Economic Paleontologists and Mineralogists.

2. The *upper* portion, 5 to 40 feet (1-1/2–12 m) thick, consists of sparse, thin, lenticular, discontinuous beds of porous, dolomitized skeletal wackestone, also partly replaced by anhydrite which is locally leached, and interbedded with dense, cemented wackestone/grainstones. Constituents include peloids, clotted and lumped micrite, ooids, pisolites, calcispheres, and skeletal detritus. This facies thickens southward and becomes partially anhydritic.

Zone A is a 60-foot (18-m) cap of thin-to thick-bedded anhydrite at the top of the Mission Canyon. It is characterized by a variety of structures that include: (1) chicken-wire mosaic, (2) thin-bedded mosaic, (3) laminated to medium-bedded, (4) ropy displacive, and (5) burrowed replacive (Maiklem *et al.*, 1969). Both a dolomite matrix and interbeds of laminated dolostone are associated with the anhydrite beds. In upper portions of zone B and at the base of zone A, there are pseudomorphs of anhydrite after selenite crystals, anhydrite porphyroblasts, and local laminated crusts.

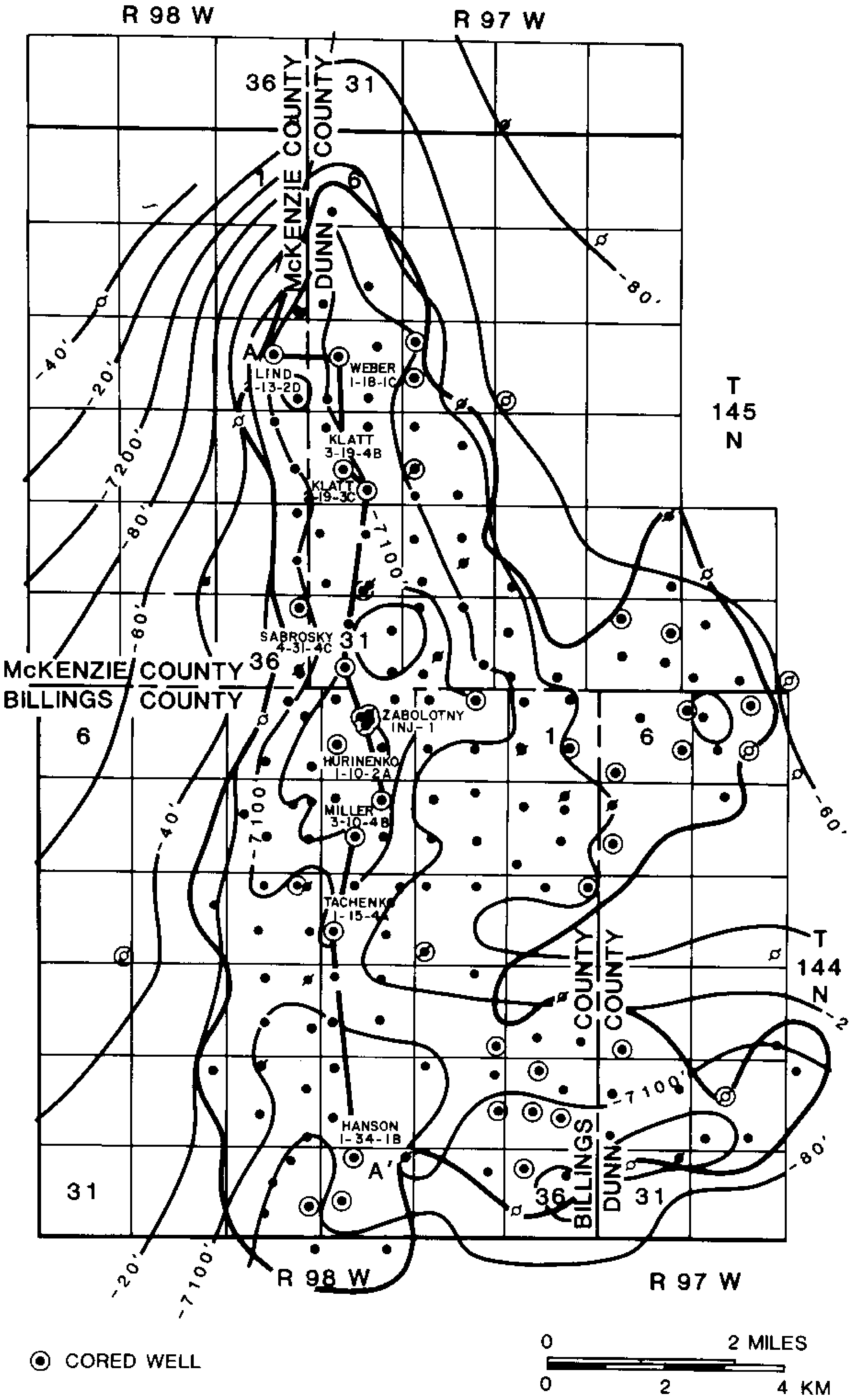


Fig. 10-2. Structure on top of the Mission Canyon Formation in Little Knife Field. Cross-section line A–A' refers to Figure 10-7.

Depositional Setting

The Mission Canyon as a whole is a shallowing-upward, regressive sequence characterized by a general upward change in lithology from carbonates to anhydrite (Lindsay, 1982; Lindsay and Roth, 1982) (Figs. 10-3, 10-5). It is analogous to the lime mud-to-sabkha cycle of Wilson (1975, p. 297–298). Most of the carbonates are interpreted as subtidal, deposited in five recognizable subenvironments from the base upward: (1) basinal "deeper water" carbonates in basal zone F (zone X of Irwin, 1965); (2) open shallow-marine in zone F (zone X-Y of Irwin, 1965); (3) transitional marine between open marine and a shallow protected shelf in zones E, D, and C (zone Y-Z of Irwin, 1965); (4) a protected restricted marine shelf in zones C and B (zone Z of Irwin, 1965); and (5) a thin, narrow marginal marine belt in mid-upper zone B (zone Z of Irwin, 1965).

This subtidal setting was interrupted by several subsidiary shallowing-upward carbonate cycles beautifully displayed in cores (Lindsay and Kendall, 1980; Lindsay and Roth, 1982). In the lower two-thirds of the Mission Canyon (zones F, E, D, and C), carbonate cycles are repeated several times, probably in response to subtle eustatic fluctuations in sea level, which formed major cycles in the open marine (zone F) and minor cycles in the transitional open-restricted marine (zones E, D, and C). Major carbonate cycles consist of medium-to thick-bedded, burrowed mudstone grading up into skeletal packstone/grainstones deposited in the open-marine environment (Fig. 10-3).

Minor carbonate cycles consist of medium-to thick-bedded, burrowed, pelletal mudstones grading up into skeletal wackestones. Skeletal fragments were washed in from the open marine and

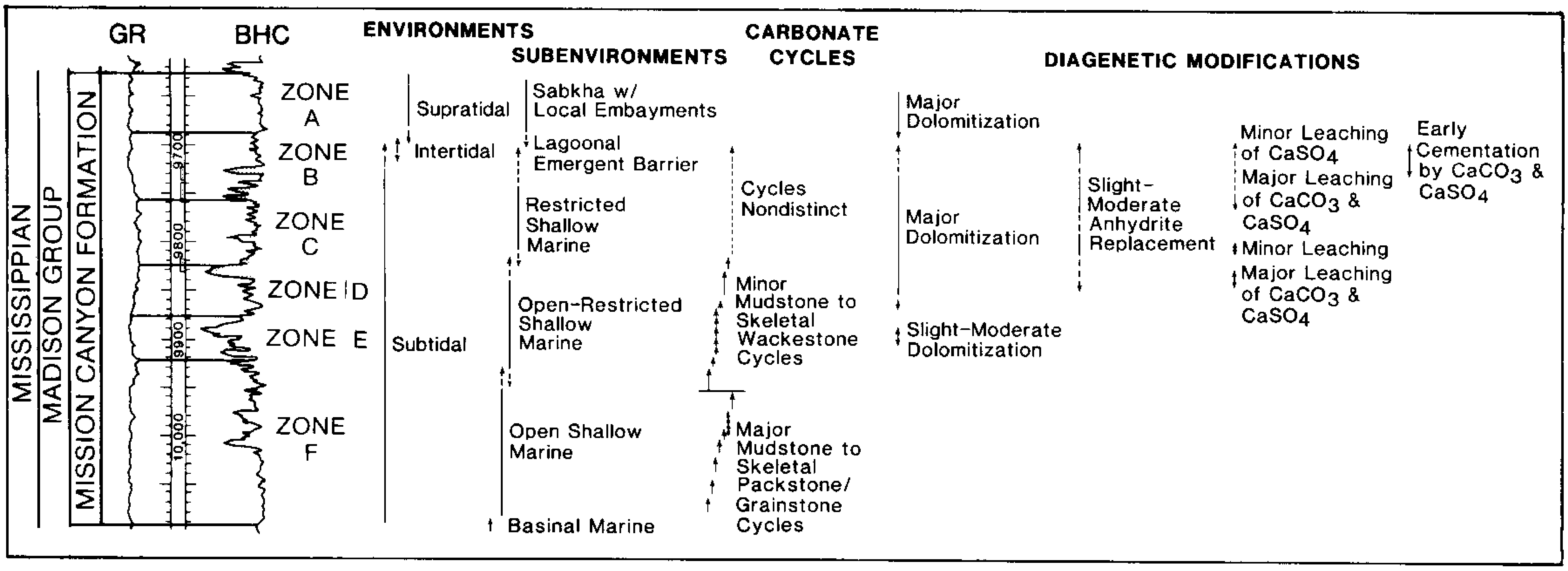


Fig. 10-3. Type gamma-ray/sonic log of Mission Canyon Formation in central portion of Little Knife Field. Depositional environments, carbonate cycles, and diagenetic modifications are from a composite section of several cores. Stippled areas indicate hydrocarbon accumulations.

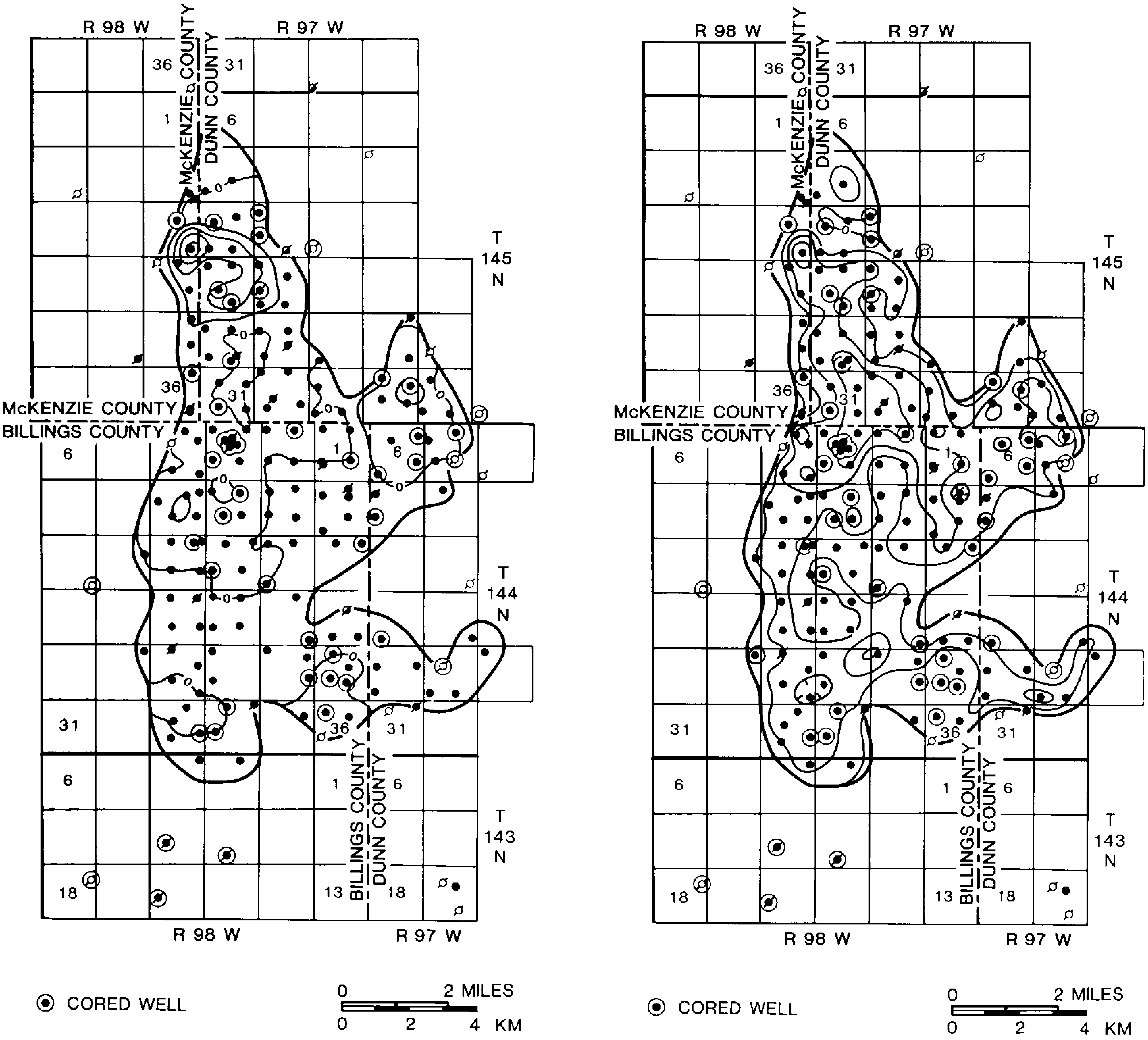


Fig. 10-4. Net pay isopach maps of the Mission Canyon Formation in Little Knife Field. *A*. Uppermost restricted marine interval in middle part of zone B, in northern part of the field. *B*. Remainder of restricted marine interval, in lower zone B and upper zone B, throughout the field.

deposited with accumulating lime mud in the transitional open-to-protected shallow-shelf subenvironment, where further shallowing, wave energy reduction, and loss of circulation occurred. These minor cycles eventually gave way to burrowed, sparsely skeletal, pelletal muds in the restricted inner parts of the protected shelf subenvironment (mid-lower zone B and upper zone C).

The barrier island buildup facies (mid-upper zone B) forms a thin veneer of variable thickness, which terminated subaqueous deposition. A low-energy environment with little tidal exchange is suggested, with barrier beaches reworked by storms that periodically washed over them. Dense, thin lagoonal limestone beds are immediately behind and interfinger with the buildup facies. These beds then interfinger with, and are overlain by, supratidal anhydrite beds.

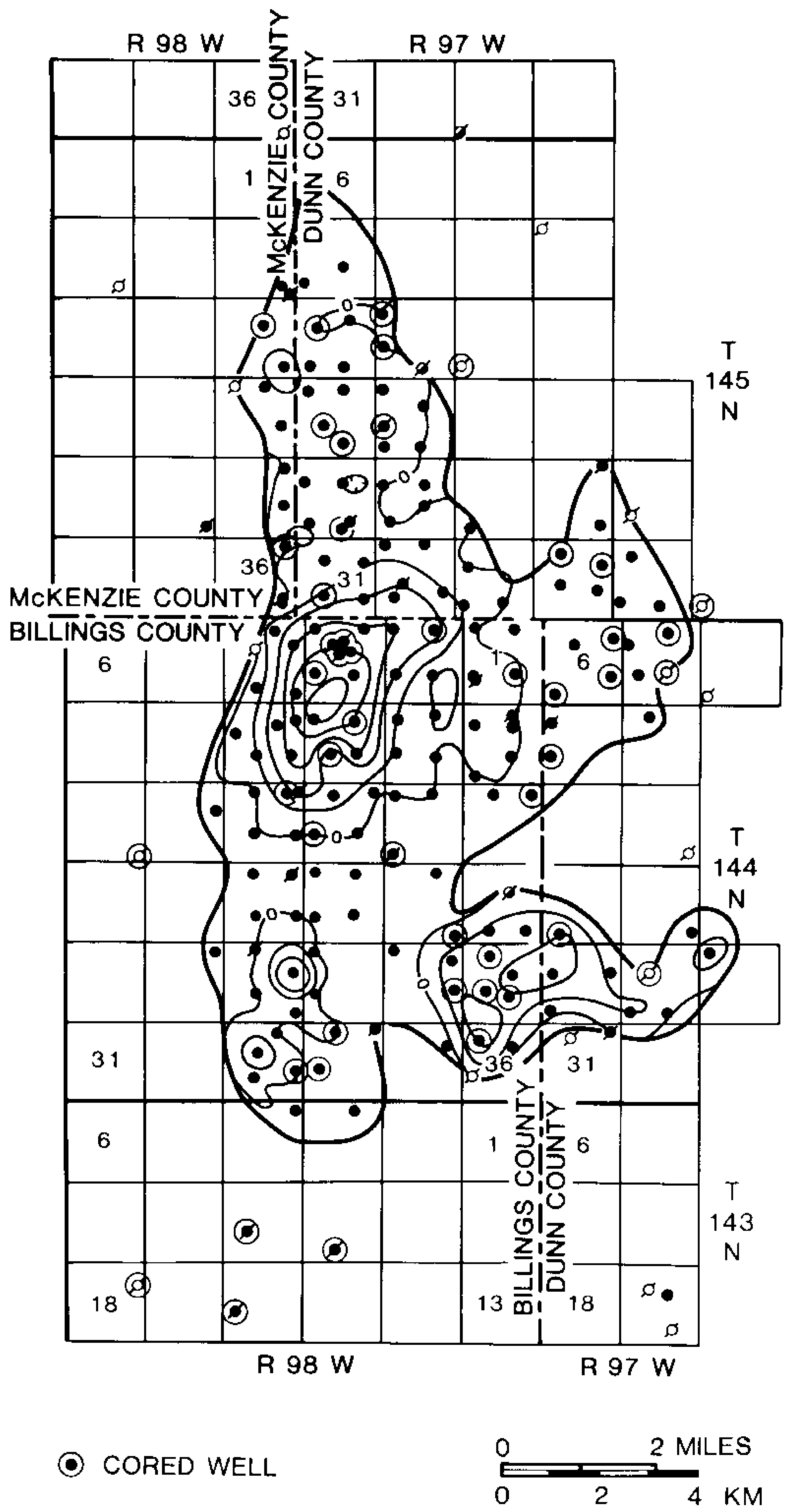


Fig. 10-4C. Transitional, open-to-restricted marine facies in productive central and southern portions of the field (upper zone D and basal zone C). See Figure 10-7 for stratigraphic relationships.

Anhydrite cements, pseudomorphs of anhydrite after selenite crystals, anhydrite prophyroblasts, and localized laminated crusts (upper zone B and base of zone A) are the first indications of higher salinities and subaerial exposure as supratidal sequences prograded toward the depocenter. Anhydrite beds overlie these first indicators, displaying subfelted to felted textures.Thin interbeds of laminated dolomite are the only other lithology present, and record storm-washover ponds or playas and local embayments onto the sabkha.

Reservoir—General

A typical log from the central part of the field displays hydrocarbon accumulations in the upper half of the Mission Canyon (stipple pattern, zones B, C, and D; Fig. 10-3). The Little Knife anticline involves average dips of 1/4 degree east, and 1/2 degree west, converging in a structural nose to the north. Hydrocarbon accumulations disappear progressively up- and off-structure. To the south, closure is by lateral facies changes (described later), which create stratigraphic entrapment.

Diagenetic modifications to the protected shelf and transitional marine sediments rich in lime mud created what are now the principal reservoirs, as illustrated by core photos in Figure 10-6. Porosity of these facies was enhanced by partial to complete dolomitization. Skeletal constituents were partially replaced by anhydrite, which was later dissolved. In restricted marine beds (zone B) the result is an abundance of ghosts and molds of pellets preserved as dolomite-rhomb rimmed "necklaces" grading into dolomite intercrystal pores. In transitional open-restricted marine beds (zone D), porosity occurs in dolomitized skeletal wackestone, which consists of both skeletal fragments and skeletal molds partially replaced by anhydrite and leached and intercrystal pores within the dolomite matrix.

Cores reveal discontinuous vertical, planar, hairline fractures that may have been initiated at the present depth of the field, as tensional release

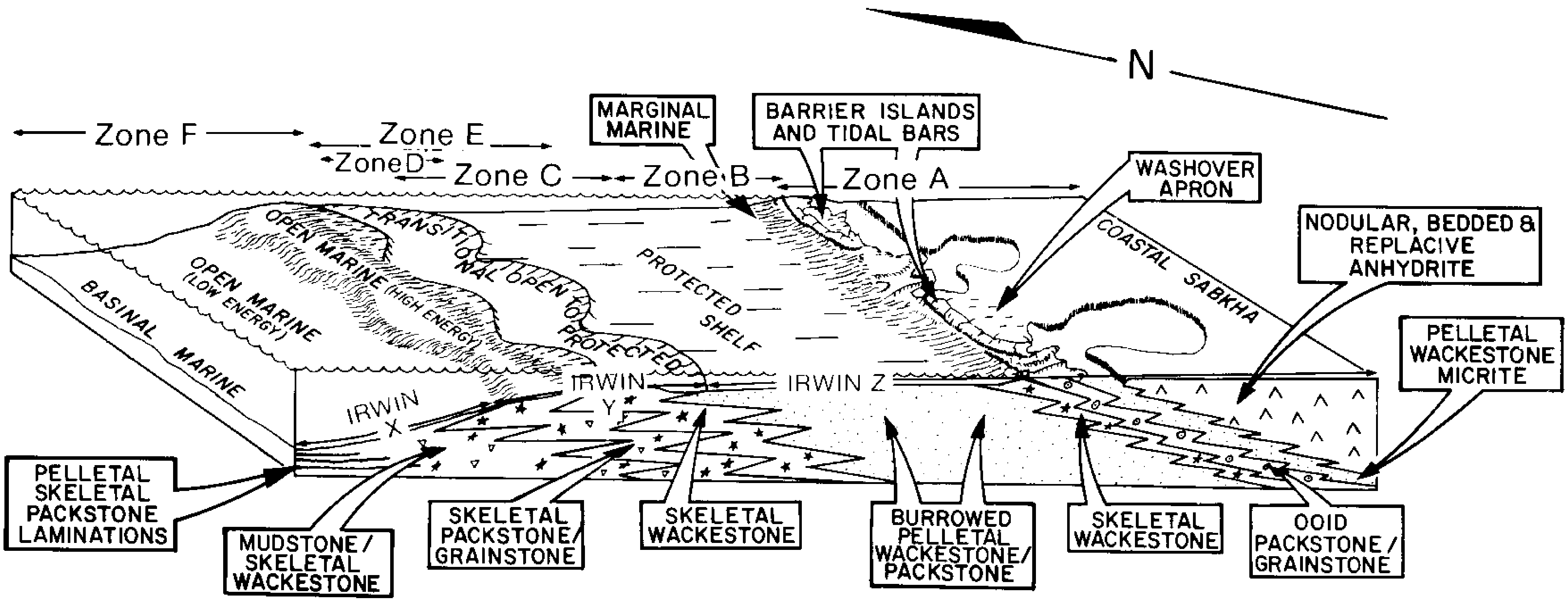


Fig. 10-5. Idealized depositional setting of Mission Canyon Formation at Little Knife Field. Informal log zonations A–F (top) and Irwin's (1965) epeiric sea energy zones X, Y, and Z (base) illustrate respective positions occupied in the depositional system.

features (Narr and Burruss, 1982; W. Narr, personal communication, 1981). Fractures are found in all facies except in anhydrite beds. No displacement along fractures can be demonstrated, and fractures continue, for example, through skeletal and oolitic-pisolitic constituents with no lateral offset. Fractures at Little Knife Field increase overall permeability two-fold (Nettle *et al.*, 1981; Desch *et al.*, 1982, 1983, 1984).

Reservoir Development

The various hydrocarbon-bearing porous beds associated with Little Knife Field have locally well-developed porosity that deteriorates laterally. Major intervals of porous carbonate occur in restricted marine beds in middle to lower portions of zone B, and transitional open-restricted marine beds in portions of zone D (Fig. 10-3). For simplicity, lower zone C porosity is included in the discussion of zone D porosity. Other porous intervals are much thinner and more lenticular, and either cannot be correlated from log to log, or else form only thin persistent sections (upper zone B and mid-portions of zone C). Other beds of porous rock occur lower in the Mission Canyon (zones E and F) but do not contain hydrocarbons.

Transitional Open-Restricted Marine Reservoir Interval (Zone D)

The lowest hydrocarbon-bearing beds in the reservoir interval are within the transitional open to restricted marine facies in dolomitized skeletal wackestones, at the top of the last well-developed minor carbonate cycle (zone D; Fig. 10-7). This portion of the reservoir is confined to central portions of the field, where there is slight additional structural flexure and better porosity development. The reservoir is structurally confined on the east, west, and north, and is bounded by edge water on the northeast, north, and west. A facies change from beds of porous dolomitized skeletal wackestone to dense beds of skeletal packstone forms a southward stratigraphic trap (Fig. 10-8C). Reduction in porosity is due to limited amounts of carbonate mud available to be dolomitized. Skeletal detritus is composed of crinoid columnals, less common brachiopod shells, and sparse bryozoan fronds.

Porosity Generation

Porosity was generated where more carbonate mud associated with skeletal wackestone was

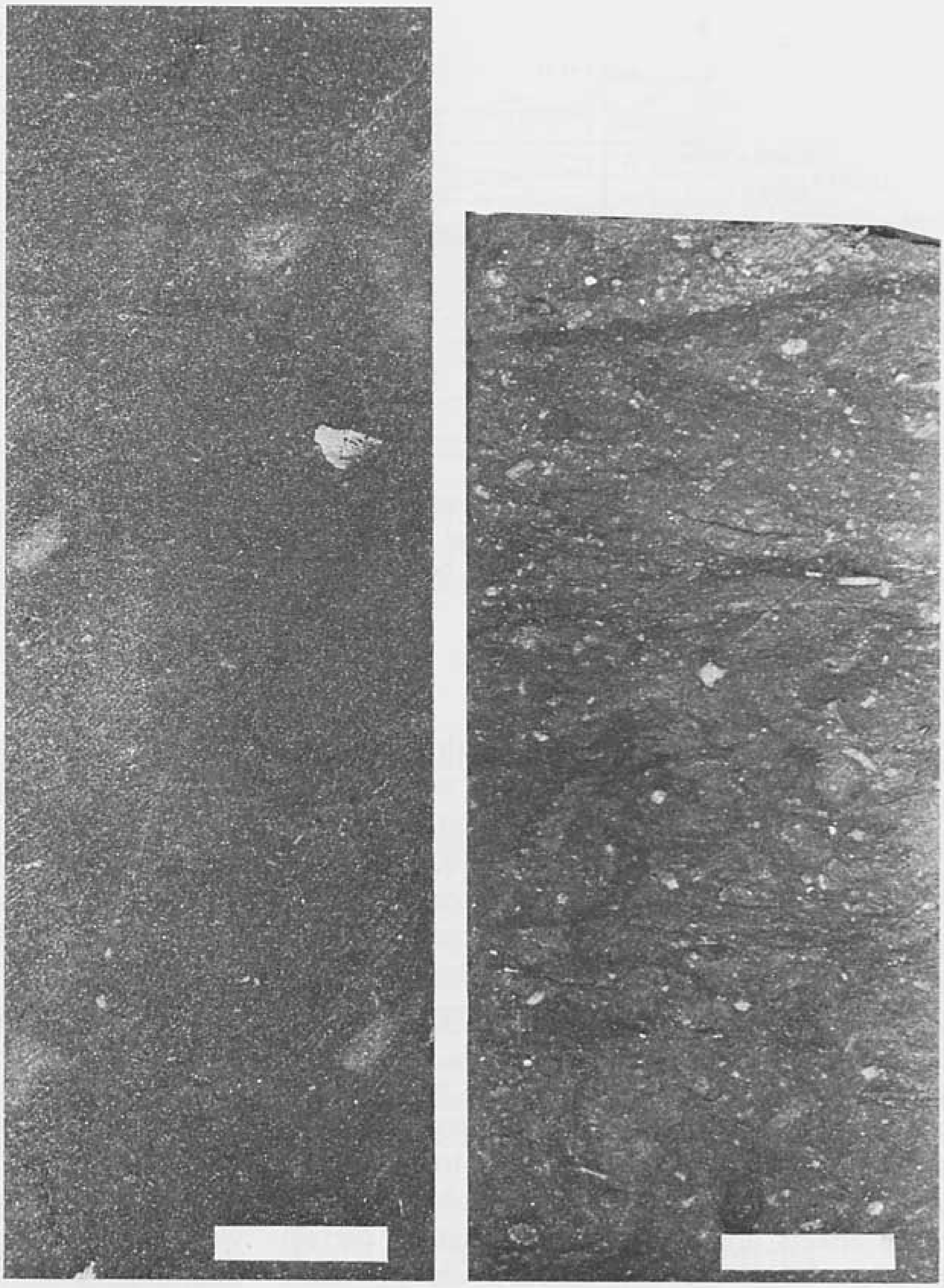


Fig. 10-6. Photographs of core slabs of porous Mission Canyon beds in central part of Little Knife Field. LEFT is restricted marine facies from zone B in Gulf Sabrosky well 4-31-4C, 9733 feet (2967 m); 17% porosity and 10 md permeability. Rock is a dolomitized, thoroughly burrowed, sparsely skeletal, pelletal wackestone/packstone, with coral fragment in upper right. RIGHT is transitional open-restricted marine facies from zone D in Gulf Sabrosky well 4-31-4C, 9816 feet (2992 m); 20% porosity and 98 md permeability. Rock is a partially dolomitized, burrowed, skeletal wackestone. Bar scale is 2 cm long.

available to be converted into dolomite with intercrystal porosity. Once most mud had been dolomitized, local sources of carbonate ions for dolomitization were the crinoid and brachiopod skeletal constituents (see Murray, 1960). At approximately 60 to 70 percent conversion to dolostone, some skeletal fragments were dissolved, leaving larger crinoid columnals and brachiopod fragments to "float" in a matrix of porous, sucrosic dolostone, ringed by dolomite-rhomb "necklaces." Laterally, where skeletal detritus is more abundant, only incipient dolomitization of finer muds (less than 50%) has occurred, with little or no porosity enhancement.

Apparently, where larger volumes of lime mud were available, fluids moving through the subtidal

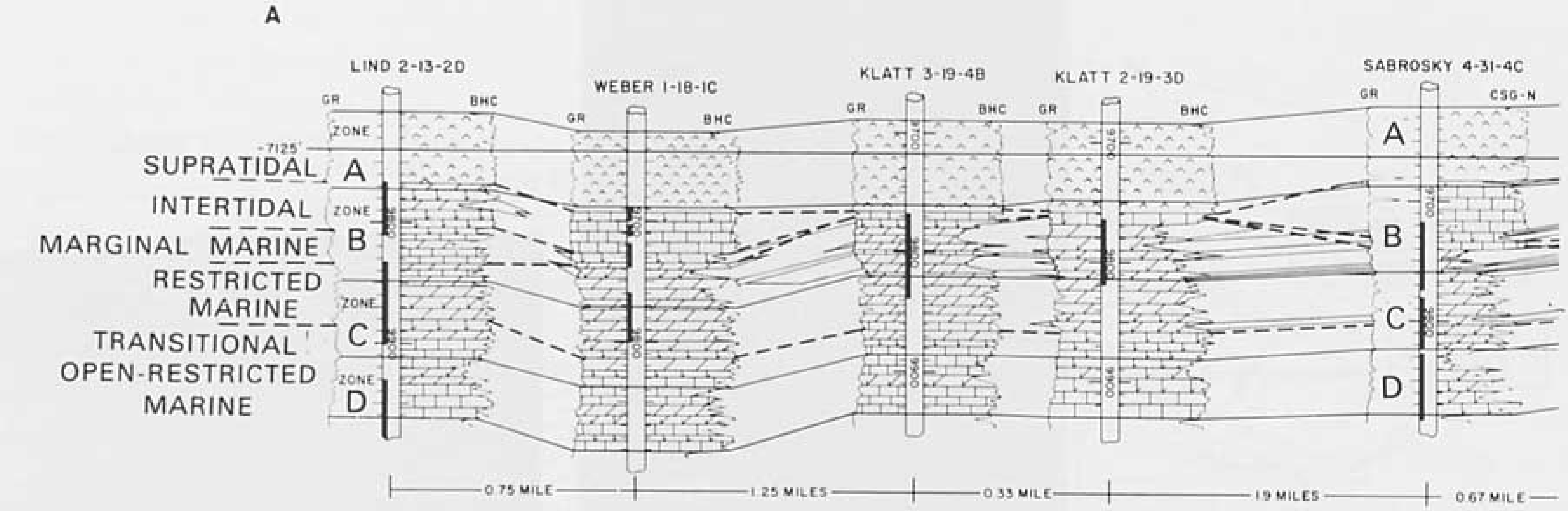


Fig. 10-7. North-south structural cross-section of upper half of the Mission Canyon Formation through cored wells in Little Knife Field. Black vertical bars represent cored intervals; shaded areas are porous hydrocarbon-bearing intervals; and dashed lines are boundaries between depositional settings. Intertidal includes low-lying

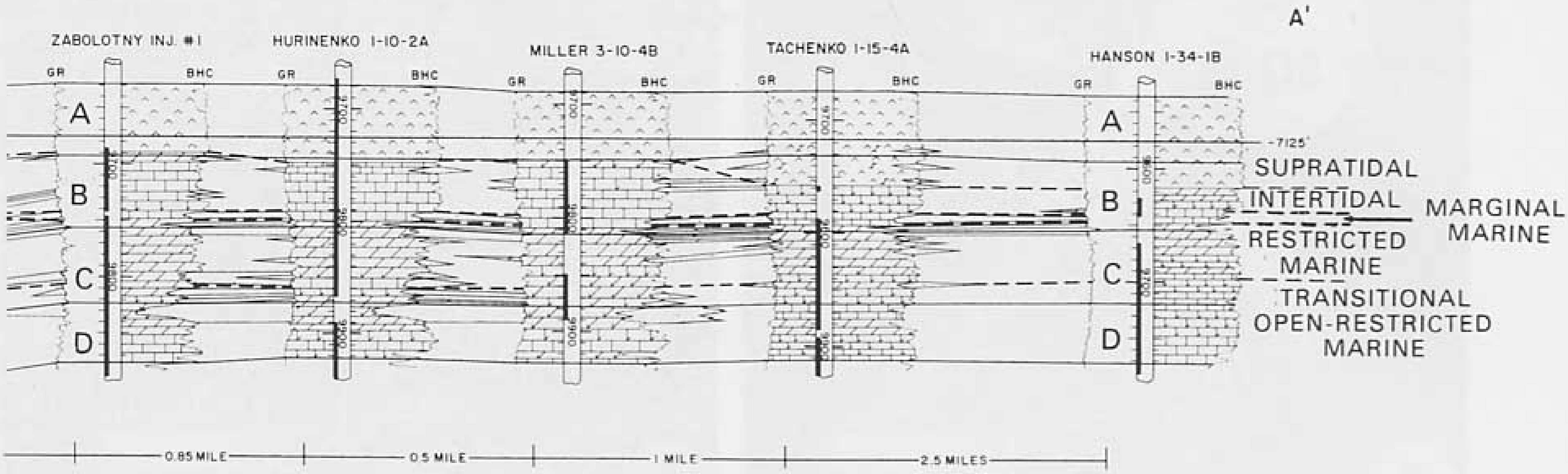
beds became less concentrated with respect to magnesium, and nucleation sites were spread farther apart, promoting the creation of porous, fine-grained dolomite (Asquith, 1979, p. 22–23). We speculate that the lack of dolomitization in places is the result of: (1) smaller volumes of carbonate muds; (2) a lack of more homogeneous permeable pathways, due to incomplete homogenization by burrowing organisms; and (3) increased amounts of skeletal detritus which, when their mud matrix was compacted, formed a mud-supported (grains nearly compacted together) texture that inhibited fluid flow. It is probable that all these effects are interrelated so that, at certain locations within the field, lateral sweep efficiency of dolomitizing solutions through the same horizon produced different styles or types of dolomitization and degrees of porosity development. Later, leaching of anhydrite-replaced skeletal detritus further increased porosity (Lindsay and Roth, 1982).

Restricted Marine Reservoir Interval (Zone B)

Restricted marine portions of the reservoir interval (zone C and B) are composed of beds of burrowed, muddy, sparsely skeletal, pelletal wackestone/packstone that have been partially to completely dolomitized. Porosity commonly decreases laterally as in the transitional open-restricted marine beds (zone D), but with a gentler gradient and over greater areas (Fig. 10-7). These sediments were apparently deposited in a restricted, protected subtidal setting with low amounts of circulation. This more restricted environment promoted more accumulation of carbonate mud and pellet-rich sediment. The original sediments were homogenized by burrowing. Only sparse skeletal detritus occurs, as fine, broken crinoid columnals. Laterally, away from the well-developed porous intervals, a facies change into less porous beds of sparsely dolomitized, burrowed, slightly less muddy, skeletal to pelletal wackestone/packstones of marginal marine subtidal origin occurs. Further lateral shifts in facies commonly involve the lowest beds of "dense," cemented, ooid-pisolitic packstone/grainstones, which represent the first sediments to emerge above the subtidal realm at the strand line, where localized waves and storms produced barrier island buildups (mid-upper zone B).

Porosity Generation

Best porosity developments are associated with partial to complete dolomitization of both mud and particles (Figs. 10-8A, B, D, E), in a sequence like that described for the transitional open-restricted marine beds (zone D). Pellets have dolomite-rhomb "necklaces" that seem to have formed prior to grain leaching, producing



barrier island buildups, intertidal beaches, and lagoonal limestones. Note thickening of anhydrite beds to the south (A') (zone A–uppermost zone B). Also note southward changes in restricted marine (zone B) and transitional open-restricted marine (zone D) beds from porous dolostone to dense limestone.

dolomite-rhomb rimmed, small moldic pores of oval shape (Fig. 10-8E). Schmidt (1965, p. 143–144) noted similar dolomite rim cements, as did Kaldi and Gidman (1982), and concluded that the rim cement was early diagenetic.

Changes in porosity in restricted marine beds (zone B) are far more complex than in transitional open-restricted marine beds (zone D). Vertical as well as lateral changes in porosity development subdivide restricted marine beds (zone B) into more than one porosity unit. These expand laterally and join thicker porous beds or contract to bifurcate or pinch out. This increase in complexity is thought to be due to the relationship between the original subtidal muddy wackestone/packstones and the intertidal rocks that both directly overlie them and pass laterally into them (Figs. 10-2, 10-7). These intertidal rock suites were cemented early by calcite and anhydrite, thus occluding interparticle porosity and forming the lowest beds of discontinuous caprock over the field. The true seal is the overlying anhydrite beds.

Besides being dolomitized, the porous beds of zone B have also undergone slight to moderate levels of anhydrite replacement and later leaching (Figs. 10-8A, 10-B). Skeletal constituents, namely very fine crinoid fragments, though diminished in volume and size, are preferentially replaced. This enhancement of porosity development by anhydrite dissolution is common at Little Knife.

Presumably, brine-enriched solutions concentrated Ca^{+2} which combined with SO_4^{-2} as beds of anhydrite-isolated nodules and replaced skeletal fragments. This effectively reduced the SO_4^{-2} and Ca^{+2} concentration and in increased the Mg^{+2}/Ca^{+2} ratio to promote dolomitization, though at much slower rates (Bathurst, 1975, p. 531–532). Certain beds are composed of dense microcrystalline dolostone. These may reflect areas where multiple, closely spaced dolomite-crystal nucleation occurred.

Pore Types and Geometries

Four pore types and sizes are recognized in the Mission Canyon (Lindsay, in press) (Fig. 10-9). *Moldic* pores (Choquette and Pray, 1970), produced by leaching of anhydrite-replaced skeletal constituents, are largest and measure approximately 30 to 300 microns wide. These large moldic pores are surrounded by dolomitized muddy matrix housing *intercrystal* pores and associated pore throats, between sets of dolomite crystals (Fig. 10-8). *Polyhedral* pores are the largest intercrystal pores, surrounded by several dolomite crystal faces, and form complex polyhedron shapes approximately 10 to 50 microns wide. *Tetrahedral* pores are intermediate-sized intercrystal pores, which form triangular shapes reduced in size to 3 to 10 microns. *Interboundary-sheet* pores are the smallest pores and

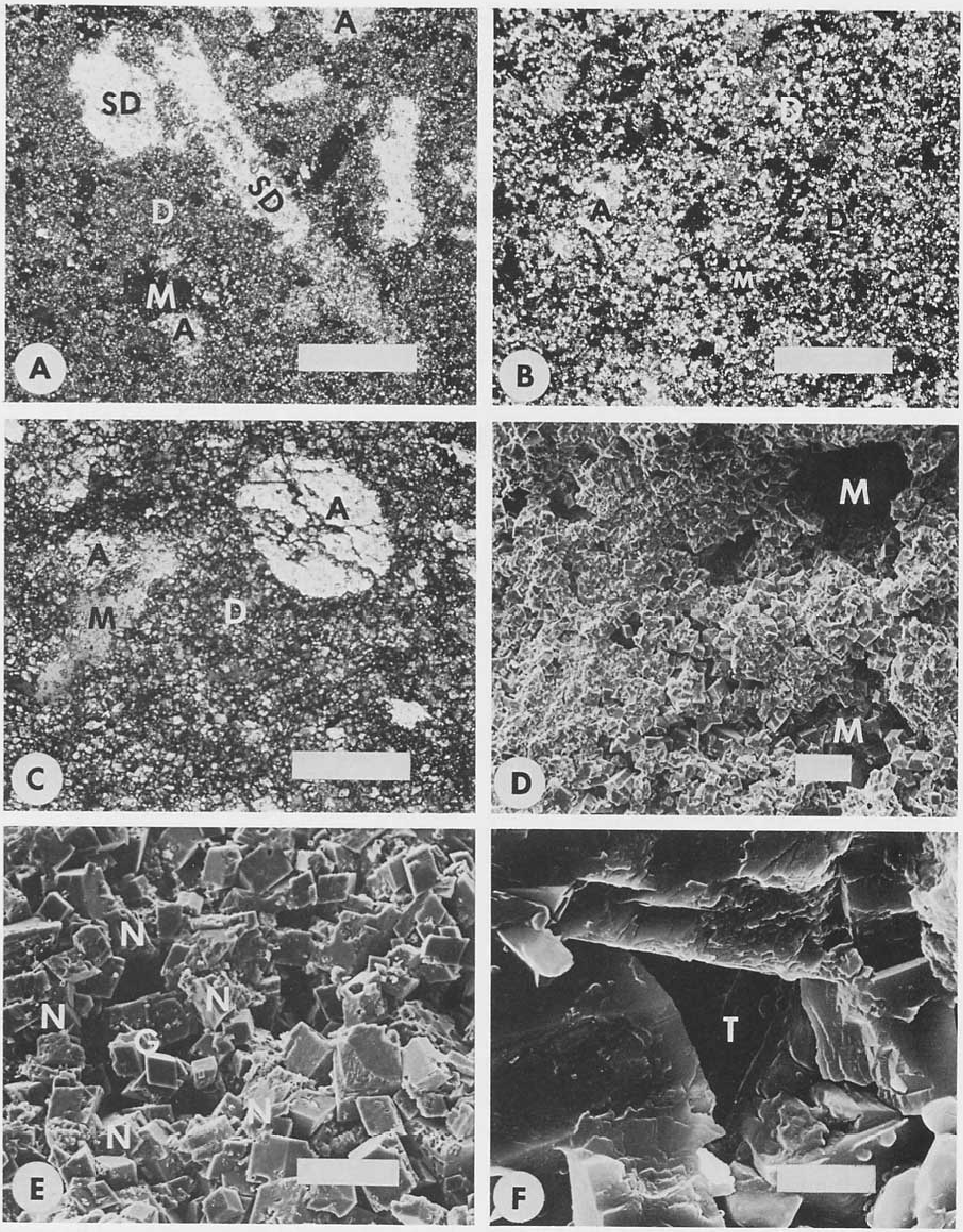
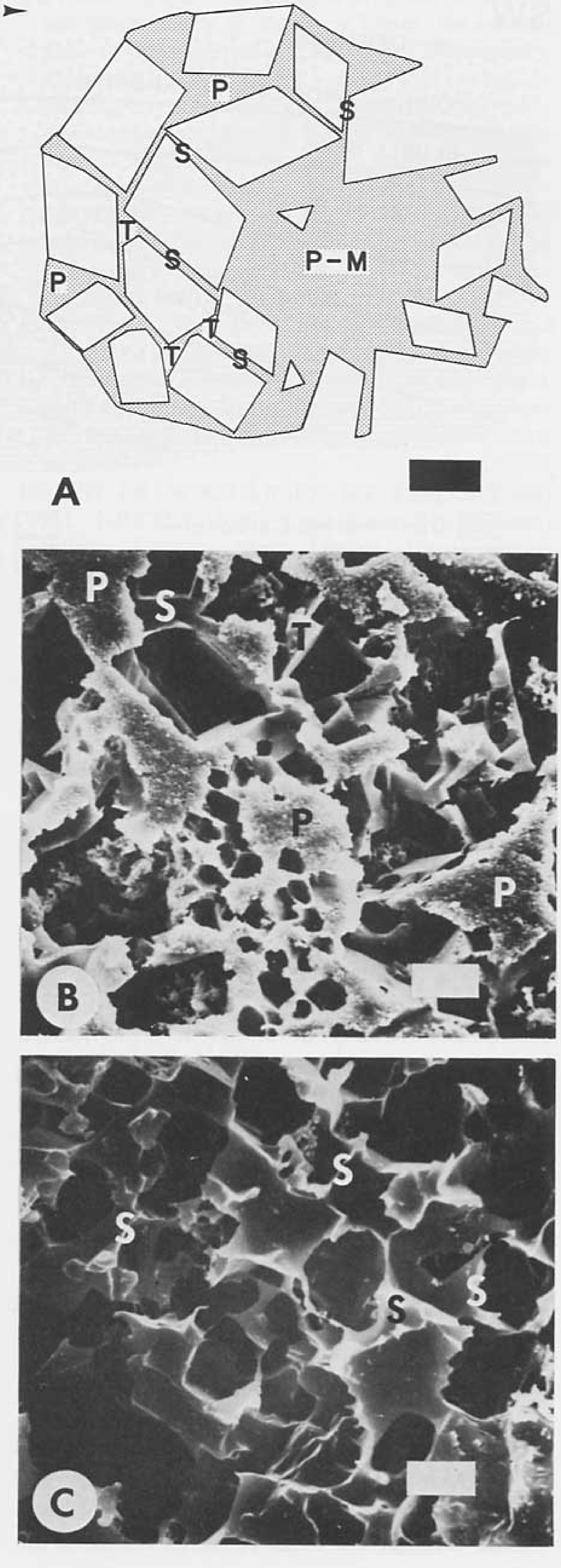


Fig. 10-8. Photomicrographs (*A,B,C*) and scanning electron micrographs (*D,E,F*) of the Mission Canyon Formation at Little Knife Field. *A*. Porous marginal marine dolomite facies (uppermost zone B). Originally skeletal wackestone with completely dolomitized matrix (D), with dolomite impinging into skeletal detritus (SD). Moldic pore space (M) formed where anhydrite replaced skeletal detritus and was later leached, leaving remnants of anhydrite (A). Gulf Lind well 2-13-2D, 9783 feet (2982 m), 20% porosity and 6 md permeability. Cross-polarized light. Bar is 500 μ long. *B*. Porous restricted marine facies (middle zone B). This rock is completely dolomitized (D). Replacement anhydrite (A) is mostly leached, producing moldic (M)

Fig. 10-9. Generalized diagram and scanning electron micrographs (SEM) of pore casts from porous dolostones of Mission Canyon Formation at Little Knife Field *A*. Various pore types and throats in porous portions of the Mission Canyon. Stippled area is pore space surrounding dolomite crystals. (P-M) is a small moldic pore transitional to a large intercrystal polyhedral pore. Polyhedral pores (P) have complex polyhedron shapes. Tetrahedral pores (T) are intermediate-sized intercrystal pores, formed where three dolomite crystals impinge together forming a triangular shape in two-dimensional view. Interboundary-sheet pores (S) are the smallest and form between closely spaced dolomite crystals. Bar is 30 μ long. *B*. Porous transitional open-restricted marine facies (zone D). Large polyhedral pores (P) give way here to smaller polyhedral, tetrahedral (T) and interboundary-sheet (S) pores. Both large and narrow throats connect the individual pores. Gulf Sabrosky well 4-31-4C, 9820 feet (2992 m), 23.6% porosity and 167 md permeability. Bar is 20 μ long. *C*. Porous, transitional open-restricted marine facies (zone D). Narrow interboundary-sheet pores (S) still provide some effect on permeability, although pore space is highly reduced. Gulf Sabrosky well 4-31-4C, 9820 feet (2993 m), 23.6% porosity and 167 md permeability. Bar is 10 μ long.



pores associated with smaller intercrystal pores. Gulf Klatt well 3-19-4B, 9781 feet (2981 m), 15% porosity and 36 md permeability. Cross-polarized light. Bar is 500 μ long. *C*. Porous transitional open-restricted marine facies (upper zone D). Originally skeletal wackestone with a dolomitized (D) matrix and replacement anhydrite (A). Crinoid columnal left of center was replaced by anhydrite and later partially leached, leaving a moldic pore (M). Gulf Sabrosky well 4-31-4C, 9821 feet (2993 m), 24% porosity and 133 md permeability. Plane light. Bar is 500 μ long. *D*. Porous restricted-marine facies (lower zone B). Two moldic pores (M) are surrounded by a completely dolomitized matrix containing intercrystal polyhedral pores. Gulf Miller well 3-10-4B, 9812 feet (2991 m), 26% porosity and 36 md permeability. Cross-polarized light. Bar is 100 μ long. *E*. Porous restricted marine facies (mid-lower zone B). A pellet "ghost" (G) has been leached to form a moldic pore surrounded by a "necklace" of dolomite rhombs (N). Gulf Sabrosky well 4-31-4C, 9733 feet (2967 m), 17% porosity and 10 md permeability. Bar is 100 μ long. *F*. Porous restricted marine facies (mid-lower zone B). Dolomite crystals have partially grown together reducing pore space to a tetrahedron-shaped tetrahedral pore (T). Gulf Sabrosky well 4-31-4C, 9733 feet (2967 m), 17% porosity and 10 md permeability. Bar is 10 μ long.

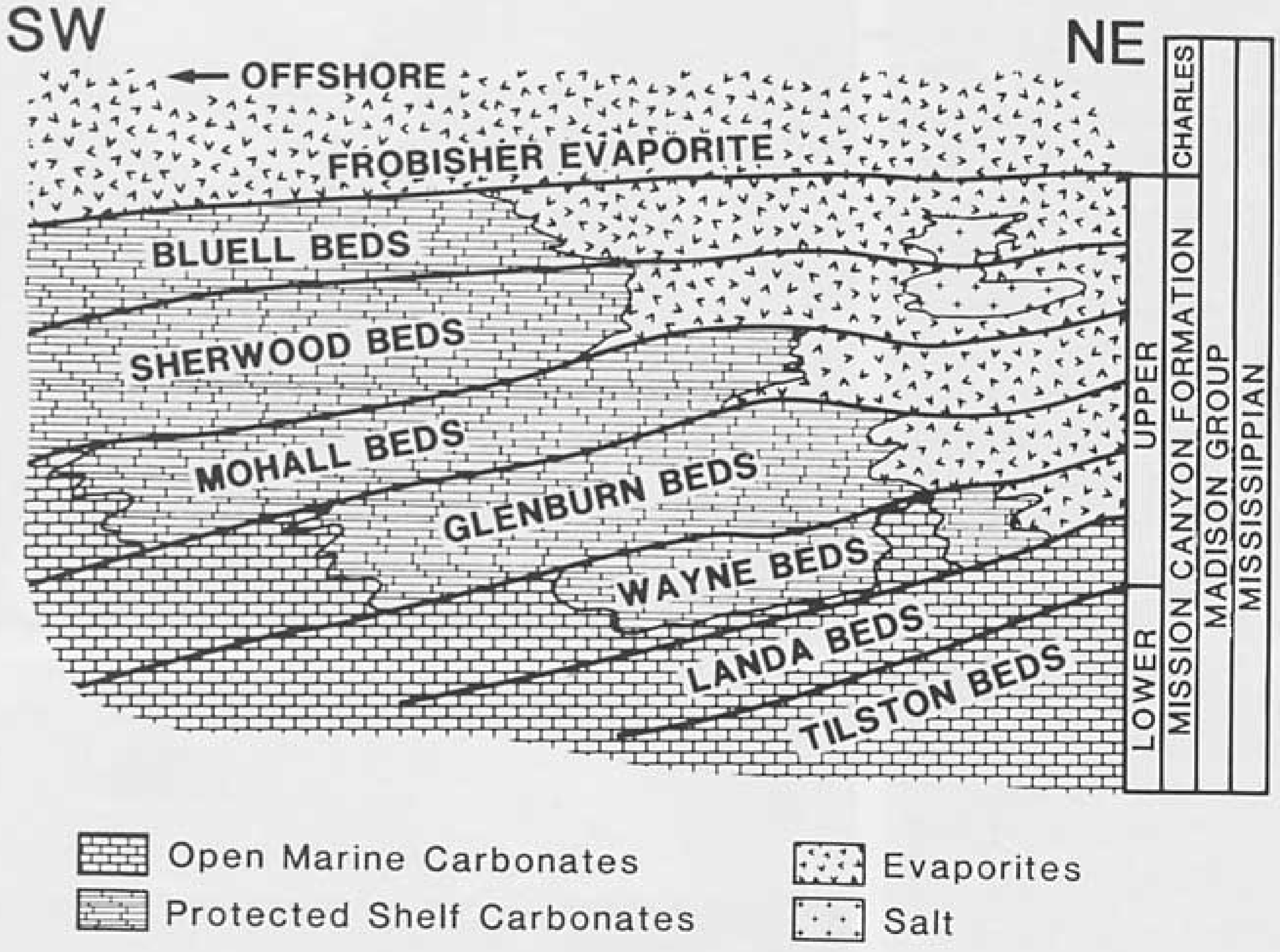


Fig. 10-10. Regional cross-section of Mission Canyon Formation across North Dakota portion of the Williston Basin. Modified after Harris et al. (1966) and Malek-Aslani (1977).

pore throats, found between individual dolomite-rhombs, where pores appear to be reduced to long, very thin spaces approximately 1.6 microns wide. These intercrystal pore types are similar to those described by Wardlaw (1976) and Wardlaw and Taylor (1976).

Pore-to-throat size ratios are highly variable, ranging from 40:1 where larger moldic pores are well-developed, down to 4:1. The average pore-to-throat coordination number, or average number of throats connected to each pore in a two-dimensional view, is 3 to 5 (Lindsay, in press). Permeability development is dominated by two pore throat sizes in the Mission Canyon: (1) interboundary-sheet pores/pore throats, with 0.8 micron radii, and (2) 1.6 to 4 micron pore-throat radii. Both sizes of pore throats interconnect all four pore types in three dimensions.

Brine Source

A source is needed for the large volumes of water containing calcium, magnesium, and sulfate ions to form the thick sequence of anhydrite beds, and at the same time to dolomitize the subtidal muddy sediments below. A coastal sabkha with a seaward flow of brines enriched by evaporation could have been such a source. As these brine solutions moved through the inner recharge zones of the coastal sabkha, aragonite and gypsum or anhydrite precipitated out, increasing the Mg^{2+}/Ca^{2+} ratio to favor dolomitization (Butler, 1969). A sabkha, prograding toward the Williston depocenter, may have provided a regional, long-continued, predominantly lateral and downward movement of enriched brines (Jacka and Franco, 1974). In a regional view of the Mission Canyon provided by Harris *et al*. (1966) and Malek-Aslani (1977), an eastward thickening of evaporitic beds suggests that brines in adequate volumes were derived from subaerially exposed areas at the time the carbonate sediments were accumulating (Figs. 10-5 and 10-10). Sediment compaction on the coastal sabkha, as well as the density of the brines, may have provided needed energy to force the brines seaward into the subtidal muds (Lindsay and Roth, 1982).

Source Beds

The source for hydrocarbons now entrapped in the Mission Canyon Formation is widely thought to be the Bakken Shale (Williams, 1974). Stratigraphically, the Bakken Shale straddles the Devonian-Mississippian boundary and underlies the Lodgepole Limestone. It is a highly organic-rich shale with high organic carbon content, especially toward the basin center. Migration from maturing organic matter is calculated to have begun at approximately 7000 feet (2150 m) of burial, with maximum expulsion of hydrocarbons during the Cretaceous (Dow, 1974). A second possible source for the generation of hydrocarbons is the Lodgepole Limestone, which in parts of the Williston Basin is reported to have sufficient quantities of organic matter (Williams, 1974). Migration paths were probably along vertical fractures and then laterally beneath the Mission Canyon evaporites until entrapment occurred.

Conclusions

Reservoir development and hydrocarbon accumulation in Little Knife Field are primarily the result of structural flexure and stratigraphic entrapment, coupled with diagenetic porosity development. The Mission Canyon Formation represents a prograding carbonate sequence punctuated by upward-diminishing cyclic carbonate sedimentation as a result of an overall regression. Depositional environments changed with time from dominantly open shallow-marine settings into transitional and restricted, low-energy, shallow-marine environments on a protected shelf, to emergent barrier island and back-lagoon sections overridden by prograding supratidal flats. Within the mud-enriched protected shelf setting, the transitional open shallow-marine to restricted-shallow marine facies (zones B, C, and D) were dolomitized and contain all hydrocarbon-bearing beds. Subtle facies variations in original lime-mud content, burrowing, and compaction combined to cause parts of the formation to be more susceptible than others to the development of porosity through anhydrite replacement, dolomitization, and later leaching of anhydrite.

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