THE RICHFIELD MEMBER OF THE LUCAS FORMATION OF THE DETROIT RIVER GROUP (LOWER MIDDLE DEVONIAN), MICHIGAN BASIN, MICHIGAN, USA

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ABSTRACT: The Richfield Member of the Lucas Formation is composed of numerous anhydrite and carbonate cyclothems which prograded across the Michigan Basin from the west to the east forming a wedge of sediments. The sulfates were precipitated as either anhydrite or gypsum (1) from the evaporation of pore fluids in the supratidal facies, (2) as lath crystals in the intertidal and subtidal facies, and (3) as subaqueous palmate crystals within the ponds on the supratidal flats and in the deeper basin. The low-relief platform was frequently inundated by basinal waters with only slight changes in water level. Thus, the sabkha was flooded with sheets of water which caused subaqueous palmate gypsum to precipitate so that a single anhydrite bed had both supratidal and subaqueous origins. The intertidal and supratidal zones were characterized by dolomitic algal mats which frequently were partially or totally dolomitized by replacement. The dolomite is typically euhedral to sub-euhedral with an idiotopic texture forming intercrystalline porosity. The subtidal facies was composed of peloids, ooids, and micrite with partial dolomitization. Basinal ionic concentrations regulated whether anhydrites or carbonates were deposited in this zone. Maximum thickness of the Richfield, up to 225 feet, occurred on the western edge where the maximum number of cyclothems were developed. To the east, the unit has fewer carbonate-anhydrite cyclothems and greater amounts of unaltered limestone which thinned to a feather edge.

THE MICHIGAN BASIN: CRATONIC BASIN

The Michigan Basin is a major downwarp or intracratonic basin within the interior of the North American plate. Significant thicknesses of strata have accumulated as a result of this downwarping. More than 3 km of sediments were deposited in the Michigan Basin between Ordovician and Jurassic times (Sleep and Sloss, 1980).

Questions as to what caused the development of the circular to ovate basins of the North American craton have been met with no conclusive theories (Cox, 1973). The common denominator for the Williston, Michigan, Hudson Bay and Illinois Basins is that each subsided steadily so that sedimentation and subsidence were in balance. Bally and Snelson (1980) noted that each of the North American cratonic basins was underlain by an ancient rift system, implying that failure of the rift may cause cratonic subsidence later. This theory has gained acceptance for carbonate-evaporite sequences. For example, the Michigan Basin overlies a linear positive Bouguer anomaly which has been considered an arm to a triple junction rift. Fowler and Kuenzi (1978) interpreted the anomaly as a reflection of a proto-oceanic basaltic crust. They suggested that the Michigan Basin developed over the thinned and subsiding crust along this rift. Continued subsidence during the Late Cambrian to Jurassic would have been caused partly by the weight of sediment overburden.

Sedimentation patterns on cratonic platforms and in basins are dominated by broad, shallow depositional systems and are markedly affected by the patterns of regional and global cyclicity proposed by Sloss (1963), Vail *et al.* (1977), and Sloss (1984). The Devonian Michigan Basin has been suggested to be a reflection of cyclicity of water levels and evaporation rates.

Bouguer Gravity Relationships to Facies Deposition

The Midcontinent Rift System, formed about 1.2 billion years ago, was the site of deposition of Keeweenawan volcanic material composed predominantly of basalt and andesite. This trend of rocks can be traced using geophysical and geologic data for at least 1300 miles from central Kansas to

CARBONATES AND EVAPORITES, v. 4, no. 1, 1989, p. 9-43

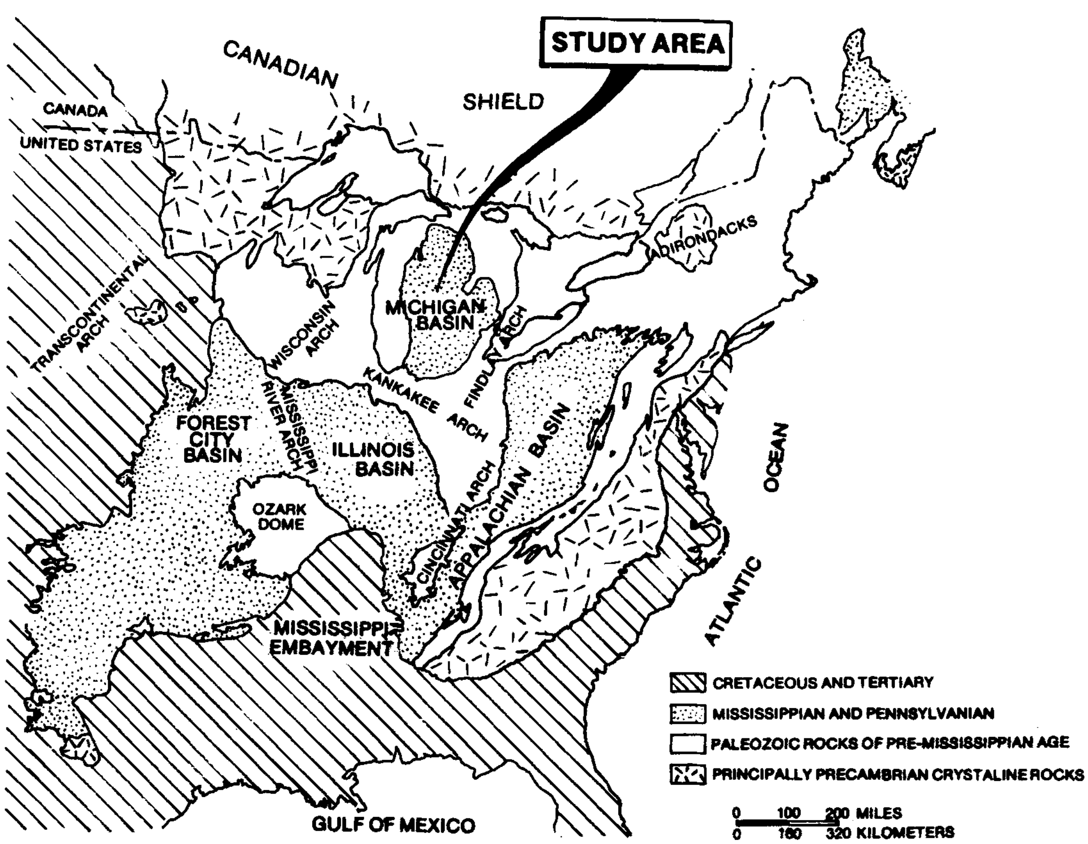

Figure 1.--Tectonic features surrounding Michigan basin (from Potter and Pryor, 1961).

Lake Superior and down through the southern peninsula of Michigan (Figs. 1 and 2; indicated by positive Bouguer anomaly trend on figure 2). Lake Superior was the site of a triple junction with the failed arm trending north into Canada. This rift system has outcrop exposures occurring along the northern shoreline of Lake Superior.

The southern peninsula of Michigan is characterized by a positive anomaly trend (Fig. 3) with three orientation changes (Fig. 4). This trend may be the second arm of the triple junction.

Ball (1972) demonstrated with modern and ancient carbonate environments that what was considered to be a structural platform for deposition was characterized by a regional gravity and/or magnetic anomaly. These platforms regulated the initial topography, which also influenced water currents and subsequent development of carbonate depositional facies. Ball (1972) studied the relationships of structural platform deposits ramping into deeper water facies and their relationships with the bouguer anomaly values. In every example, a striking correlation of the gravity anomaly existed with the depositional platform topography. The topographically low intraplatform straits and basins were always sites of negative anomalies; whereas, the shallow water and partially exposed areas were characterized by positive anomalies. Figure 5 presents an overlay of Richfield facies of Lower Middle Devonian age over the bouguer gravity map representing the Precambrian basement. The close relationship of the Richfield carbonate subcrop perimeter with the positive anomaly band of the Midcontinent Rift through Michigan has close parallelism to Ball's findings. The Richfield is very anhydritic along the positive anomaly directly reflecting a topographic high which was characterized by very shallow water deposition with frequent exposure. The negative anomalies are characterized by shelf and basin deposits where the Richfield facies graded into intertidal and subtidal carbonate facies. The transitional zone between supratidal and subtidal mudstones defines the potential Richfield carbonate reservoir fairway.

Figure 2.--Simple Bouguer Gravity Map of Lake Superior district illustrating the mid-continent rift (Hinze et al., *1982).*

Stratigraphic traps were created on the flanks of tectonic structures or on the crests of depositional or erosional features. These trap boundaries were determined by nontectonic factors which for the Richfield Member included truncation, offlap, onlap, and depositional and/or diagenetic changes. Knowledge of depositional and diagenetic facies changes in the Richfield is crucial for locating potential traps. Subsequent tectonic movements during the Mississippian and Pennsylvanian caused structural movement on the stratigraphic traps greatly altering the diagenetic fabric and trapping mechanisms in the Richfield.

Tectonics of the Michigan Basin

The Michigan Basin existed during the Cambrian in an embryonic form. Its negative character allowed clastics and carbonates to be deposited on top of the Precambrian crystalline basement. Positive features surrounding this basin (Wisconsin Arch, Cincinnati Arch, Findlay Arch and Kankakee Arch) influenced deposition and erosion within the basin throughout its history (Fig. 1).

Youngest sediments (Jurassic) are concentrated in the center of the basin with progressively older rocks exposed outwards (Fig. 6). In cross-section oriented perpendicular to the basement trends, figure 7 illustrates ages, unconformities, thicknesses and major structural basement anomalies. It is interesting to note the location of the basement-rooted anticline (West Branch Field) and the location of updip truncation of the Richfield corresponding with location of the mid-continent rift extension.

By the Middle Ordovician, the Michigan Basin developed its current circular shape, as evidenced by thickened stratigraphic units within the basin center. Sediments have taken on a symmetrically downwarped stratigraphy. Based on Ells' (1969) study, the basin dips one degree towards the center.

Maximum subsidence of the basin occurred in two time periods during the Paleozoic. The central part of the basin received 4,000 feet of sediments in the Silurian, and the Devonian contributed another 4,000 feet of sediment by way of limestone, dolomite, evaporite and shale (Fisher, 1979).

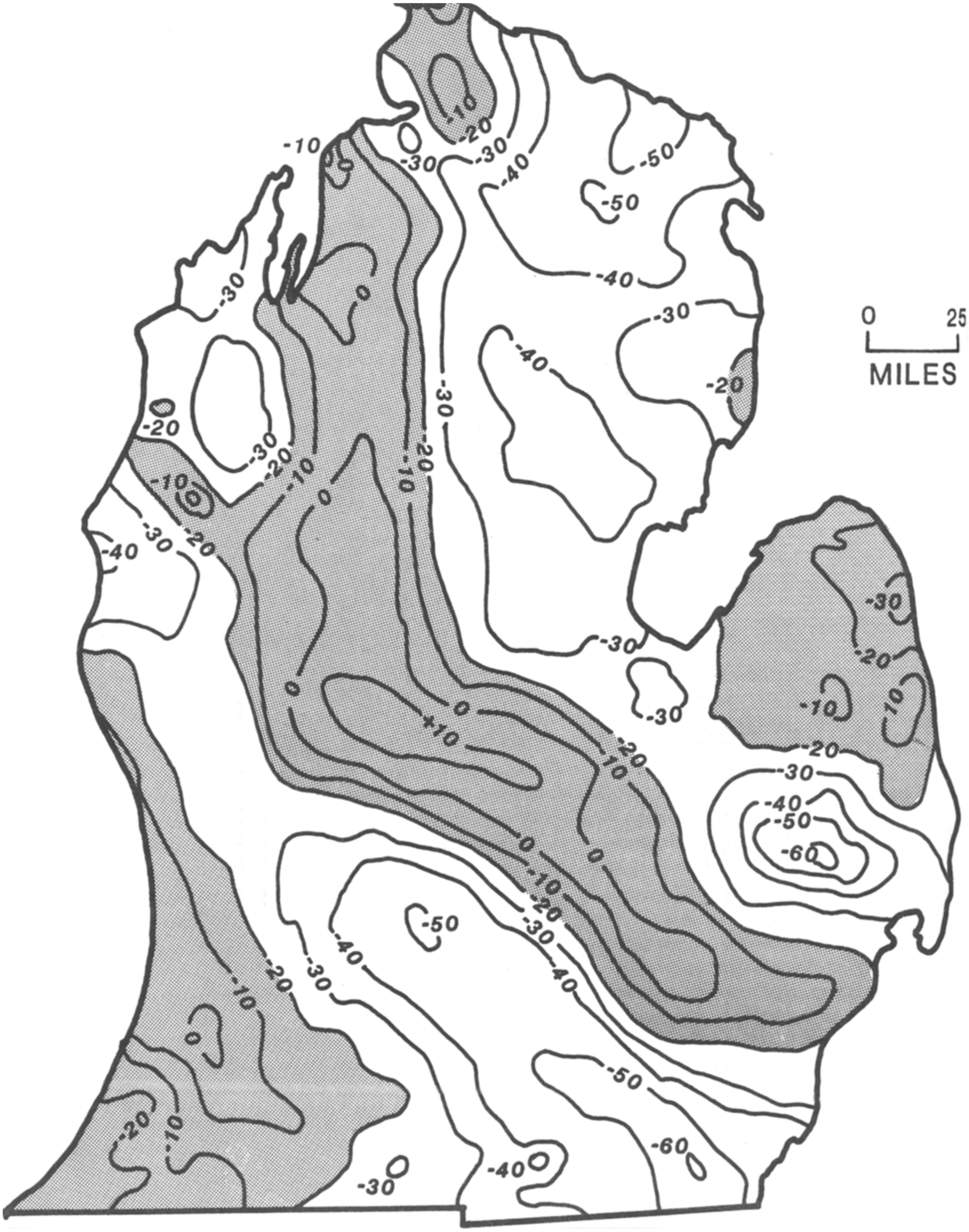

Figure 3.-- Michigan segment of mid-continent rift Bouguer Gravity anomaly (from University of Wisconsin and Klasner and others, 1982).

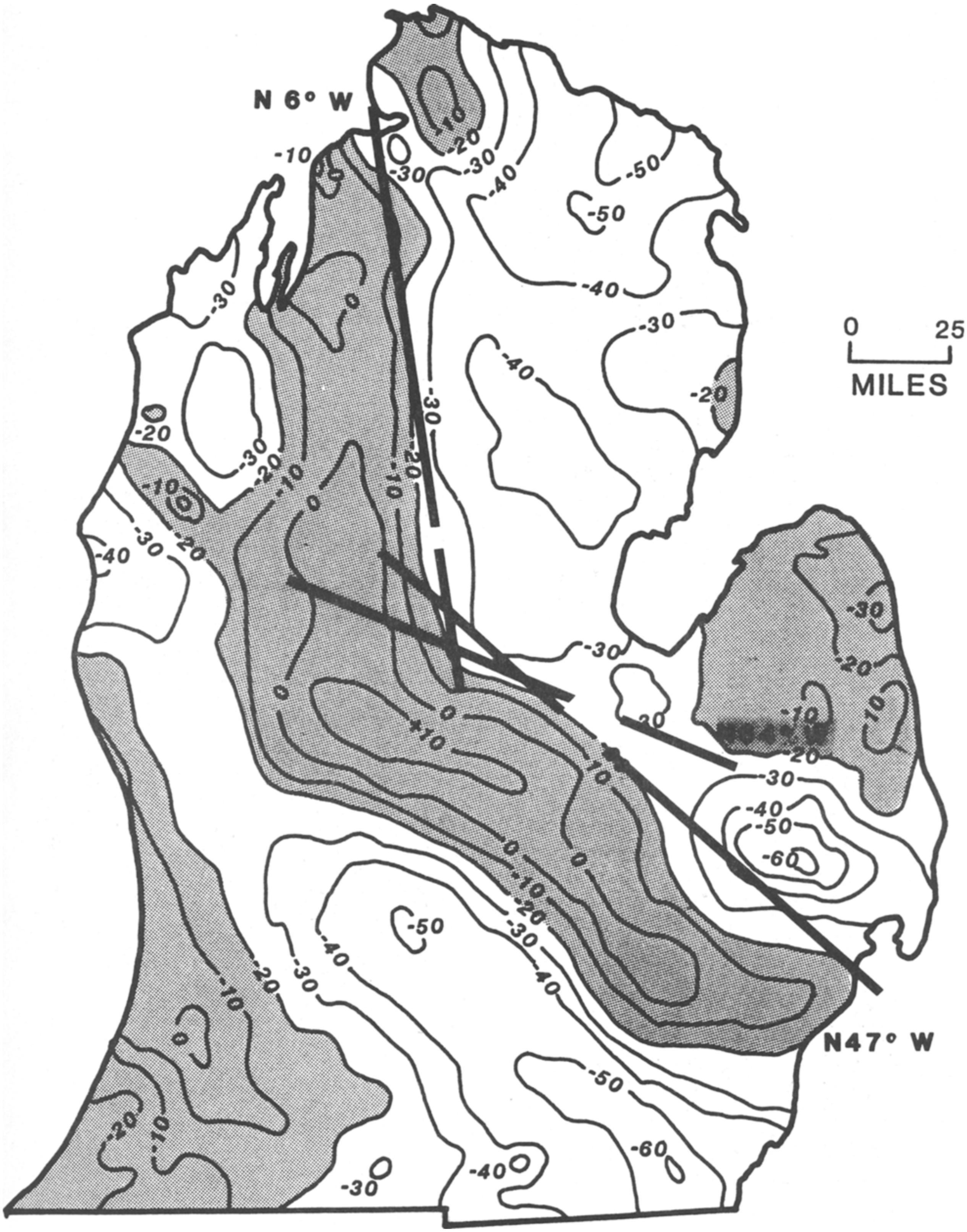

Figure 4.--Simple Bouguer Gravity Map with orientations of Michigan segment of the mid-continent rift (from University of Wisconsin and Klasner and others, 1982).

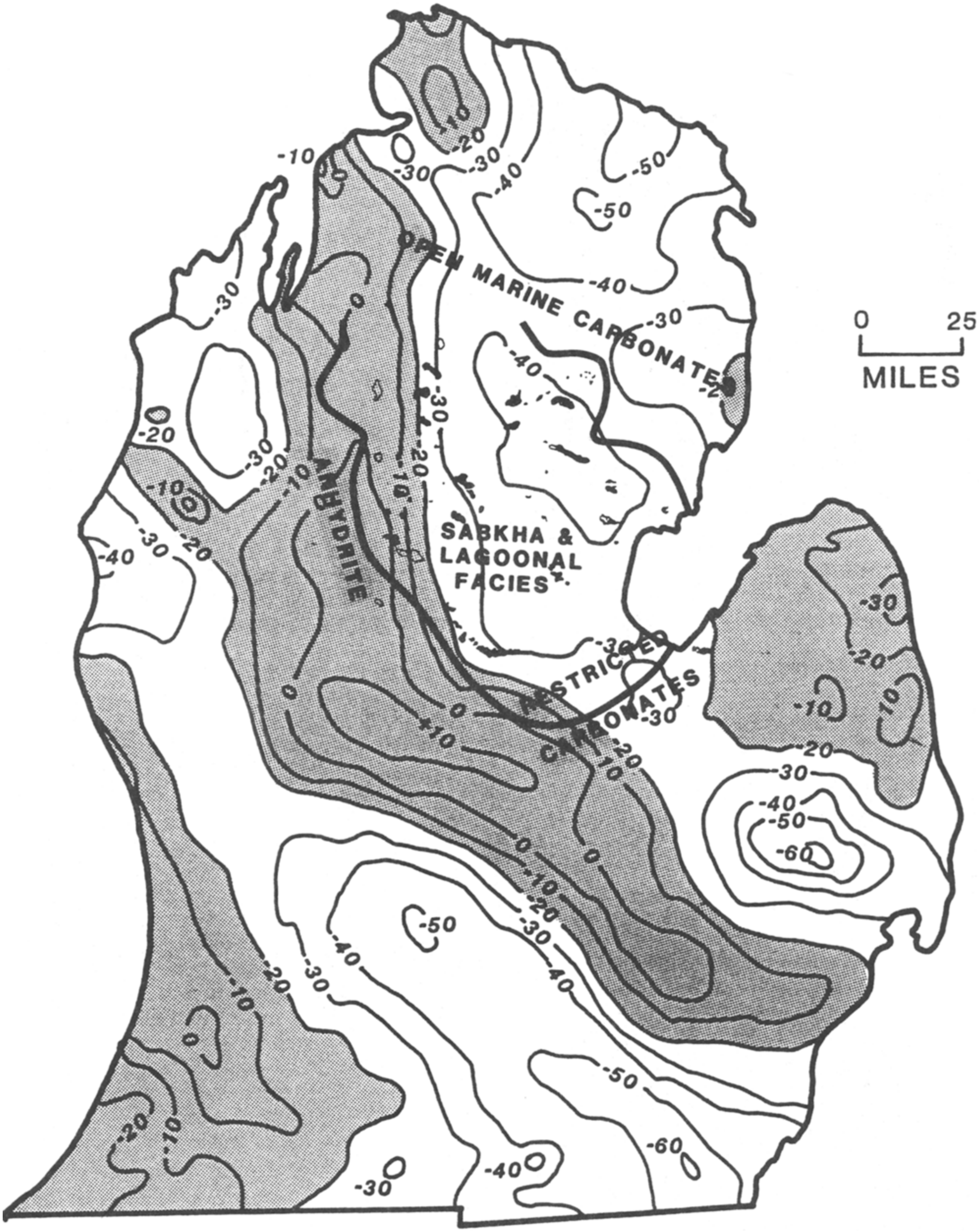

Figure 5.--Simple Bouguer Gravity Map of Michigan reflecting Precambrian basement rock (from University of Wisconsin and Klasner and others, 1982) with Devonian Richfield facies overlay (from interpretation of Judith L. Melvin).

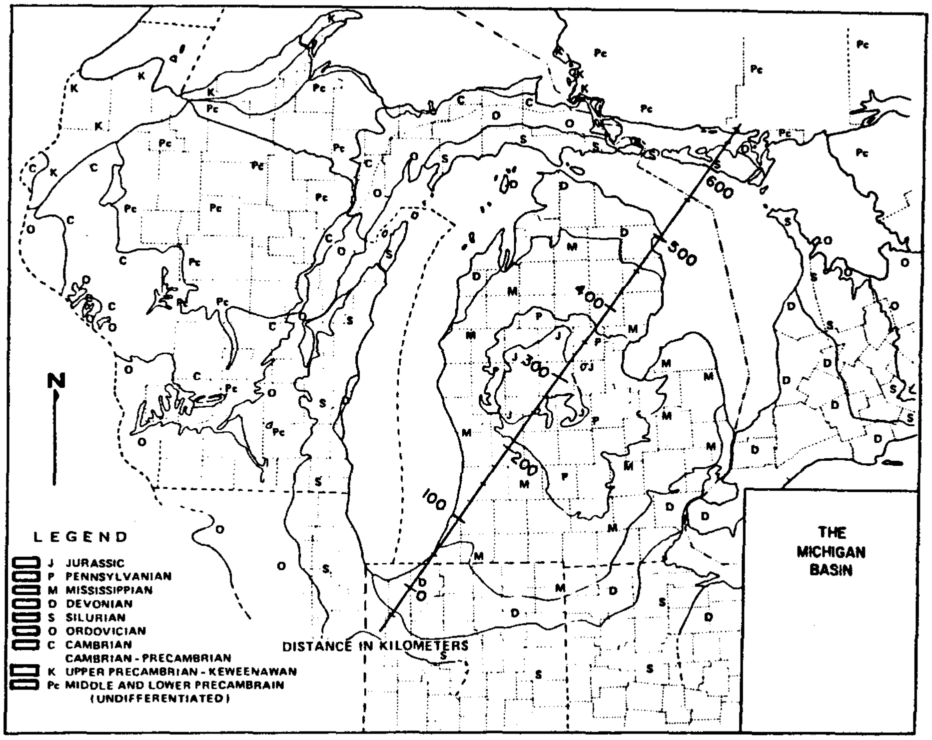

Figure 6.--Preglacial subcrop map of the Michigan basin (after Stonehouse, 1969). The path of the cross-section in figure 7 is roughly perpendicular to Keewenawan trends in the basement (by permission of the Michigan Basin Geol. Survey).

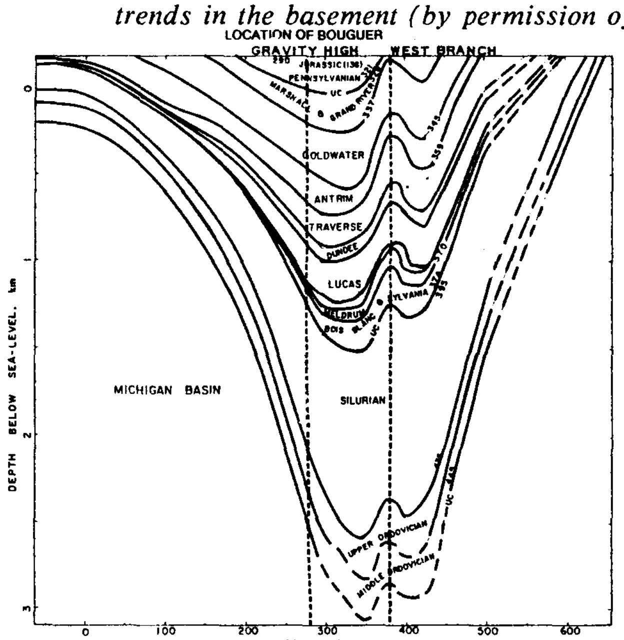

Figure 7.--Post-Sauk cross-section of the Michigan basin (after Sleep and Snell, 1976). Major unconformities (Sloss, 1963) are marked with UC and the ages above and below given. Absolute ages are given where possible for formation boundaries. The anticline at 380- km is due to late Paleozoic tectonism. Some minor structures were omitted.

By Mississippian time, movement occurred along basement faults that extended up into the Coldwater Shale of early Mississippian age. Stresses from the Appalachian Orogeny during early Pennsylvanian time also affected the basin. According to Fisher (1979), vertical movements along basement faults formed the northwest-trending folds in the central part of the basin. Prouty (1983), using LANDSAT imagery, presented considerable data for a wrenching model encompassing both shear faults and shear folds based on lateral (horizontal) offset.

STRATIGRAPHIC NOMENCLATURE

Lucas Formation Nomenclature

The Richfield Member was discovered by Sun Oil Company in 1941 with the Bauman Number 1 in the St. Helen Field when a "deep test" well was drilled. The term Richfield was derived from Richfield Township in Roscommon County in Sec. 29, T24N-R1W. Landes (1951) established the Lucas Formation with its first officially designated member - the Richfield Member. Landes credited Ehlers (1950) with placing the Lucas Formation in the upper part of the Detroit River Group of Middle Devonian age. Dating of the formation was established by E.C. Stumm with the discovery of the fossil *Prosserellas lucasi* in the State-Mancelona A-1 well in Antrim County (after Gardner, 1974).

In 1952, Hautau wrote "The Richfield Challenge" with the aid of two Sun geologists, for the Michigan Geological Survey. Although the purpose of the paper was not to define the Detroit River Group in its entirety, it presented names for two more zones - the Massive Anhydrite and the "Sour Zone". The term "Sour Zone" differentiated the sweet-crude-producing zone at the base of the evaporite sequence from the sour-producing zone of the overlying evaporite sequence. The "sour zone" was deemed to be "below the lowest massive Detroit River salt bed and above the Massive Anhydrite." This stratigraphic designation was determined to be informal because it did not recognize previous stratigraphic nomenclature - it only used "oil-field terms". However, by using the Code for Classification, the Massive Anhydrite should be recognized as a formal unit. The "Sour Zone" is not properly classified - it is a series of cyclothems. The name was based on the kind of hydrocarbons produced, and not on rock type within a specific geographic boundary. Later, it would prove that the interval containing numerous salt beds also should be designated a "Sour Zone" based on type of hydrocarbons produced.

Sanford (1967) defined an unconformity at the top of the Bois Blanc. The Detroit River Group was thus extended through the Sylvania Sandstone. Ellis (1969) removed the Sylvania Sandstone from member status as defined by Landes (1951).

Shell Oil (1973, manuscript) issued an in-house report of their nomenclature. Because it was proprietary information, this nomenclature could not be accepted according to the Code rules of Article 13, paragraph (c). In this report, all zones above the Massive Anhydrite were designated as the Detroit River Evaporites. Their "Detroit Sour" zone was defined as "the zone above the lowest most salt". This was quite contradictory to Hautau's and Sun's terminology because Shell defined the Detroit River Group in the northern reef trend. Once again, production of certain kinds of hydrocarbons, rather than rocks within a geographical area, defined the stratigraphic section.

Gardner (1974) accepted the previous formal terms and acknowledged that a problem of nomenclature existed above the Massive Anhydrite. He defined the entire Detroit River Group in the basin (Fig. 8). He chose three Sun wells as the type sections for three members which he would properly define according to the Code of Stratigraphic Nomenclature.

In ascending order, the type section for the Meldrum Member (Black Lime) was characterized by Sun Oil's Meldrum #1 in Sec. 28, T22N-R1W (Gardner, 1974). The Meldrum Member has been credited with containing the Filer sandstone which is limited to the western flanks of the central basin. This sandstone body was not present in the type well for the Meldrum Member.

The Richfield Member, as defined by the type section in St. Helen Field, is composed of 4-5 major anhydrite cycles. It is overlain conformably by the Massive Anhydrite, but its base is time transgressive. Gardner (1974) chose to use the base of the lowest-most anhydrite as the base of the Richfield. However, this method is suspect because in effect the stratigrapher is jumping correlations across the basin. Maximum development of anhydrite cycles occur in Missaukee and Clare Counties. The number and thickness of cycles decrease towards the east. The best pick for the base of the Richfield is to use a marker within the coralline Black Lime in the central basin and migrate the correlations to the dense Amherstburg lime on the basin margins. A three-dimensional cross-section illustrates that this method is far superior and best reflects the changing depositional environment.

The Iutzi Member was defined as being composed of the "Lower Sour Zone" and the Massive Anhydrite. The type section was depicted by Sun's Airlie & Iutzi B-2 well in Hamilton Field, Sec. 6, T19N-R3W between the depths of 4978-5137 feet. It is defined as the sequence of alternating anhydrite and carbonate below the lowest most salt. Gardner honored all previous stratigraphic boundary designations established by Hautau (1952) and Sun for what was defined as the "Sour Zone". He chose not to break the section into lesser informal units as Sun procedure dictated. Sun divided the Iutzi Member (without naming it thus) into the Lower Sour, Middle Sour, and Upper Sour. But then Sun had a problem as to what to call the overlying 1,000 feet of sediments in the central basin which also produced sour hydrocarbons. Shell was faced with totally the opposite problem. They defined their sour zone down to the base of the salts based on the

GROUP	FORMATION		MEMBERS	INFORMAL NOMENCLATURE	TYPE WELLS FOR SECTION
DETROIT RIVER GROUP	LUCAS FORMATION	DETROIT RIVER SOUR	HORNER MEMBER	UPPER SOUR ZONE	SUN OIL COMPANY SUN-HORNER #17 SEC.12,T24N-R5W NORWICH FIELD between depths of 3505-4285 ft.
			IUTZI MEMBER	LOWER SOUR ZONE MASSIVE ANHYDRITE	SUN OIL COMPANY AIRLI & IUTZI etal B-2 SEC.6,T19N-R3W HAMILTON FIELD between depths of 4978-5137 ft.
			RICHFIELD MEMBER	RICHFIELD FREER SANDSTONE	SUN OIL COMPANY BAUMAN #1 SEC. 29, T24N-R1W ST. HELEN FIELD
	AMHERSTBURG FORMATION		MELDRUM MEMBER	FILER SANDSTONE BLACKLIME	SUN OIL COMPANY MELDRUM#1SEC.28,T22N-R1W
				SYLVANIA SANDSTONE	

Figure 8.-- Subsurface nomenclature of Detroit River Group showing location of "type logs" (Gardner, 1974).

stratigraphic characteristics in the Northern Reef trend. The common dividing interval was the base of the lowestmost salt in the central basin accepting the fact that it was time transgressive with anhydrite on the western side of the state.

Gardner (1974) named all strata containing halite, anhydrite, and carbonate as the Horner Member after Sun's Horner #17 in Norwich Field, Sec. 12, T24N-R5W occurring between the depths of 3505-4285 feet. He proceeded to call this interval in the Central Basin the Upper Sour which was compatible with the sour zone which Shell described in the Northern Reef trend which also produced sour hydrocarbons throughout the Michigan basin.

The most impressive feature of Gardner's nomenclature was that the members were divided according to cyclothems of varying salinities within the basin in relationship to kind of sediments deposited. His designation of members was based on rock type and cyclothems.

Matthews (1977) used the nomenclature of Horner and Iutzi as defined by Gardner. However, Matthews' paper was directed towards salt. He used Sun's Mills Estate #1, Sec. 4, T18N-R2W in Grout Field as his type section for salt development.

Lastly, in a publication of the Michigan Geological Survey (Lilienthal, 1978) cross-sections defined the "Sour Zone" as being in the middle of the Horner Salts. According to Lilienthal, "this zone is not as easily recognized nor correlated in the basin". This was because he was trying to use only gamma-ray logs. He also defined the "top of the Lucas" as being the first Detroit River salt, when a purist would call it the first anhydrite. He did not honor previous stratigraphers' work nor Article 5, which stated that "boundaries are placed at sharp contacts ... both vertical and lateral boundaries are based on the lithologic criteria that provide the greatest unity and practical utility". Also according to Article II, paragraph (b) states that "the term 'well established' is difficult to define, but acceptance of a name by several authors is generally taken as establishing it".

The Richfield Member, Iutzi Member and the Horner Member are components of the Lucas Formation. The Amherstburg Formation, which contains the Meldrum Member, and the Lucas Formation, are known collectively as the Detroit River Group. The Detroit River Group is correlative, in part, to southwestern Ontario (Rickard, 1984), but the Richfield is contained only within a limited part of the Michigan Basin.

Freer Sandstone Nomenclature

Landes (1951) claimed that the Richfield Member contained sandstone beds which attained 50 feet in thickness on the west flank of the central basin. The type well used to illustrate this localized sandstone was the Jennie Freer #1 in Clare County, Section 18, T17N-R6W, drilled by Pure Oil. Offset wells to the Jennie Freer did not encounter the small sand pod. Early wells drilled in the 1940s in Winterfield also were described by geologists in driller's logs as containing scattered sandstone grains at the stratigraphic level of the basal Richfield. The Freer #1 had an extraordinarily thick section of sandstone, which became known as the Freer Sandstone of the Richfield Member, a name given for a singular pod. Other areas in which the Freer Sandstone has been encountered have not demonstrated such a thick section. In Grout Field, the sandstone attains 25 feet in thickness, and in other areas its presence is marked by scattered quartz sand grains within the carbonate rock. Gardner (1974) mapped the Freer Sandstone as three sub-parallel but isolated sand pods with a northwest orientation across the width of the basin. Gardner theorized that this sand with probable source from the west was another indication of regressing seas. Some of the core descriptions report the sand as being quartzose, whereas others describe it as being dolomitic. All workers agree that the fine- to medium-grained sand was cemented by calcite.

It is suggested that the sand is much more prevalent than previously thought by Landes (1951) and Gardner (1974). Quartz sand occurs throughout the early Richfield depositional setting across the basin as sheet sands, pods and storm deposits following the positive Bouguer Gravity Anomaly in a generalized north-south direction (Fig. 9). Quartz deposits occur throughout the Richfield stratigraphic column simply as 1) localized facies changes within the carbonate matrix of the nodular anhydrite facies, 2) scattered along algal laminae and as 3) offshore bars with evidence of cross-bedding and bioturbation. For this reason, the Freer nomenclature should be abandoned for it is not a distinctive bed with well defined limits meriting nomenclatural status.

RICHFIELD FACIES ANALYSIS

The first published vertical profile of the typical components of a Richfield facies model was constructed by Gardner (1974). He noted close similarities of facies assemblages depicting sabkha cyclothems as seen in the Persian Gulf, Trucial Coast, supratidal flats of the saline Kor al Basan, and the Devonian Williston Basin. Gardner (1974) made a brief note of some subaqueously deposited anhydrite, but Melvin (1984) proposed both supratidal and subaqueous anhydrite throughout the Richfield depositional basin and interpreted that a sabkha-chenier complex existed during late deposition. It is suggested that tidal pools, ponds, and lagoons precipitated subaqueous anhydrite and halite during periods of intense evaporation. In West Branch Field bedded halite occurs four feet thick in a very localized area. On the western margins anhydrite pseudomorphs of halite are random through the rock record.

Most carbonates in the Richfield have been dolomitized and according to Friedman (1980) dolomites in the rock record commonly formed under conditions of hypersalinity. He noted that a close lateral and vertical relationship existed between dolomite and evaporite deposits. In most examples the dolomite is a replacement product of calcite as evidenced by the abundance of euhedral rhombs in an idiotopic fabric. Some primary or penecontemporaneous dolomite formed as crusts together with evaporites in areas where seawater evaporated at high rates. Two depositional environments may have aided in the formation of primary dolomite: 1) supratidal flats with subaerial exposure, and 2) shallow tidal lagoons in a subaqueous setting. The dolomite-evaporite association coupled with evidence of desiccation textures suggests evaporitic conditions and subaerial exposure.

Cyclic sequences of carbonates and evaporites reflect the sensitive response to climate change, brine concentrations and water depths. Both supratidal and subaqueous depositional cycles may have occurred. The most well-known vertical profile model of coastal sabkhas was constructed

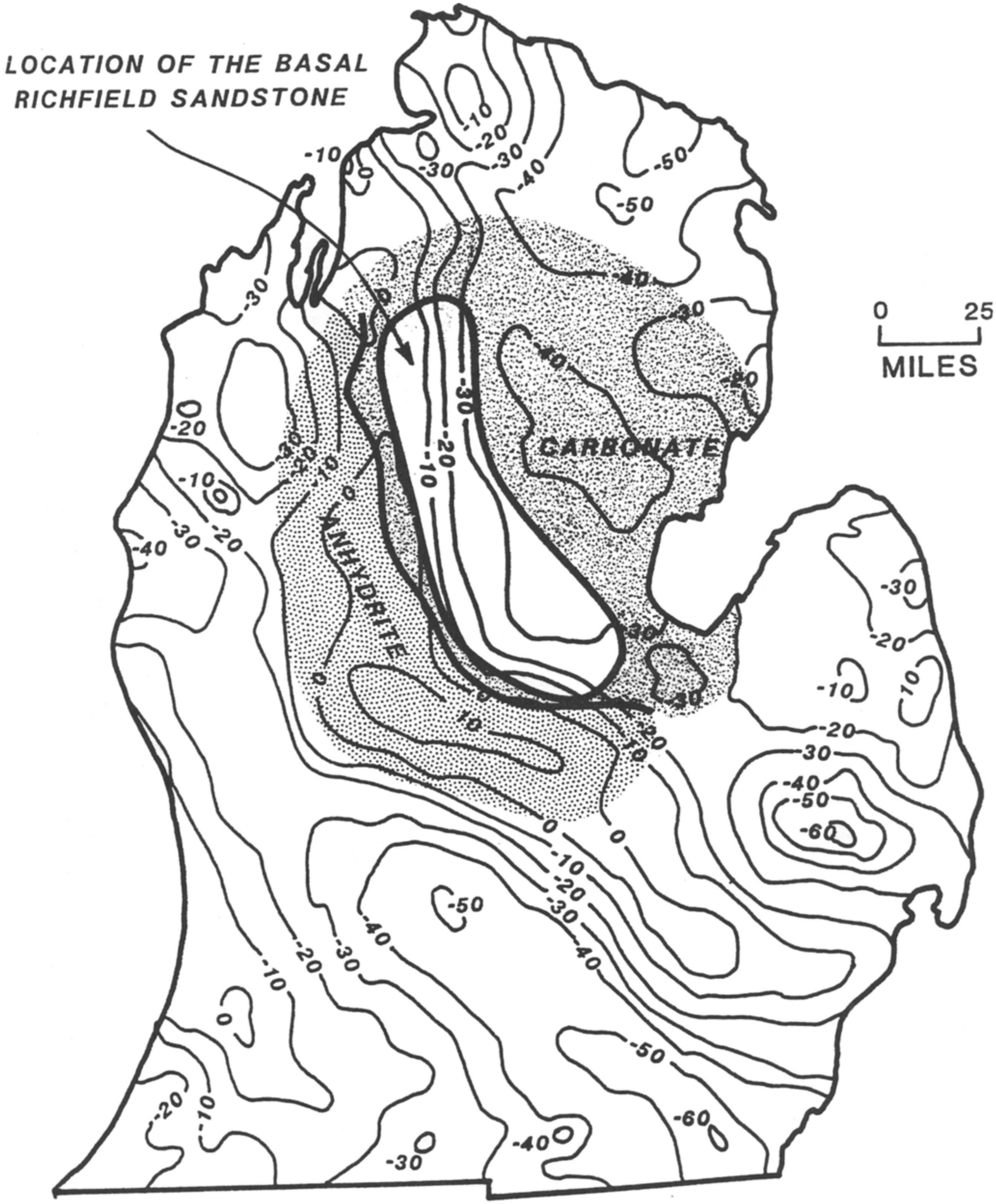

Figure 9.--Basal Richfield lithofacies map illustrating depositional area for sandstone bodies.

by Kinsman (1969) reflecting Recent sedimentation in the Persian Gulf, whereas Shearman (1963) has been credited with the discovery of supratidal anhydrite and the sabkha succession. With Shearman's discovery, many evaporite depositional settings have been modified to also reflect that evaporites form with exposure as well as subaqueously. Because of this, caution must be used in interpreting these cycles because they may indicate a build-up or progradation under stable water levels, but may also be products of brine evaporation and falling water levels. Many cycles of recharge and evaporation have been suggested for major evaporite basins such as the Mediterranean Messinian and the Silurian Michigan Basin. Melvin (1984) and Gardner (1974) have also suggested this process for the Devonian Detroit River Group in the Michigan Basin.

Sea-level fluctuations during Richfield deposition are reflected in the evaporite-carbonate successions. Sea-level transgressions, regressions, and stillstands were produced by 1) changes in the amount of marine water flowing into the basin, 2) changes in the amount of freshwater run-off from the Wisconsin highlands, 3) basin subsidence, and 4) changes in evaporation rates. The effects of regression were 1) emergence of tidal-supratidal platforms, 2) formation of prograding sedimentary sheets in tidal flats and shallow offshore areas, 3) shoaling sequences, 4) emergence of cryptalgal structures, and 5) migration of mat communities and geochemical zones (Logan *et al.*, 1974).

A sabkha is defined as a surface of deflation down to groundwater, or down to the capillary zone where cement forms in a sea-marginal flat in an arid environment (Friedman and Sanders, 1978). The Richfield sabkha environment evolved only centimeters below and above sea level. This caused the sabkha to be sensitive to changing tides by nature of its geomorphic position. Slight rises in sea level caused reworking of sediments and dissolution of evaporites. Lowering of sea level caused emergence, evaporite cementation, evaporite deposition and dolomitization. During still-stands, evaporites and carbonates formed in both sabkha and subaqueous environments determined by water currents, water depths and salinities. Storms also played a role by ripping up clasts and transporting foreign material.

The rocks of the Richfield Member were deposited in a sabkha and lagoonal environment. Anhydrite beds are the key to which process was active during different times of deposition. It is suggested that laterally discontinuous anhydrite beds evolved in a sabkha environment; and that laterally expansive and vertically thick anhydrite beds evolved in a shallow water lagoonal environment. A sabkha-chenier complex is suggested for Richfield deposition throughout the basin. Regardless of whether supratidal or subaqueous deposition occurred, a very strong relationship existed - one could not exist without the other.

Richfield Sabkha

The intertidal-supratidal zone is transitional between marine and continental conditions and is strongly influenced by sediment type and fluid composition. This zone was emergent for significant periods each year, so climate played an important role in the hydrology and diagenesis of the system. Climate controlled the evaporation of supratidal pore fluids which caused geochemical reactions to take place. The supratidal-intertidal interface experienced the movement of continental fresh water by vadose movement through the sediments, the movement of hypersaline marine waters from the restricted basin, and the run-off of fresh waters from the continent and rainfall. Also, the position of the groundwater table influenced the growth of thick algal mats. Logan *et al.*, (1974) suggested that algae could only grow where groundwaters were close to the surface. The mixing of all these waters, each with a distinctly different chemical composition, geochemically aided in the sabkha's evolution and destruction.

Evaporation of pore fluids in the supratidal zone encouraged evaporite deposition, whereas hypersaline waters from the lagoon bathed the sediments with high concentrations of $SO_4^{=}$, Ca^{++}, Mg^{++}, and Cl^- ions. According to Krauskopf (1979), the following chemical precipitates formed contemporaneously:

$$\underset{\text{(water)}}{2H_2O} + \underset{\text{(brine)}}{Mg^{++}} + \underset{\text{(sulfate)}}{SO_4^{=}} + \underset{\text{(aragonite)}}{2CaCO_3}$$

$$\downarrow$$

$$\underset{\text{(dolomite)}}{[CaMg(CO_3)_2]} + \underset{\text{(gypsum)}}{[CaSO_4 \cdot 2H_2O]}$$

Marine waters which contained much higher concentrations of $SO_4^{=}$ than Ca^{++} caused preferential precipitation of gypsum. Kastner (1983) stated that the mechanism for dolomite formation was low dissolved sulfate ($SO_4^{=}$) content. Mechanisms for reducing the free sulfate ion include 1) either dilution of the marine waters with an abundance of fresh water which lowers the $SO_4^{=}$ overall concentration in the water, or 2) by precipitating $SO_4^{=}$ out of the system through gypsum formation. Gypsum formation removes Ca^{++} ions which raises the Mg^{++} concentration. As Mg^{++} concentration increases, dolomitization occurs. Within this mixing zone, gypsum occurs as lenticular to tabular crystals within the algal mats. The degree of marine flooding over the sabkha, intensity of evaporation, and groundwater movement of freshwater differentiated the facies at time of deposition.

Algal mats making up the carbonate sediments of the sabkha intertidal zones are characterized by flat-lying algal-bound laminated sediments. The causes for laminations are 1) diurnal, monthly, seasonal and episodic sediment influx, 2) fluctuations in depositing currents expressed by differing grain size, composition, etc., 3) variations in organic mat and intergranular cement (Logan, *et al.*, 1974).

Increased temperatures and pressures with burial gradually transformed gypsum into anhydrite by dehydrating the crystal lattice with a 50% reduction in rock volume.

Continental waters flowing through these sediments enabled dolomitization to proceed in the upper intertidal facies. After partial lithification, movement of water occurred with dissolution of anhydrite cement and laths producing moldic porosity. These vugs either remained empty, were filled with cementing agents, or were lined with secondary minerals. Pseudomorphs of minerals often left the imprint of previous mineral suites. Dolomitization of carbonates was intense in a depositional band along the Richfield carbonate subcrop with decreasing dolomitization of the sediments towards the east and northeast accompanied by decreasing abundance of anhydrite beds.

Basin infilling of sediments occurred prior to Richfield deposition with the reefal facies of the Black Lime and dense limestones of the Amherstburg. Evidence of subaerial exposure of the Black Lime is abundant in Clare County with fresh water cements, broken reefal material, and dedolomites. With subsequent minor subsidence along the Mid-Continent Rift transgression of the seas moved across the depositional basin. Deposition proceeded faster than subsidence in parts of the basin.

The subsiding shoreline received the thickest sequence of sabkha sediments as progradation occurred. Subsidence and loading of the sediments kept pace with sedimentation. Along the Precambrian Rift zone, as subsidence and loading occurred, cyclicity of sediment deposition created new pulses of subsidence. Likewise, sediments that were deposited in sabkhas and intertidal zones subsided causing an ever greater wedge of sediments to form. After burial the lithostatic pressure caused differential compaction of the sediments. Carbonates and evaporites are physically different and respond differently to burial. The specific gravity of anhydrite is 2.98 gr/cm^3, whereas that of limestone is 2.71 gr/cm^3. With burial, compressibility of the sulfates would amount to about a 50 percent reduction in bed thickness, whereas the carbonate would be relatively incompressible. Thus, evaporites are downwarped not only because of underlying basement structure, but also because of the greater density and compressibility of the evaporites in relationship to carbonates.

A gypsum bed deposited in a sabkha complex would require 1000 years to deposit 1 meter of sediments allowing 1-2 km of progradation, whereas, subaqueously deposited gypsum would deposit 1-40 meters of sediments in the same time (Kinsman 1969).

Active subsidence during Richfield time is suggested by a thick succession of shallow-water sediments. As the supratidal zone prograded seaward (toward the northeast), the supply of fine-grained material in the shallow marine zone was reduced. Eventually, sedimentation balanced erosion and progradation of the sabkha stopped. Slow subsidence occurred and once again the sea moved across the land reworking the sediments during a minor transgression. Carbonate production was re-activated and fine-grained carbonates were deposited along the sabkha front, inducing progradation towards the basin. The shallow basin would show facies in cross-section which were not necessarily deposited as contemporaneous layers. The sediments would be time transgressive with the younger sediments occurring in the direction of shoreline movement.

The end result of a regressive cycle is a vertical sequence which in ascending order would be subtidal-intertidal-supratidal-exposure. This form of cycling occurred repeatedly. An immature cycle was one in which a facies was absent as a result of erosion or non-deposition. The number of mega-cycles identified in each well aids in placing the well within the basin. The highest number of major anhydrite cycles are located at the basin margins in the west and reflect maximum progradation of the sabkha and chenier. The smallest number of immature cycles occurs in deeper waters along the northeastern perimeter.

Transgressions typically reworked the previously deposited sediments and dissolved evaporites and highly soluble carbonates. This left an unconformity or disconformity which oftentimes was unrecognized in the rock record.

In a carbonate sabkha, in which most of the Richfield rocks were deposited, the carbonates were bathed in highly concentrated sulfate water. The precipitation of gypsum ($CaSO_4 \cdot 2H_2O$) caused an increase in the Mg:Ca ratio which promoted the dolomitization of the rock. The calcium ions released through the dolomitization of the rock made the Mg:Ca ratio very low. The Ca^{++} ions then combined with the residual sulfate brines whereupon more calcium sulfate precipitated (Shearman, 1978). These reactions are illustrated below:

1) $2H_2O + Ca^{++} + SO_4^{=} \rightarrow CaSO_4 \cdot 2H_2O$ (gypsum) $+$ Residual $SO_4^{=}$

2) $Mg^{++} + 2CaCO_3$ (aragonite) $\rightarrow CaMg(CO_3)_2$ (dolomite) $+ Ca^{++}$

3) $Ca^{++} + SO_4^{=} \rightarrow CaSO_4$ (anhydrite)

The overall effect is to produce twice as much calcium sulfate. Once again, sulfate ions are the generators allowing each diagenetic step to occur. Likewise, it becomes readily apparent why anhydrite is so prevalent throughout the Richfield as 1) primary crystals, 2) concretionary masses, and 3) cement.

Characteristics of each prograding sabkha facies preserved in the geologic record in one complete mature cycle in the Richfield Member are, from bottom to top (Fig. 10):

1) Subtidal: This is a limestone facies with some dolomitization. Ghosts of the former fabric are generally preserved after dolomitization. Fossils of brachiopods, ostracods and trilobites are found on close examination. Bioturbation of the sediments occurred during periods of near-normal salinities. Also, a pelletal facies is common. Ooids, generally with evidence of having been reworked, are common. The oolitic shape is preserved either as ghosts, moldic porosity, interparticle porosity or geopetal porosity. Algal mats are characterized by columns, mounds, or crenulate layers with burrowing.

2) Lower Intertidal: this facies is characterized as laminated with crenulose algal mats and isolated authigenic anhydrite. In areas of intense dolomitization the algal mats are destroyed. In the lowest interval a pelletal facies with abundant anhydrite laths is common.

3) Upper Intertidal: these algal-laminated limestones and dolomites contain anhydrite laths and concretionary anhydrite nodules. This transition zone from intertidal to supratidal is composed of convoluted algal mats caused by gypsum ($CaSO_4 \cdot 2H_2O$) dehydrating to anhydrite ($CaSO_4$) thereby displacing the sediments around the nodule. Concretionary anhydrite nodules of fairly large size at the supratidal-intertidal interface are present. Dolomite by replacement is most abundant. In areas of intense dolomitization, the original fabric is destroyed. In most cases, this zone is composed of euhedral and sub-euhedral rhombs with idiotopic texture. Porosity is very high because of the homogeneous crystal size, but permeability is low. This facies serves as the reservoir rock for hydrocarbons, as well as a major source rock. Rich organic matter was derived from the blue-green algal mats. Quartz grains also occur scattered along algal laminae. In the lower zone, depending on growth habit of the algae, horizontal laminae occur. This facies is the most diverse for anhydrite varieties - concretionary, authigenic and cement.

4) Supratidal: this environment is characterized by nodular anhydrite with limestone squeezed between nodules. These nodules form as a result of precipitation due to movement of waters rich in Ca^{++} and $SO_4^{=}$. Displacement growth causes enterolithic structures. Quartz deposits are prevalent within the squeezed limestone and anhydrite nodules.

Detailed mapping using core descriptions and well cuttings suggests that quartz particles

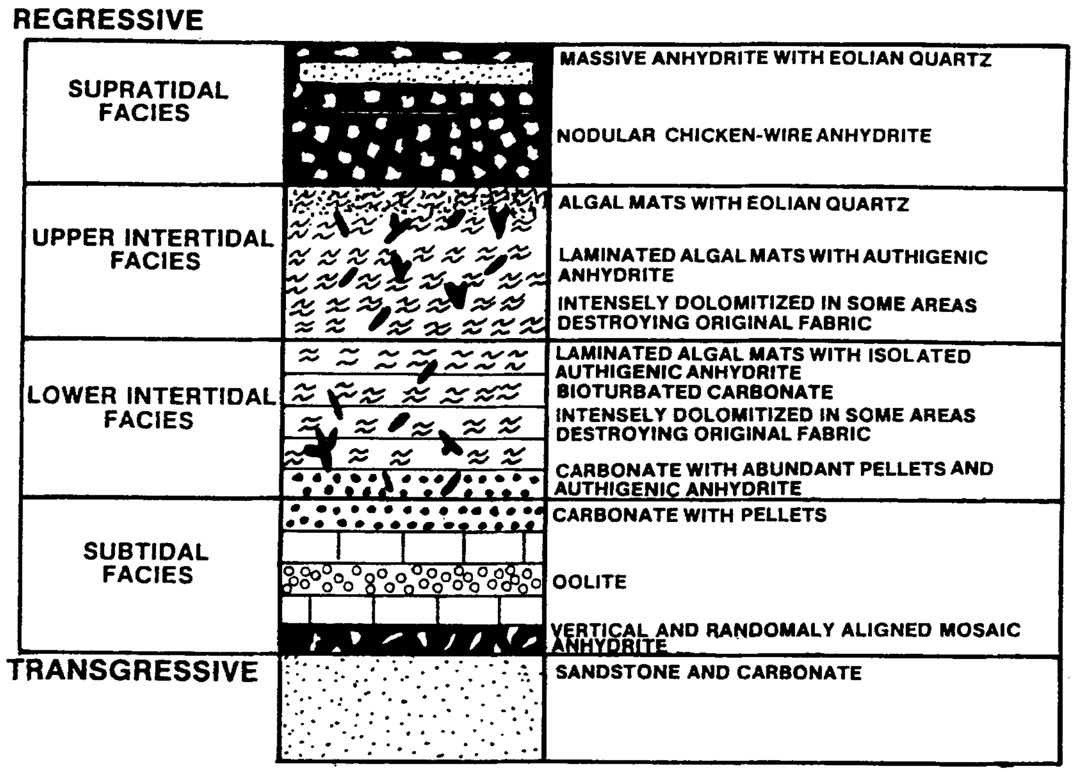

Figure 10.--Vertical sequence showing the facies changes in the Richfield Member.

occur throughout the basin in the basal Richfield Member. At Norwich Field in Missaukee County, the rock volume in one interval is 35% quartz. Quartz and a carbonate matrix range up to 70 feet thick in the basal Richfield Member in Midland County. Quartz is also prevalent in Kawkawlin Field, North Buckeye, Nellsville, Rose City and Grout Fields. In thin section, the quartz is well-rounded, bimodal, and silt sized with strong evidence of metamorphic provenance. Metamorphic overtones are displayed by migratory extinction patterns, fused grains, fluid inclusions and Boehm lamellae. Because of the bimodal distribution, it is suggested that two different provinces provided the quartz.

Richfield Lagoon

Below the sabkha-intertidal facies is the subtidal facies (lagoonal facies). Depending on the salinity of the water, either limestone or anhydrite will be deposited. A limestone subtidal facies occurs with each influx of normal marine water into the basin resulting in a cyclic transgression. An anhydrite lagoonal facies formed because of the concentration of salts with regression caused by evaporation and no influx of water. However, a rise or fall in sea level is not the same as a transgression or regression. Shelf-edge subsidence appears to always be faster than eustatic sea-level change, and so transgressions can actually occur during periods of falling sea level if the rate of lowering is sufficiently slow. Conversely, regressions can occur locally during periods of rising sea level if there is an adequate sediment supply (Miall, 1984).

Restriction of water, either in localized tidal pools and ponds or as isolated smaller basins occurred when excess evaporation caused a profound shallowing of the water. Usiglio (1849) hypothesized that in a standing body of water with no new water influx, calcite would be precipitated first followed by anhydrite, halite and potash salts. A very localized halite deposit occurs in West Branch Field suggesting a localized salt pan deposit of subaqueous origin.

On a regional scale, subaqueous gypsum (or anhydrite) deposition occurred with segregation of brine densities in the basin. Regional halite deposition cannot be documented during Richfield deposition. Anhydrite, with density 2.98 gr/cm^3, accumulated in the low lying areas, whereas carbonates ranging between 2.71-2.81 gr/cm^3 formed along the perimeters of the basin. Gypsum deposition ceased during each cycle either because evaporation rates decreased or because outflow of bottom waters increased. During either process, a carbonate lagoon evolved.

Kendall (1979) concluded with his studies of subaerial and subaqueous evaporites that both can occur together in a depositional setting. Seibold and Berger (1982) suggested that seas in an arid environment have excessive evaporation, which commonly created an exchange pattern with the open ocean. This pattern was demonstrated as surface water moving into the restricted basin and the deeper water moving out of the basin toward the open sea. With this model, the incoming water is of low density and near-normal saline concentrations. With excess evaporation, the arid sea increases in density and concentration of saline constituents. Because of the higher density, the water sinks. Thus, the arid basin fills up with heavy, saline, surface-derived water. The heavier water pushes over the sill and back out to an open marine environment with a strong exchange pattern. However, with waning currents, the heavy, highly concentrated waters precipitate anhydrite (Fig. 11).

With this exchange pattern, supratidal anhydrites precipitate from pore fluids, and subaqueous anhydrites precipitate from the basinal waters. Kendall (1979) illustrated that the supratidal sabkha deposits prograded over the basinal anhydrites. Melvin (1984) suggested this phenomenon in Winterfield and Wise fields based on differing characteristics within the same bed of anhydrite. Schreiber *et al.* (1982) also proposed the progradation of sabkha-derived anhydrites over subaqueous anhydrites as a most common occurrence in marine-marginal settings.

CORE AND THIN-SECTION PHOTOGRAPHS

Cores

Specific intervals have been used to illustrate differing characteristics found within the

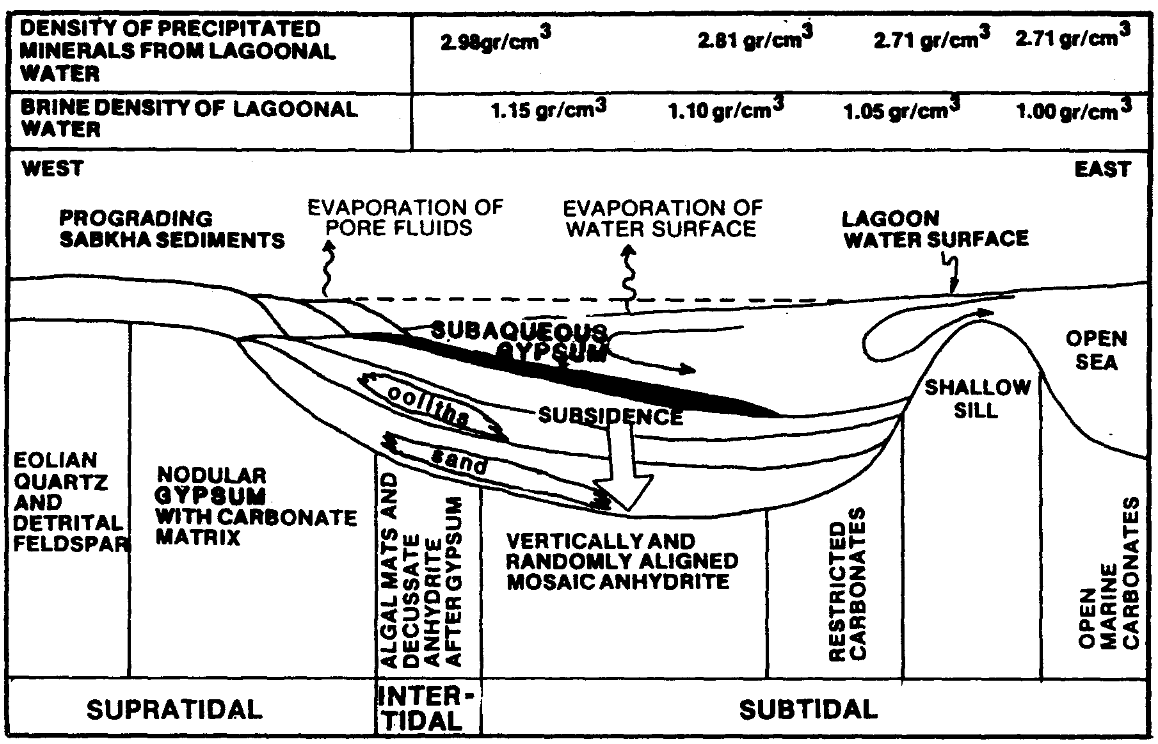

Figure 11.--The depositional environment of the Richfield had several processes occurring contemporaneously. Prograding sabkha cycles were composed of sediments similar to the Persian Gulf sequences. Lagoonal cycles were a reflection of brine salinity, strength of water currents, evaporation of lagoonal water, amount of recharge from the open sea and degree of desiccation of the lagoon during severe periods of evaporative draw down. The resultant facies across the Richfield basin reflect sabkha environments prograding over subaqueous environments.

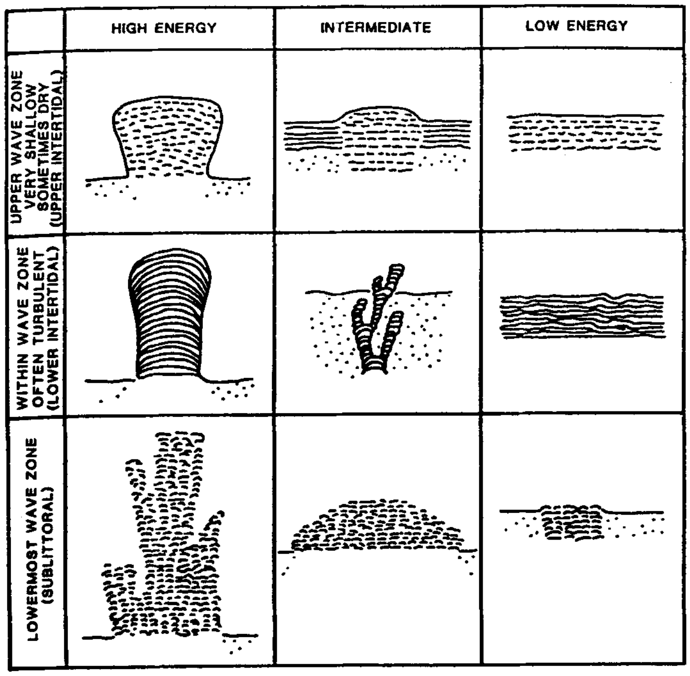

Figure 12.--Environmental distribution of stromatolite morphotypes (J.L. Melvin and B.C. Schreiber, manuscript; modified from Hoffmann, 1974).

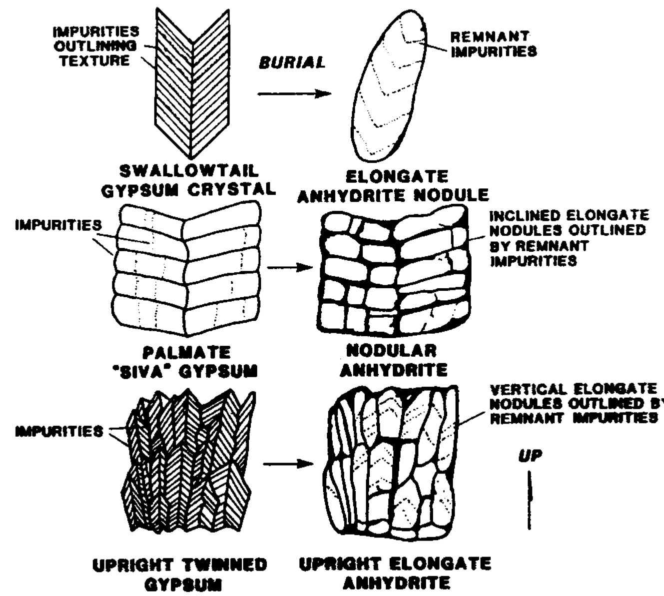

Figure 13.--Morphological characteristics of individual gypsum and anhydrite crystals and beds of crystals before and after burial (courtesy of John K. Warren).

Richfield Member. Classifications for algal growth and environmental regime are from Hoffmann (1974) as depicted by figure 12. Subaqueous gypsum morphology characteristics are depicted in figure 13.

Figure 14 illustrates an interpreted prograding and oscillating shoreline of a chenier plain being overlaid by sabkha sediments. Beginning in the lower right corner at 4,470 ft is relict palmate gypsum indicative of very shallow subaqueous deposition. Scattered anhydrite nodules in algal laminae represent the intertidal zone. Overlying this interval at 4,739 ft are coalesced anhydrite nodules with faint laminar bedding characteristics reflective of a sabkha flat. In the middle core at the top of the anhydrite bed is an erosional surface. This marks the end of one sabkha-sequence cycle. In the interval 4,738 ft are flat-lying algal-bound sediments which are a result of variation in sedimentologic factors that operate in the intertidal zones. At 4,737 1/2 ft are slump features resulting from rapid deposition and de-watering. The overlying laminated facies is interpreted as upper intertidal stromatolites. The sequence shown indicates regression.

Figure 15 illustrates anhydrite patterns. The former relict palmate gypsum (now anhydrite) (near base of third core on right) reflects tidal pools on the sabkha flats. During periods of storm wash-over, ponds accumulate in the low-lying depressions of the sabkha flat. Within this very quiet water, palmate gypsum grew up from the sabkha floor. This is well illustrated at 4,707 ft (first core on left). The relict palmate gypsum has maintained its original fringed edge. It grew up from a floor of evenly laminated stromatolites indicative of the upper intertidal-sabkha margins. Some deformation occurred which can be attributed to de-watering of the sediments.

Figure 16 illustrates in a very short vertical section the interpreted subtidal to intertidal zones. Wavy and broken algal laminae at 4,698 ft (third core on right) are indicative of the lower intertidal to subtidal zone in a low-energy environment. They are overlain by a massive anhydrite nodule which has enveloped algal laminae. Continuing up in sequence is relict former palmate gypsum, now anhydrite.

Figure 17 illustrates morphologies in an interpreted low-energy environment ranging from subtidal to the upper intertidal-sabkha flats. Note that some anhydrite nodules have de-watered and flattened within the algal laminae. Concretionary displacive anhydrite nodules have grown syngenetically in the algal laminae.

Figure 18 illustrates both interpreted sabkha-flat deposition and subaqueous deposition of anhydrite after gypsum. Relict palmate gypsum is recognized in the core on the left.

Figure 19 illustrates relict palmate gypsum which grew upward from the floor. Relatively little deformation of the relict gypsum has taken place. Fluid conduits are highlighted by diagenetic anhydrite laths at 4,760 ft.

Figure 20 documents algal colonization with some anhydrite deposition after gypsum.

Photomicrographs

Figure 21 shows a dolostone with oomoldic porosity, part of which has been plugged with halite. Note intercrystal porosity between dolomite crystals. Figure 22 shows partial dissolution of ooids, and figure 23 illustrates fenestral pores in stromatolites.

In figure 24 porosity resulted through the dissolution of ooids but, as in figure 21, in places oomoldic porosity has been partially filled with salt, yet some porosity may be retained (blue) (Fig. 25).

FACIES DISTRIBUTION AS RECOGNIZED IN LOGS

Significant work has been done by geologists and log analysts to determine the relationships of log response to depositional environments. Pickett (1977) employed cross plots of particular log suites, as follows:

Δt (interval transit time)	vs. ϕn (neutron porosity)
pB (bulk density)	vs. ϕn (neutron porosity)
pB (bulk density)	vs. Δt (interval transit time)
Rt (deep Laterolog)	vs. ϕn (neutron porosity)

Pickett's method is quick and may be used once a standard cluster of environments has been identified. For this study, only wells which could be cross-matched to cores and cuttings were used. Once the visual depositional environment was identified, petrographic analysis of cores and cuttings established rock type. X-ray diffraction provided an additional source of information for determination of mineralogy.

The methodology of constructing a standardized Pickett plot for a particular rock group is to cross-plot log responses on the graph for every 1-2 ft interval. Petrographic analysis on particular depths is then added to the cross-plot chart color keyed for a particular environment. Similar colors are circled establishing a cluster group of log responses for that particular environment. Once the clusters are established, log responses from wells without cores or cuttings can be cross-plotted on the chart and their carbonate rock type and depositional environment determined.

An advantage of the Pickett Plot is that proximity facies can be inferred if a well is to be drilled offsetting another well. If the majority of the data points cluster in the intertidal and supratidal areas, then it would be safe to conclude that an off-setting well could be placed nearer to the paleoshoreline.

Facies maps can be constructed using the Pickett cross-plot method. Percentages of different rock cluster types (environments) are determined, or ratios can be calculated between two clusters within a predetermined interval. In cross-plot facies mapping, if deep resistivity logs are used from both hydrocarbon-bearing and water-saturated formations, Ro (resistivity of a formation 100% water saturated) can be used in the cross-plot rather than the deep resistivity value. The formula for calculating Ro is:

$$Ro = \frac{1.0}{\phi^2} Rw$$

where: ϕ = porosity
Rw - formation water resistivity at formation temperature.

Figure 14.--Slabbed cores showing interpreted prograding shelf with chenier plain and sabkha sediments. Explanation in text (Photo courtesy Bill Harrison, Western Michigan University).

Figure 15.--Slabbed cores depicting various anhydrite morphologies, including former gypsum, now anhydrite (courtesy Bill Harrison, Western Michigan University).

Figure 16.--Slabbed cores illustrating anhydrite patterns, including anhydrite pseudomorphs after gypsum (courtesy Bill Harrison, Western Michigan University).

Figure 17.--Slabbed cores showing various algal morphologies and anhydrite nodules (courtesy Bill Harrison, Western Michigan University).

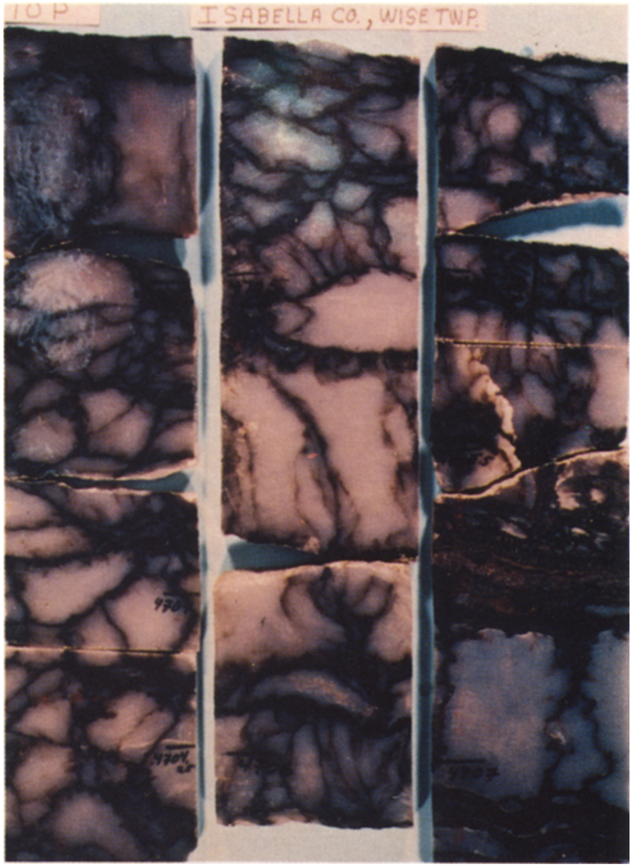

Figure 14

Figure 15

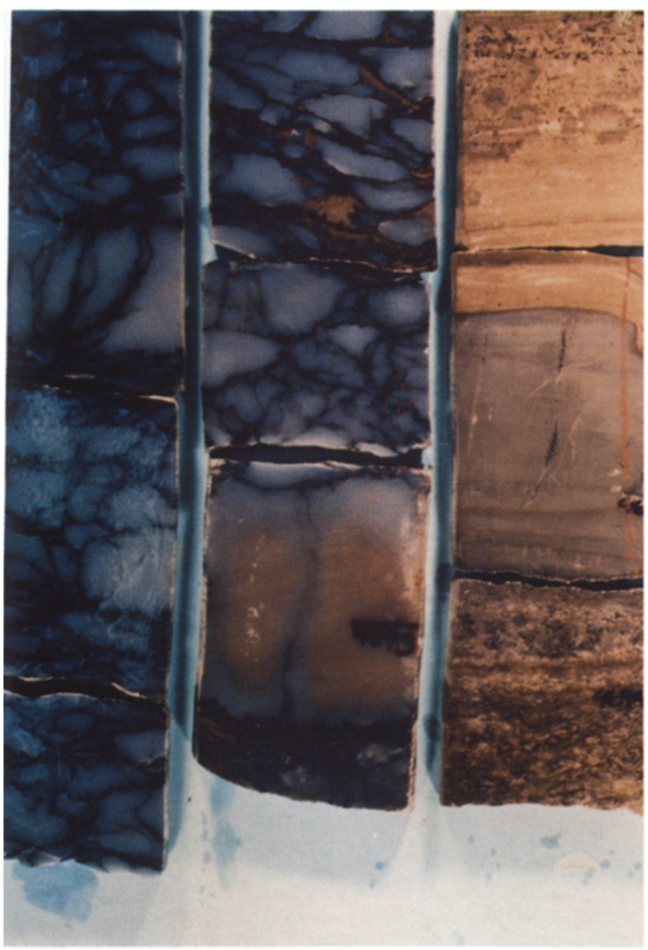

Figure 16

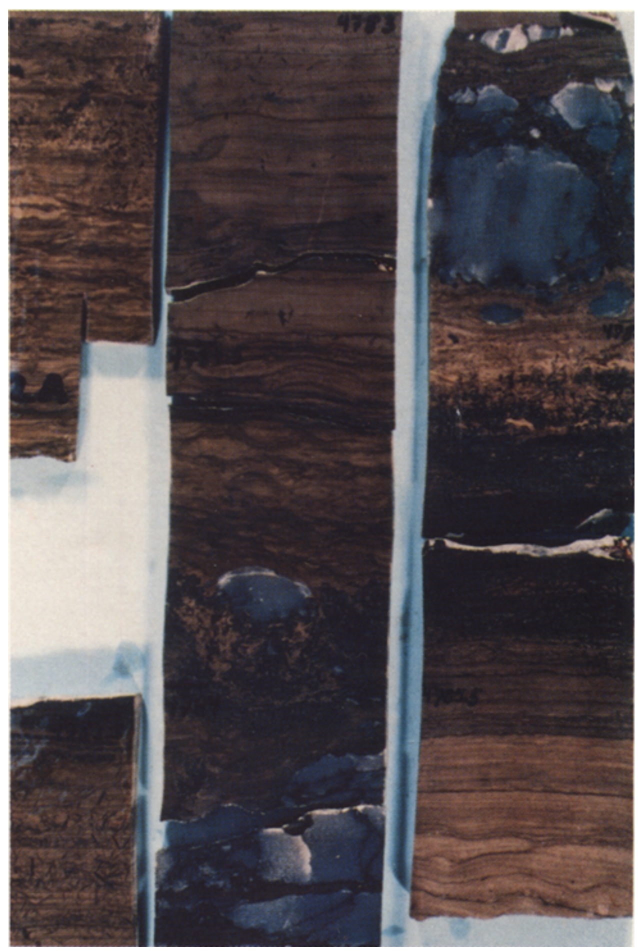

Figure 17

Asquith (1979) stated that changes in reservoir fluids (i.e., salt water to hydrocarbons) do not make differences sufficient to negate environmental analysis by cross-plotting. However, the exception is when gas is present because of the effect on the density-neutron curves.

The greatest advantage of the Pickett plot is that it maximizes the use of information. Cores or cuttings are required from a few control wells rather than from all wells. In constructing the standardized Richfield cross-plots, the author has chosen 3 wells for petrographic and core control and 2 other wells for core control to verify the results.

Figures 26 and 27 are the results of utilizing the Pickett method. It is fairly reliable in evaporite and carbonate sequences, but fails in the presence of sandstone.

RICHFIELD DEPOSITIONAL SYSTEMS

The Richfield sediments were deposited as a series of sabkha-chenier complexes during progradation from the west to the east. During early Richfield deposition, the lagoonal waters were near normal marine concentrations. This is suggested by uncommon anhydrite deposition, gregarious burrowing organisms creating bioturbated facies, tan-colored limestone indicating oxygenation and abundant peloids. As a result of excess evaporation and no recharge of the water, anhydrites developed on the platform in a supratidal setting. Evaporation of pore fluids caused the formation of nodular anhydrite among the algal mats in the supratidal zone. With further desiccation of the basin and evaporative drawdown, subaqueous anhydrites, characterized by mosaic and relict palmate gypsum, were deposited. The sabkha prograded across the platform and fingered into the subaqueously deposited anhydrites. Also, subaqueous anhydrite formed in tidal ponds on the sabkha flats after flooding and in the lagoons characterized by relict palmate gypsum. This motion created a singular anhydrite bed composed of nodular (supratidal) and mosaic (subtidal) anhydrites. This characteristic is what is referred to as a sabkha-chenier.

The supratidal sabkha variety of anhydrite is characterized as nodules which are approximately equidimensional and separated from each other by a carbonate matrix. The nodules generally range between a few millimeters to three centimeters in size.

The subaqueous anhydrites in the Richfield formed during periodic flooding of the sabkha flats by a very shallow sheet of water. So, even though the term subaqueous is used, it still refers to temporary flooding over the sabkha environment. This causes ponds and tidal pools to precipitate subaqueous anhydrites. A second process occurs when the sediments down to the groundwater level are bathed in lagoonal waters through hydrodynamic action. This causes displacement growth of mosaic anhydrite to occur beneath the sabkha-intertidal flats. The mosaic anhydrite is characterized by coalesced nodules with squeezed carbonate matrices. The mosaic nodules, because of displacive growth and squeezed character, are both randomly aligned and vertically aligned. The crystals of anhydrite forming the nodules are oriented laths easily identified in thin sections. A third process occurs when density-stratified water causes gypsum to precipitate at depth.

Each regressive cycle of the Richfield was followed by a quick transgressive pulse created by new marine waters flowing into the basin. This created some dissolution of evaporites and calcite because of differences of ionic concentrations between the sediments and lagoonal waters. As evaporation of pore fluids in the sabkha sediments and evaporative drawdown of lagoonal waters occurred, another regressive cycle commenced. Other evidence for regression and emergence is documented in the formation of dedolomite, dissolutional features and disconformities. Figure 28 is a schematic fence diagram of Richfield deposition across the Michigan Basin. On the western side of the basin are massive anhydrite beds where the Richfield is depicted as a topographically high (sabkha) platform. As the platform ramps into the basin, intertidal and subtidal facies develop. Figure 29 shows productive and non-productive Richfield tests.

The characteristic basin shape was in existence during deposition of the Black Lime and Amherstburg where the facies are equivalents. The Black Lime is characterized as the reefal facies in the subtidal zone. It trends north to south from northern Midland County, Clare, Gladwin, Missaukee, Roscommon and eastern Ogemaw counties following the Bouguer Anomaly trend. The Black Lime facies is gradational into the dense limestone of the Amherstburg.

Stagnation and desiccation of the waters caused the death of the reefal organisms in the Black Lime evidenced by a dark brown micritic mud deposited over the reef. Periodic storms

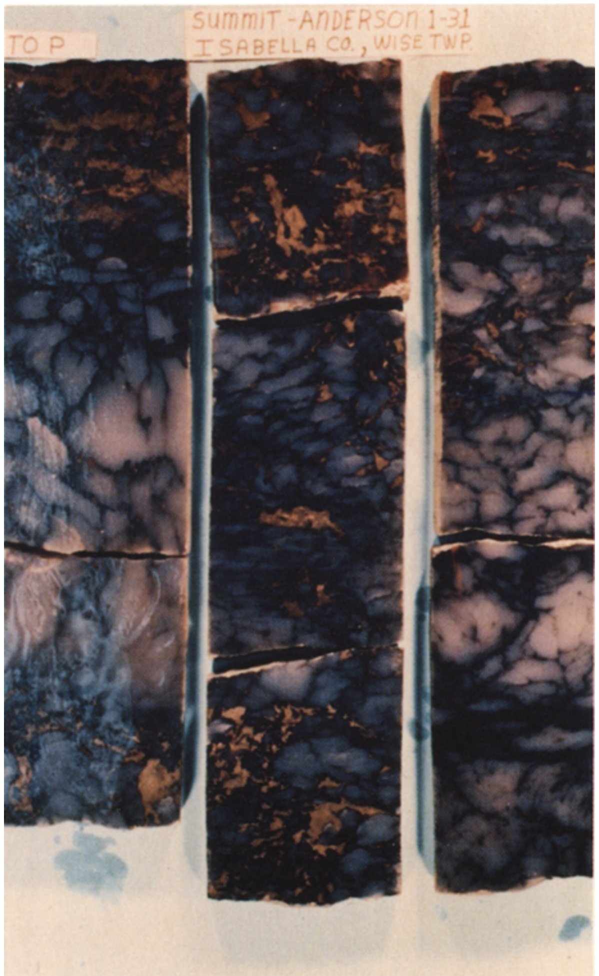

Fig. 18.--Slabbed cores showing anhydrite patterns. Core on left illustrates former palmate gypsum, now anhydrite. Note compacted nodular anhydrite in the other two cores.

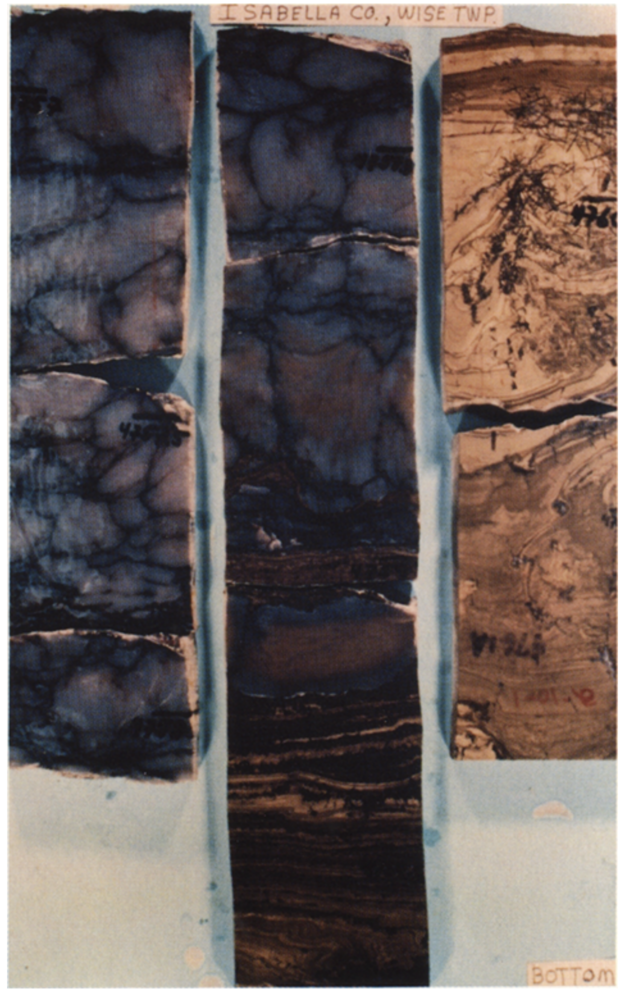

Fig. 19.--slabbed cores illustrating palmate gypsum and stromatolites.

Fig. 20.--Slabbed cores illustrating stromatolites and anhydrite.

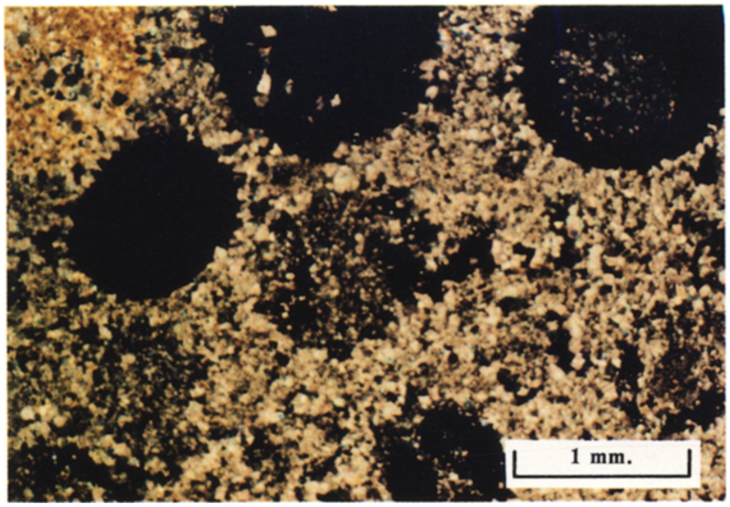

Figure 21

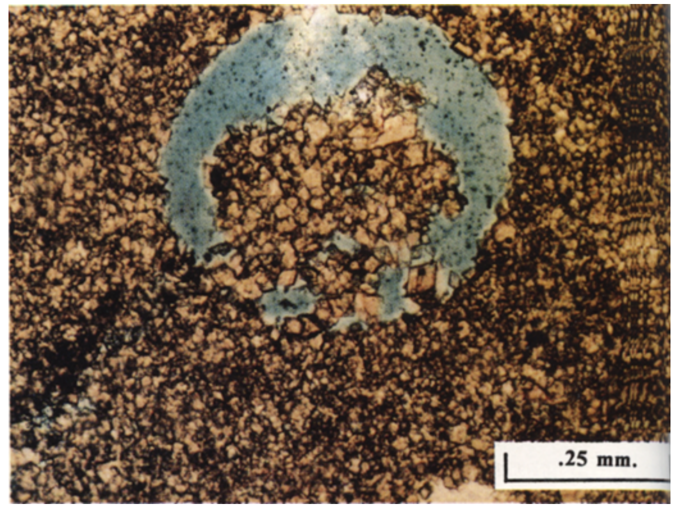

Figure 22

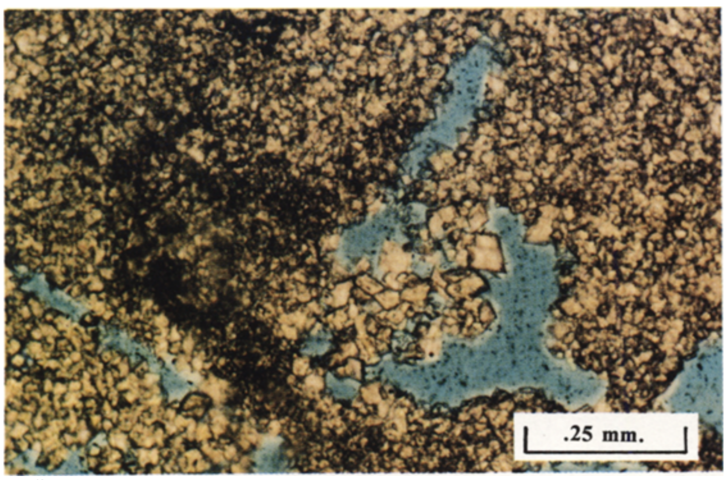

Figure 23

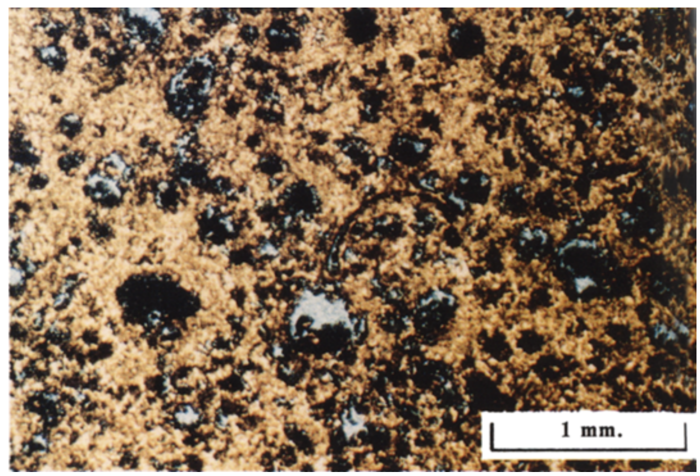

Figure 24

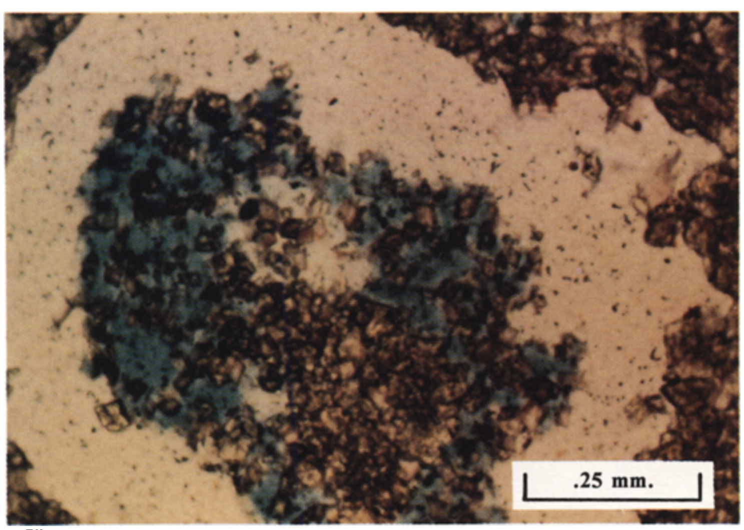

Figure 25

Figure 21.--Thin section of dolostone in which ooids have been leached out; the newly created oomolds have been partially plugged with halite.

Figure 22.--Thin section of dolostone in which ooid has been partially dissolved.

Figure 23.--Thin section showing fenestral pores in dolostone which resulted from dissolution of anhydrite.

Figure 24.--This thin section shows moldic porosity. This form of porosity (in blue) is created through dissolution.

Figure 25.--Thin section of dolomite in which oomoldic porosity has been partially filled with salt, yet some porosity (blue) has been retained.

P_b (BULK DENSITY) VERSUS ϕ_n (NEUTRON POROSITY)

CROSS PLOT OF DATA

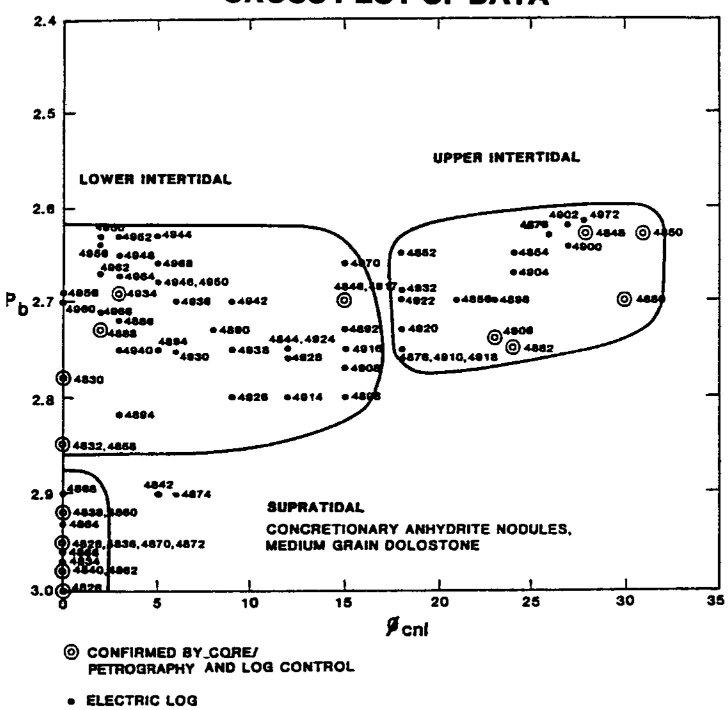

Figure 26.--Log cross plot for Richfield rocks.

Rt (DEEP LATEROLOG) VERSUS ϕ_n (NEUTRON POROSITY)

CROSS PLOT OF DATA

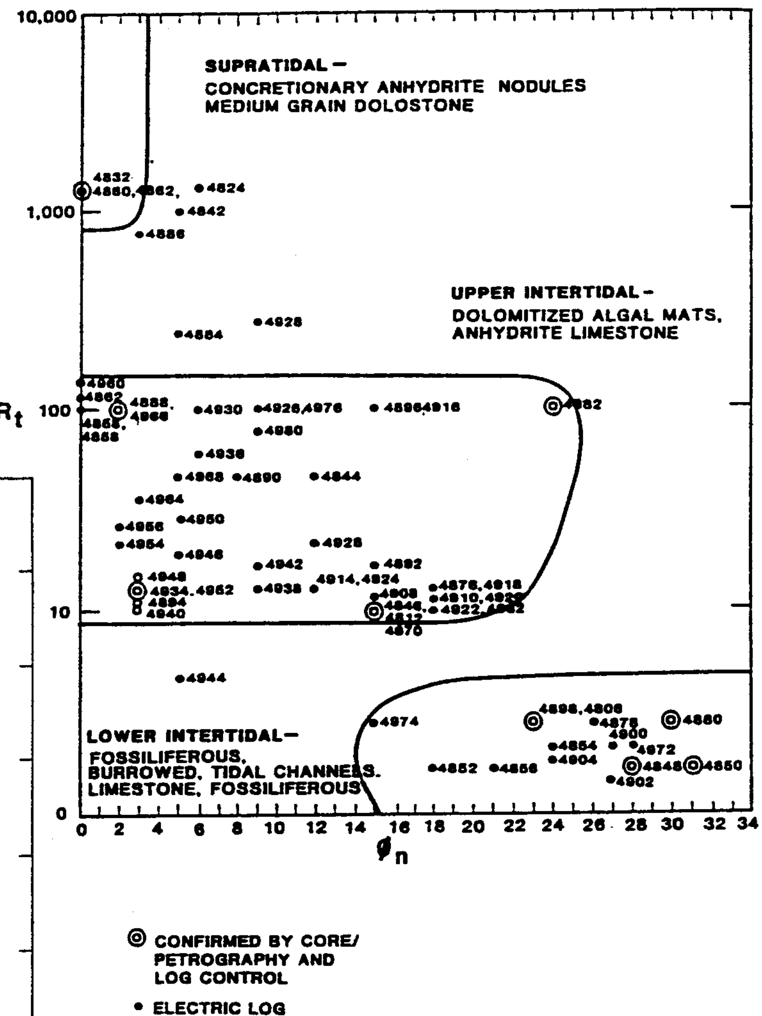

Figure 27.--Log cross plot for Richfield rocks.

ripped up the micritic mud exposing the underlying reef to reworking within the micrite. This is suggested by core data in Grout field. Subsequently, near-normal waters flowed into the basin permitting the growth of abundant life forms. This has been suggested by well-oxygenated sediments, burrowing, relict fossils, and peloids.

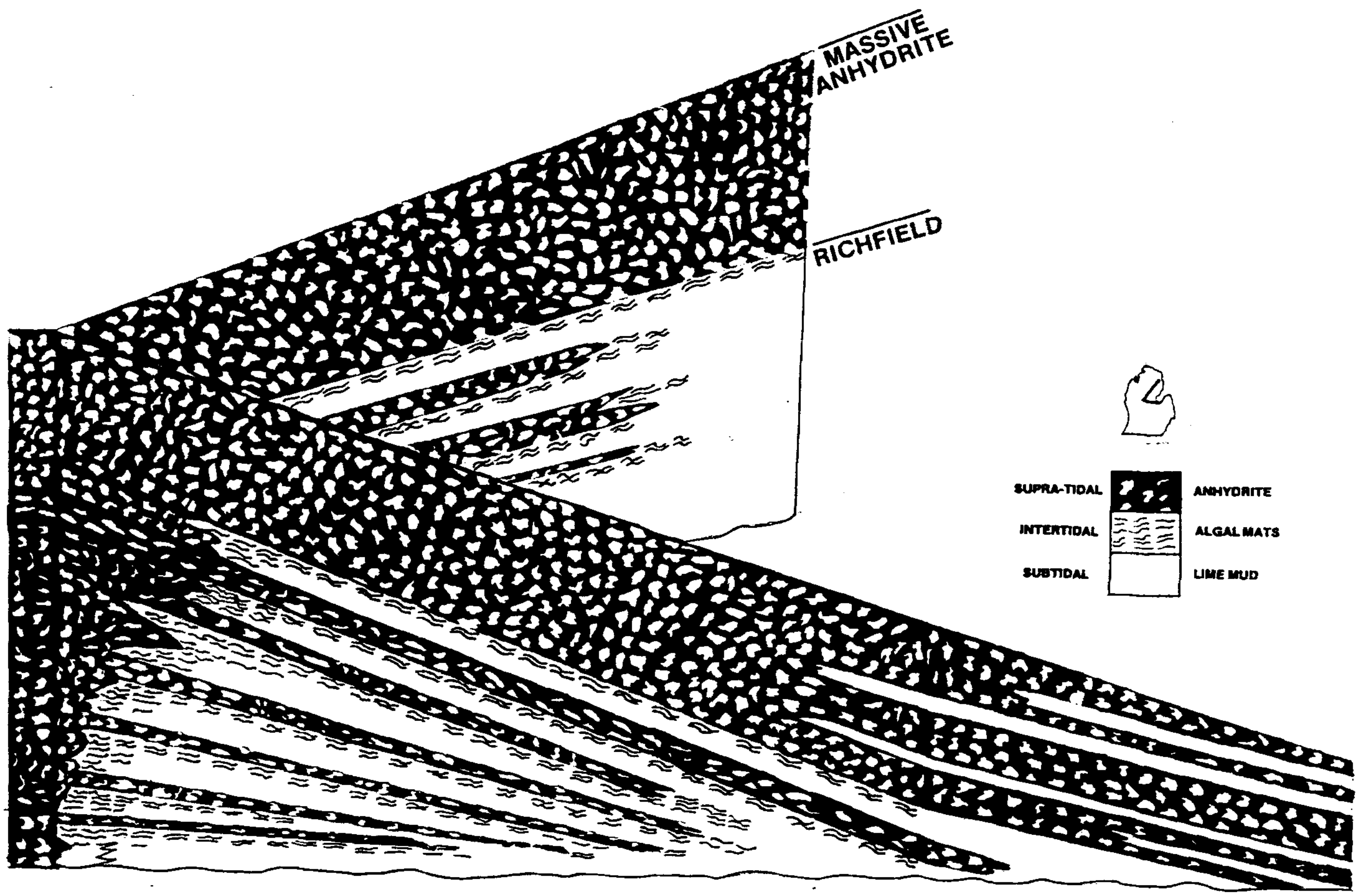

Figure 28.--Schematic fence diagram of the Richfield in the Michigan basin.

A sandstone facies (often referred to as the Filer sandstone) was deposited throughout the basin in the general pattern of the Black Lime depositional basin. The sandstone in Winterfield has been documented as a tidal bar based on slight cross-bedding and burrowing characteristics. This sandstone body more than likely served as a barrier which promoted evaporation in the back tidal areas thus promoting palmate gypsum precipitation.

Later, oolitic zones were deposited in the same general localities of the previously deposited sandstones. No significant thickness of oolites can be documented. Most subsurface information suggests thin zones of reworked ooids a few inches to 5 feet thick. No cross-bedded oolite bar has been discovered as the mother environment.

Zoned dolomites, bi-modal sizes of dolomite rhombs and dedolomites suggest subaerial exposure to fresh water and erosive transport. Norwich field contains a diversity of dolomite varieties. It is suggested that the Amherstburg dense limestone located on the basin edges was dolomitized during periods of evaporitic draw-down of the Richfield. With subsequent transgression of the seas, dolomite rhombs were redistributed due to the Amherstburg exposure and were distributed within the Richfield facies. This would explain the bi-modal size of dolomite in the Richfield.

Periods of emergence are also documented in Norwich Field with the distribution of equidimensional rhombs. Within the sediments are both dolomites and dedolomites. Purser (1975) documented that the dedolomitization process occurs when unstable dolomite rich in iron exchanges ions of Fe and Mn for Ca^{++}. This causes replacement of dolomite by calcite freeing the Fe and Mn to precipitate onto disconformities - another indication of emergence.

Evidence for exposure:

1) dedolomitization,
2) formation of pisoids,

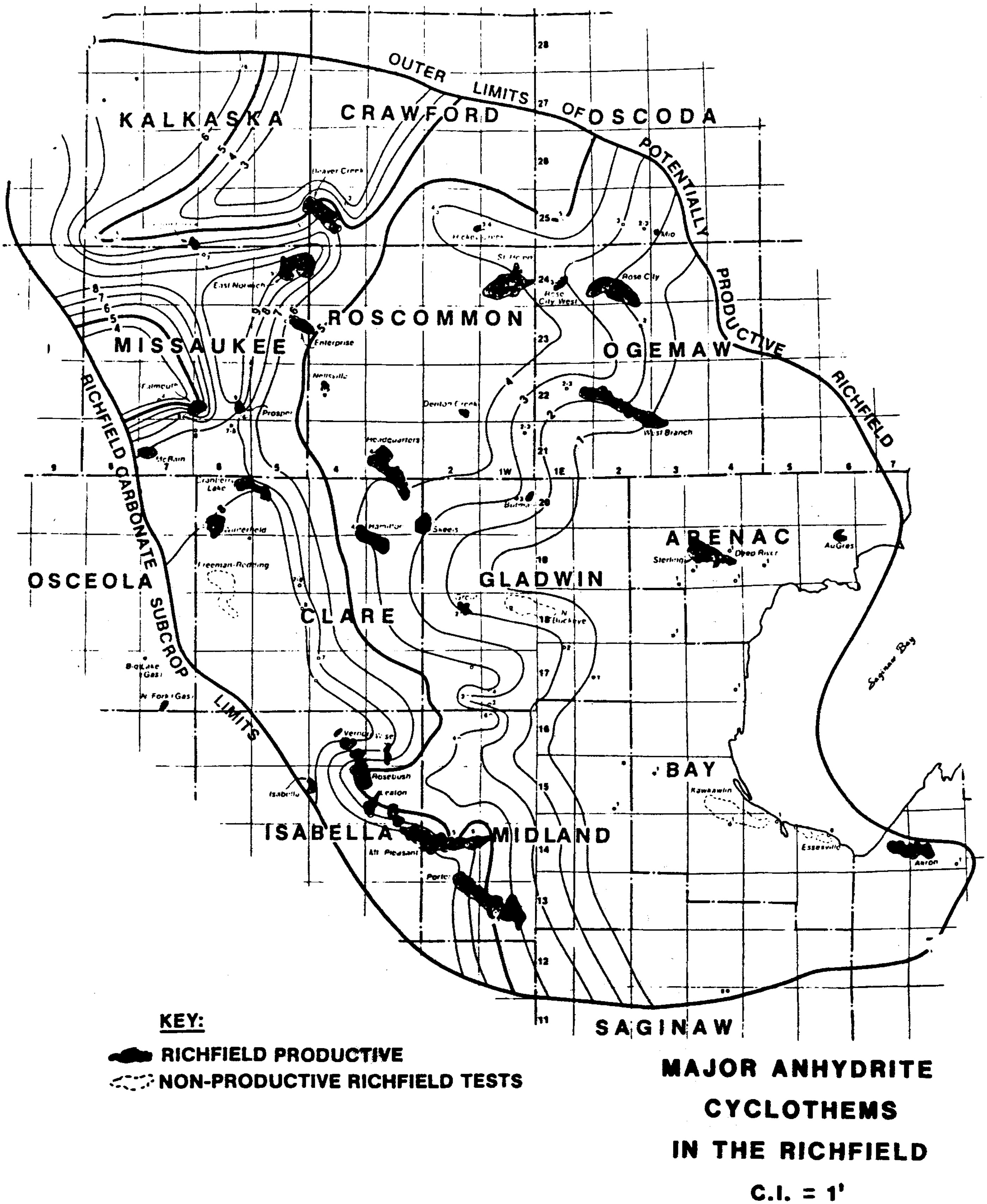

Figure 29.--Productive and non-productive Richfield tests and isopachs for major anhydrite cycles.

3) positive bouguer anomaly,
4) disconformity surfaces with Fe and Mn enrichment,
5) evaporite morphologies, and
6) stromatolite morphologies.

Each subsequent cycle of deposition was characterized by progressively more hypersaline water, the shift of the carbonate subcrop zone farther to the east, and laterally more expansive and thicker evaporites. On the east side of the anhydrite wall, running northward from Isabella and Osceola Counties, evaporites suggest multiple environments as water levels varied.

The anhydrite wall abutting against the Amherstburg limestone suggests deep-seated faulting or the re-adjustment of sediments to subsidence and lithostatic overburden with the rift zone. Studies on thermal maturation and geothermal maturation depict the basin in cross-section with a rise at the rift zone area which could regulate sediment deposition at depth (Nunn, 1981).

The Richfield is a wedge of sediments, thickest on the western side of the state in Missaukee, Wexford and Manistee Counties. The thickest depositional area which includes carbonates occurs in Missaukee County (Fig. 30). A localized thick accumulation with a thick sandstone-carbonate facies in the basal Richfield occurs in Midland and Gladwin Counties. This map also illustrates the eastward thinning of the wedge of sediments.

The Massive Anhydrite of the Iutzi Member of the Lucas Formation served as the cap rock over the Richfield. This bed is composed of nodular and mosaic anhydrite across the basin. On the eastern margins, the anhydrite bifurcates to carbonates with algal mats. The first development of thin carbonate beds occurs in Gladwin County with the total development of complete cyclothems east of Arenac, Bay and Saginaw Counties (Figs. 28 and 31). Where the Richfield is the thickest in the basin, the Massive Anhydrite is the thinnest. The Massive Anhydrite served to smooth out the wedging of the Richfield sediments, which caused basin-infilling. Because of this leveling effect, the Detroit River Sour zones composed of the Iutzi and Horner members became more widespread across the basin.

TRAPPING MECHANISMS

There are three basic kinds of traps - structural, stratigraphic and hydrodynamic - which can occur as singular mechanisms or in combination with each other. Only those which relate to the Richfield will be discussed here. In all three traps, a reservoir is bounded by a barrier. Each kind also is an isolated area of low potential, but they differ as to what causes the isolation. In a structural trap, isolation results from local structural deformation. In a stratigraphic trap, isolation results from a nonstructural lateral change that creates the barrier and the hydrodynamic trap results from the rate of water flow. Regional dip may be necessary for stratigraphic traps; whereas, the changes in regional dip causing terracing may be necessary for hydrodynamic traps. The essential point of all of the above is that all three trapping mechanisms may be filled to capacity, partially filled or totally void of hydrocarbons.

Structural, stratigraphic and hydrodynamic traps hinge on changing porosity and permeability values. These two processes interact with one another from the moment of sediment deposition through all subsequent tectonic changes. A porous carbonate as a stratigraphic trap can be changed to a structural trap with minor tilting or folding.

Porosity barriers are quite common in the Richfield through changing depositional environments on a regional scale, as well as on a local scale by the changing nature of cementation. Cementation destroys porosity, whereas solution creates porosity. The constructive-destructive process is on-going in the Richfield and petrographic studies are necessary to understand and identify the diagenetic steps to maximize reservoir discoveries and productivity. Dissolution of anhydrite by migrating groundwaters and subaerial exposure creates porosity. The most prevalent zone for anhydrite lath development is in the lower supratidal and intertidal zones. The dissolution of these laths increases porosity and increases volumes of migrating waters, which enhances further dolomitization of the sediments. Likewise, plugging by anhydrite is commonly noted. The anhydrite cement infills intercrystalline spaces, destroying the porosity created by an earlier episode of dissolution. The optimum porosity development is found where the anhydrite cement was precipitated and was subsequently leached by meteoric waters.

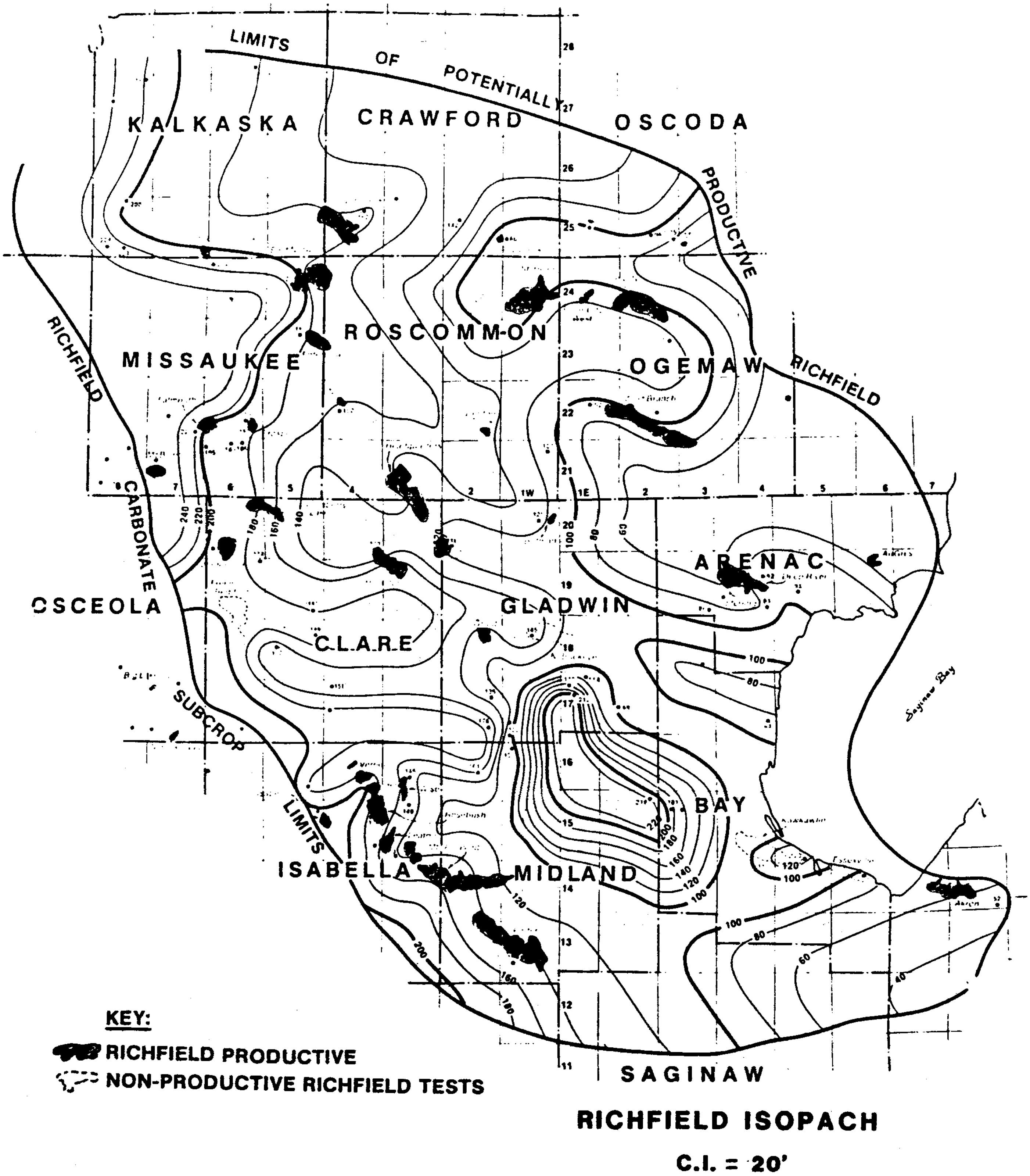

Figure 30.--Richfield isopach map of hydrocarbon potential areas.

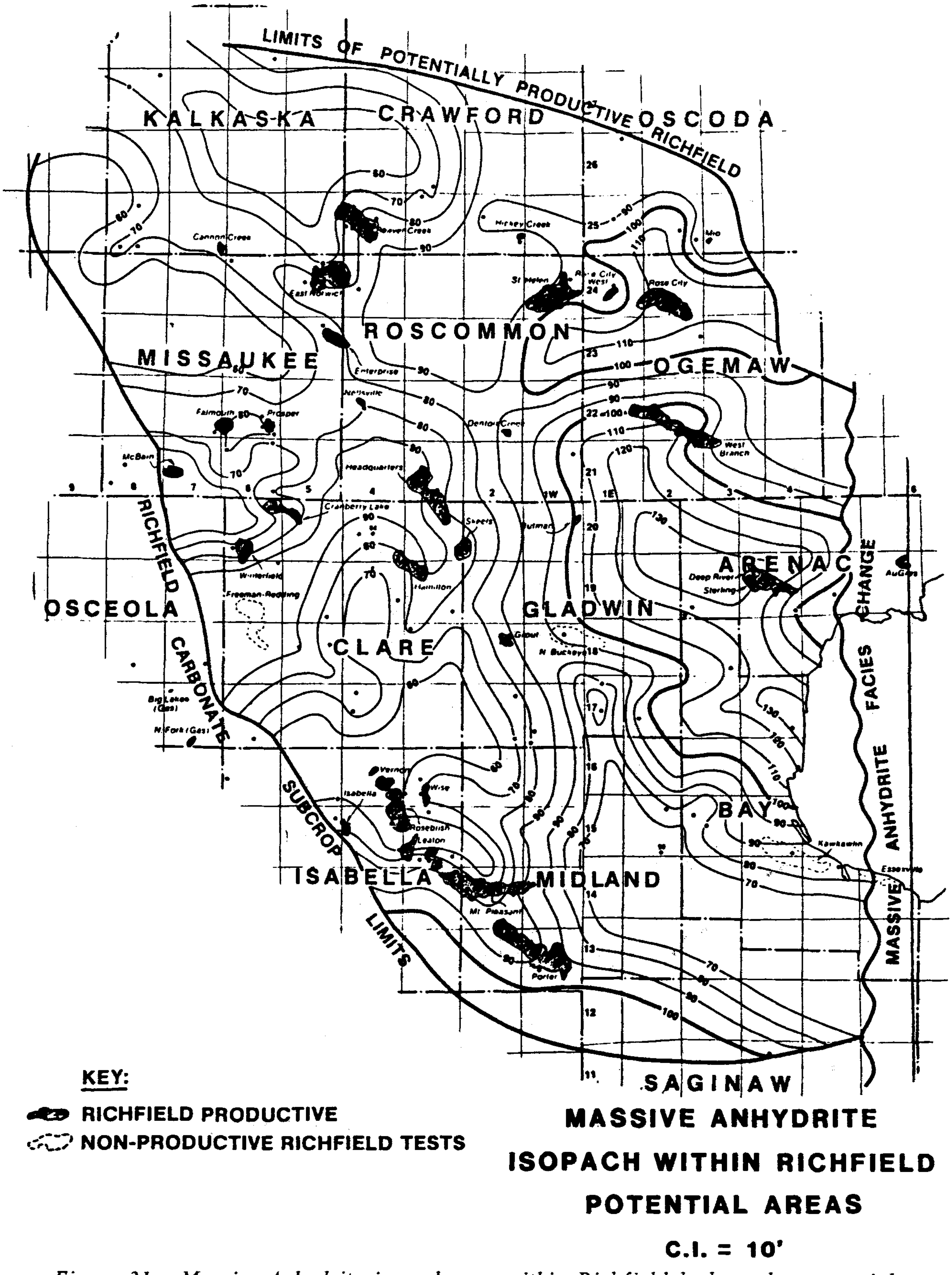

Figure 31.--Massive Anhydrite isopach map within Richfield hydrocarbon potential areas, only.

Porosity barriers in evaporitic-carbonate environments were created by the changing equilibria of ionic concentrations between migrating fluids and rock mineralogy. Where the waters were of lesser ionic concentrations than the rock, dissolution occurred; in areas of equilibrium, no changes occurred, and in areas where the waters had higher concentrations of ions than the rock, precipitation occurred (Fig. 32). The total process can occur over several feet or require several miles, or may never reach completion. This process is continually ongoing. It is also interesting to note that Sun's Richfield waterfloods are artificially promoting this process. Fresh water which is pumped into the Richfield at point A migrates to point B where both the fresh water, formation water and hydrocarbons are pumped back to the surface. The fresh water's mineralogy has changed in its migration from A to B and it has precipitated gypsum scale on tubing strings.

Porosity development and the creation of barriers can be changed at any time by slight tilting or tectonic changes which alter the water migration pattern. A zone which was anhydrite plugged may become a potential reservoir because the waters moving through the rock may leach the anhydrite.

Permeability barriers are much harder to locate than porosity barriers because electrical logs do not measure this characteristic. It is widely recognized that permeability in a homogeneous porous rock is strongly affected by grain size and pore-throat distribution. If grain size is very small, it is conceivable that the porosity can be extremely high and permeability very low. This is characteristic of the Richfield, wherein a minimum of 10% porosity is required to achieve at least .5 millidarcy permeability.

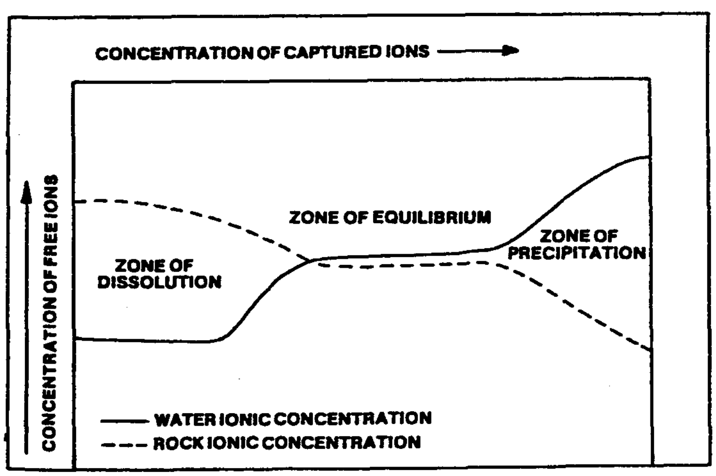

Figure 32.--Illustration of ionic concentrations of water and rock with resultant processes.

Other factors affect the migration of fluids through the Richfield rocks. One of these is viscosity of the fluids (covered in the section on source rock and hydrocarbon migration). In the Richfield where hydrocarbons of low API gravities cannot migrate through the very fine-grained rocks and thus become trapped.

Grain sizes in the Richfield change because of facies changes, degree of dolomitization, or degree of cementation; permeability barriers can occur anywhere within the rock. Oil migration can be blocked on the flanks of structures which occur in Winterfield, West Branch, and East Cranberry Lake. These traps can be referred to as either permeability barriers or as stratigraphic traps. However, permeability is the hardest characteristic to properly define without sophisticated pressure-analysis data and capillary-pressure data. Because of this, it is recommended not to use the term permeability barrier without using any qualifying definitions. It is more proper to just say stratigraphic trap.

Permeability barriers of dead oil plugging the pore throats were discovered by Longman (1981) to be prevalent in the Williston Basin, Montana, which has rock characteristics very similar to the Richfield. Longman's findings were that in petrographic studies where low permeabilities were attributed to the small size of intercrystalline pores (dolomite rhombs measured 20-30 microns), dead oil was clearly visible in 70% of the pores. Water-saturation calculations from electrical logs were between 11-20%. Longman suggested that the unproducible low-water saturation was a result of the altering of the oil by bacterial degradation, selective leakage of the light hydrocarbons, or by *fresh* water flushing of the reservoir. Thus, the low gravity of "dead" oil severely reduced reservoir quality. This same phenomon is suggested as prevalent in the Richfield, where "dead oil" is often found in rock matrices which have been secondarily cemented by anhydrite.

Stratigraphic Traps

Stratigraphic traps are subtle and difficult to find. Most have been discovered by accident. They are controlled by both primary and secondary porosity and permeability development. Several trapping mechanisms occur in the Richfield based on the trap's location within the basin during sedimentation. They are:

1. those in which a porous dolomite grades updip and subcrops against anhydrite;
2. those in which a porous dolomite grades updip into a nonporous limestone;
3. those in which a porous dolomite is confined by a disconformity;
4. those in which a porous facies grades updip into a different facies;
5. those in which a porous dolomite grades into a tight, anhydrite-plugged dolomitic facies;
6. those in which a porous dolomite grades into an equally porous but less permeable dolomite.

The first type of trap occurs only on the western edge of Richfield carbonate deposition. This is a subcrop trap which is characterized by isolated gas production. The carbonate in this depositional setting is quite anhydritic. The high quantities of $SO_4^{=}$ found in evaporitic environments permitted large colonies of bacteria to generate H_2S which aided in the degradation of the source rock. This area was originally deposited as sabkha sediments which prograded and subsided with the adjustment on the mid-continent rift. As a result, this area is currently considered to lie on the flanks of the mid-continent rise forming an up-dip trapping mechanism (Fig. 33). Isolated gas wells in Osceola County are characteristic of this trap.

The second trapping mechanism is quite common in the Richfield throughout the basin. This type is characterized as a porous dolomite which grades into a nonporous limestone (Fig. 34). This occurs on a very small scale within a field, or on a larger scale across several fields. Hamilton Field is characterized by multiple stringer reservoirs in this manner.

A porous dolomite which is overlain by a disconformity is quite common in the Richfield, but is not often recognized. Evidence of a disconformity is quite evident by iron sulfide mineralization. The disconformity serves as an effective barrier and caprock to the reservoir (Fig. 35). Disconformities are quite the norm in sabkha depositional environments because of oscillating shoreline and frequent subaerial exposures. However, this type of trap cannot be discovered by any means except through an intensive coring program.

The most prevalent form of trap is one in

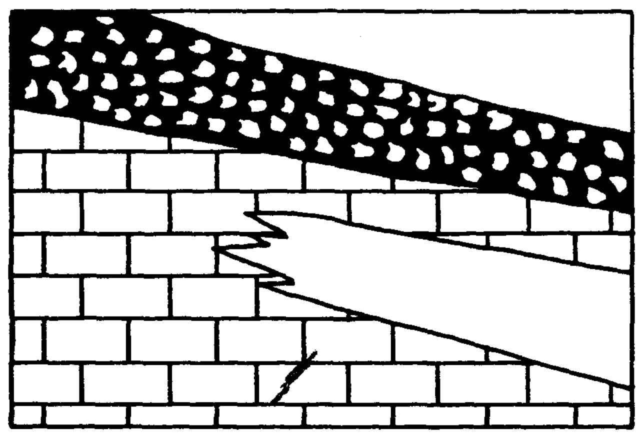

Figure 34.--A porous dolomite grading against a nonporous anhydrite.

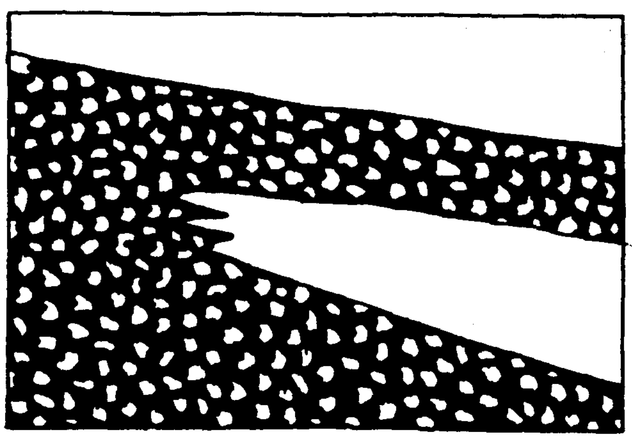

Figure 33.--Porous dolomite subcropping against anhydrite.

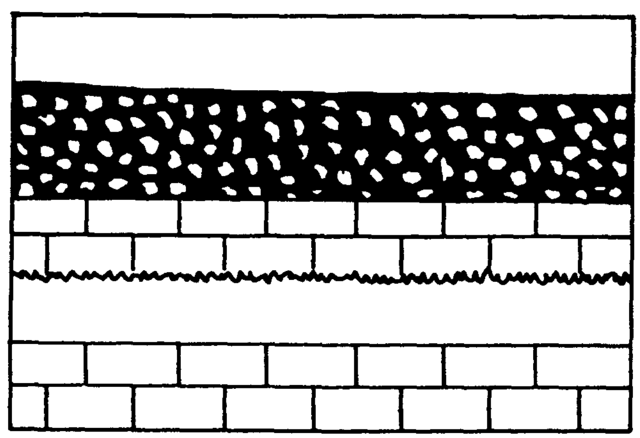

Figure 35.--A porous dolomite confined by a disconformity.

which a porous facies grades into a different facies (Fig. 36). This has the potential of easy recognition through careful scrutiny of well cuttings and cores. In Grout Field, it is characterized as an oolitic facies grading into a limestone facies, in West Branch as a dolomite grading into a salt bed, in Norwich as a dolomitic sandstone grading into dolomite.

Winterfield Field is a trap in which a porous dolomite is located downdip from an anhydrite-plugged dolomite in a structurally high position (Fig. 37). This caused initial production figures and higher total cumulative production figures to be located on the flanks of the structure. This could also be the case in North Buckeye, judging from petrographic studies of the only Richfield well.

The last form of trap is based on changing permeability in a homogeneously porous dolomite. Porosity values may be similar, but the permeability alters drastically because of fluid viscosity, grain size, cementation, etc. (Fig. 38). This is not an easily recognized trap.

Structural Trap

The Richfield was initially discovered by drilling on a structural high at the Dundee level. This established the precedence of how to drill for Richfield production by Michigan operators. Unfortunately, this method is producing more and more dry holes, because the major structures have already been drilled.

The Richfield depositional setting was one which produced initial stratigraphic traps. These stratigraphic traps were altered to structural traps

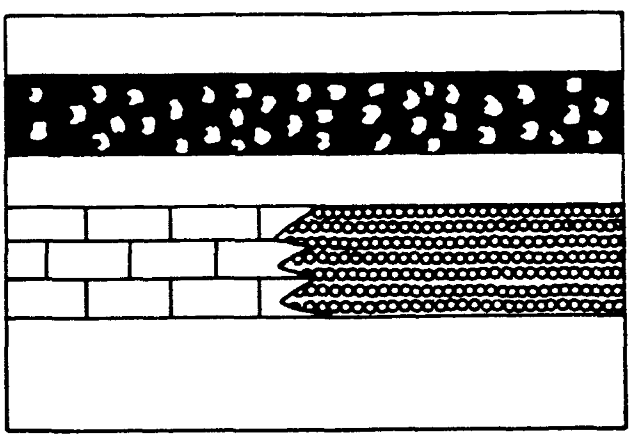

Figure 36.--A porous facies (oolite) which grades updip into a different facies.

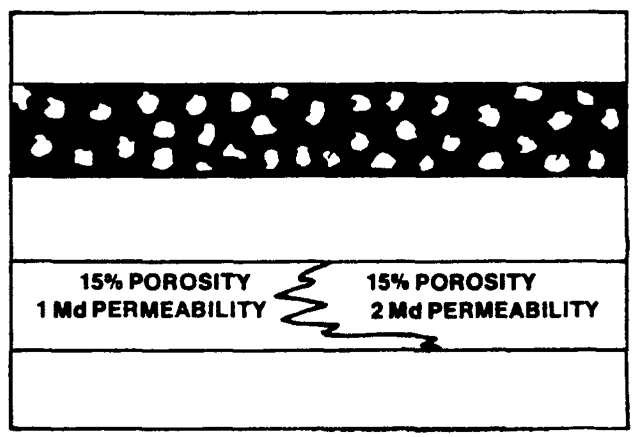

Figure 38.--An equally porous dolomite with change in permeability.

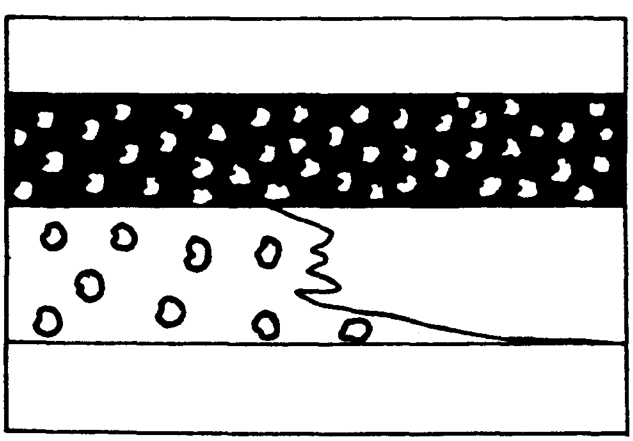

Figure 37.--A porous dolomite grades into a tight anhydrite plugged dolomite facies.

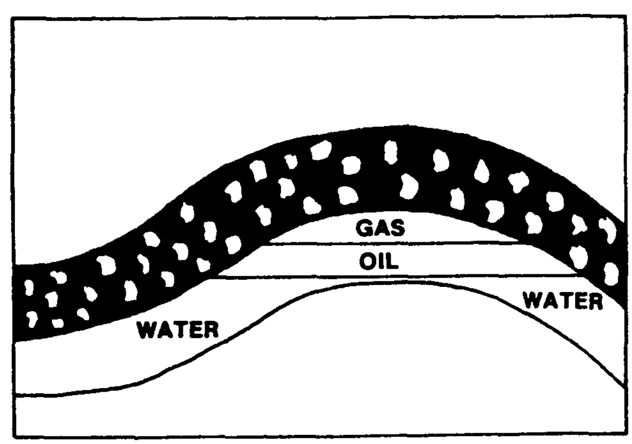

Figure 39.--Structural trapping by closure with normal segregation of fluids.

by tectonic forces within the basin. The closure formed the barrier necessary for entrapment of hydrocarbons (Fig. 39). This trapping mechanism is the most sought after thus making it the most drillable.

Hydrodynamic Traps

Dahlburg (1982) is the best source for both theory and application of this process complete with examples from large hydrocarbon basins. His examples will be used because many of his findings suggest that similar traps may occur in the Richfield.

Energy potential is crucial for understanding this principle. Laws of physics state that everything seeks lower potentials whether it is lower temperatures, lower pressures, or lower gradients. Water movement follows all of these principles in the subsurface.

The hydrodynamic environment is characterized by directional forces where imbalances exist so that there is fluid movement in response to the potential energy differences. If the energy potential of moving formation water is mapped, the orientations and the locations of oil, gas, and water interfaces can be predicted. This method aids in understanding flush-out traps, structurally offset oil and gas accumulations, and hydrocarbon accumulations in non-closed geological features as well as gas accumulations stratigraphically below water.

In a static environment, normal segregation of gas, oil and water would be stacked on one another. However, in an active hydrodynamic regime water movement tilts the oil accumulation to an off-structure position (Fig. 40). When water movement becomes intense, the tilt of the oil-water contact (as a result of flow strength and oil density) exceeds the dip of the reservoir and the oil is flushed out. The gas remains behind because of its greater buoyancy and remains in the trap to form a tilted gas-water reservoir along the flanks of the structure (Fig. 41).

With subsidence after deposition of the Richfield the most prolific fields are located on current-day structure in the deepest parts of the basin. Hydrocarbons should have migrated up the regional dip and accumulated on the eastern periphery of the basin (e.g., Arenac, Tuscola Counties), but this is not the case. The hydrocarbons have "stayed" in the deepest parts of the basin, with gas production centered in Osceola County and decreasing quantities of oil on a regional updip scale from this area.

Combination Traps Within Fields

The Richfield is composed of up to 12 major cyclothems, as demonstrated on electrical logs; these cyclothems are different from the core interpretations of cyclothems. As a result, each log interpreted cyclothem exhibits its own trapping mechanism. One must not label a field as a structural, stratigraphic or hydrodynamic trap, but label each cyclothem with the appropriate name (Fig. 42). Lumping all reservoirs into one mode assures lost opportunities for discovering hydrocarbons on the fringes. It must be remembered that each cyclothem is unique.

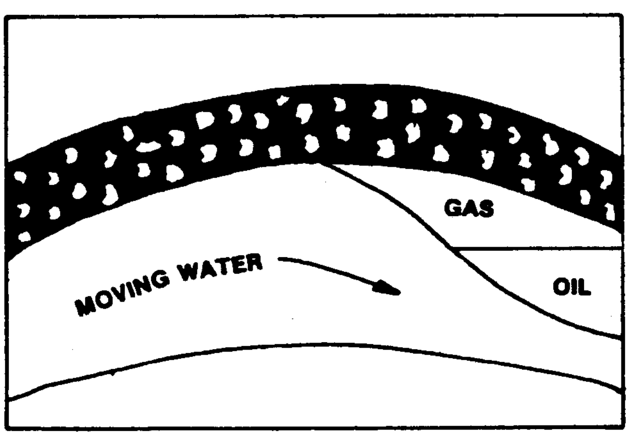

Figure 40.--Tilted hydrocarbon accumalation forms as a result of hydrodynamic water movement.

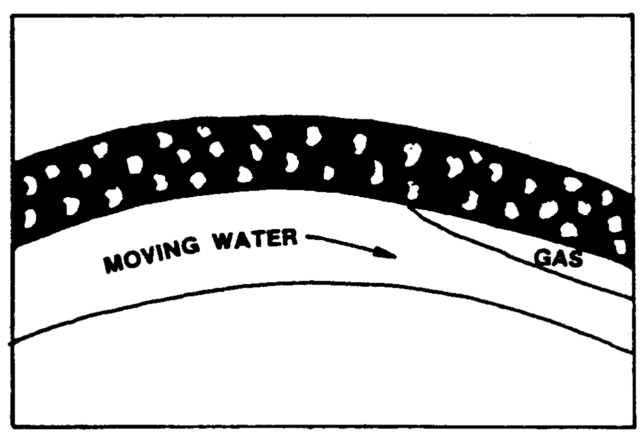

Figure 41.--Illustrating an active water drive which has migrated gas off-structure and oil has already been flushed out of the trap.

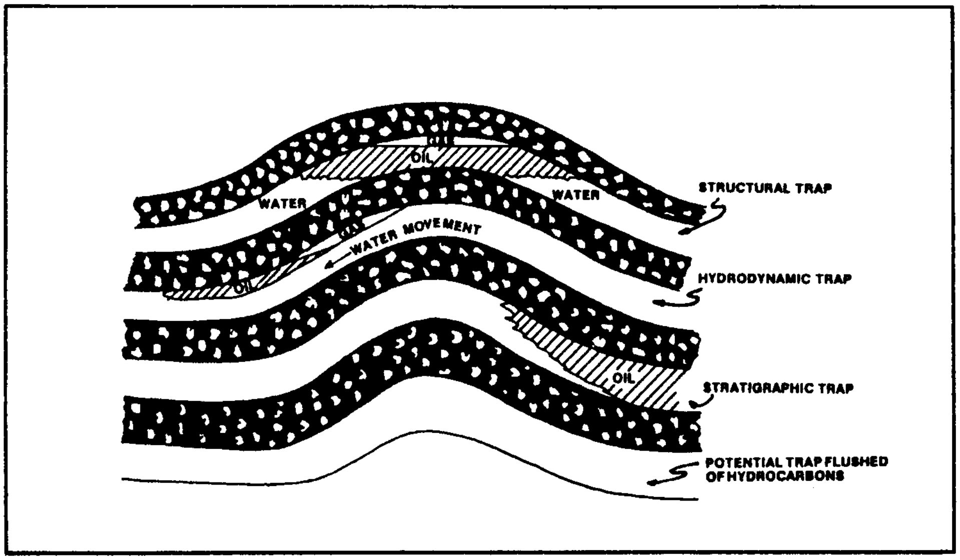

Figure 42.--Schematic diagram illustrating four general traps found in the Richfield.

CONCLUSIONS

The Richfield Member of the Lucas Formation has proven to be a very hydrocarbon-rich zone since its discovery in 1941. Early geologists played the structural highs (determined from the Dundee) for the initial new field discoveries. With continued in-field drilling to determine the reservoir limits, stratigraphic trapping mechanisms were discovered as suggested by higher porosity and permeability values, facies changes, and more productive wells on the flanks of the structural highs. Only recently have hydrodynamic responses been determined as viable trapping mechanisms. With increasing studies of the Richfield depositional and diagenetic history will come new fields to be discovered at a time when most Michigan geologists feel that all Richfield plays have been discovered.

ACKNOWLEDGMENTS

This paper is dedicated to the late Robert C. Morris, Departmental Chairman of the University of Arkansas.

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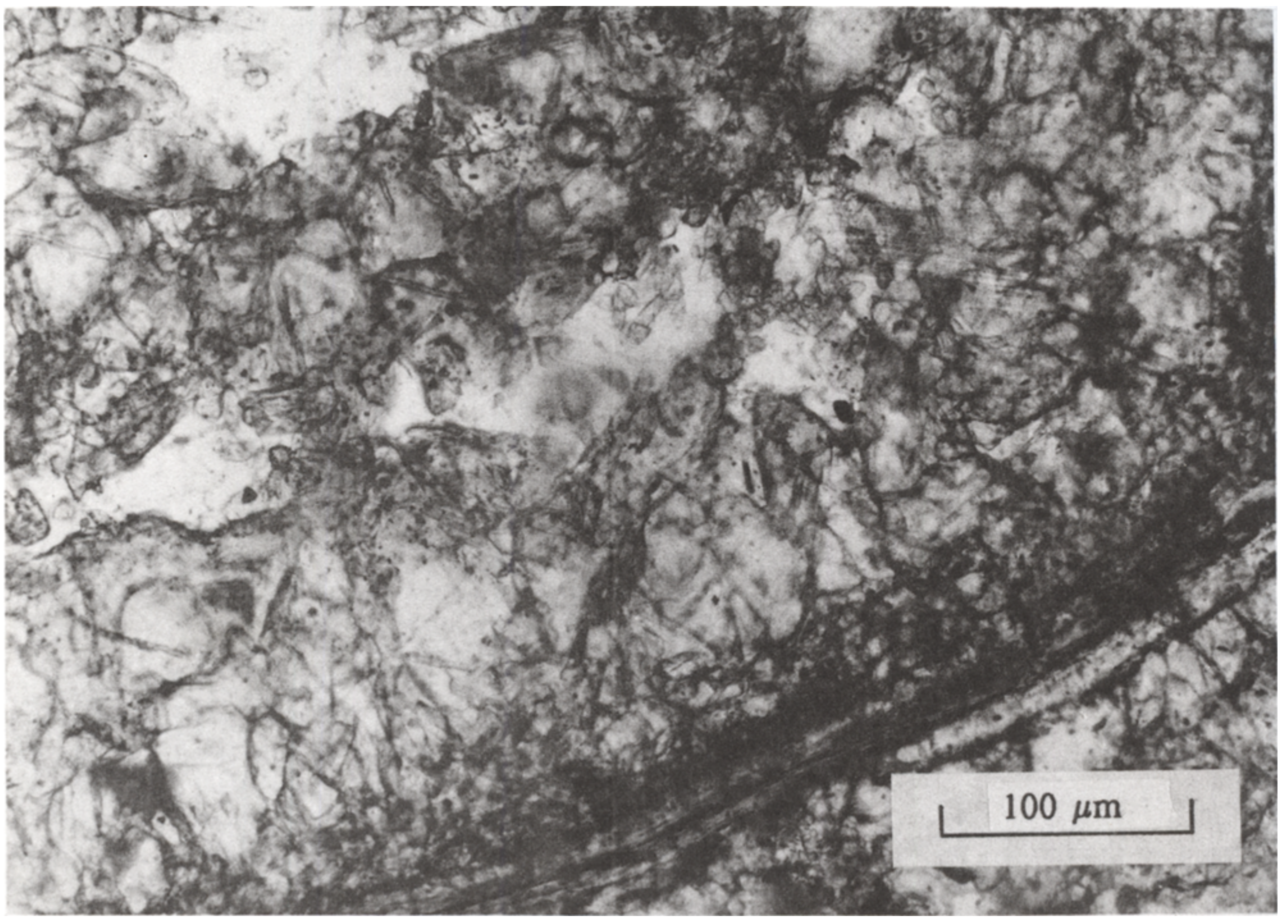
Manuscript received July , 1988
Manuscript accepted October 25, 1988



Thin section of drusy calcite in modern freshwater *Eucladium* tufa, Fleinsbrunnenbach near Urach, Baden-Württemberg, Germany (Georg Irion).