



Control and distribution of porosity in the Red River C laminated member at the Brush Lake Field
by James Roy Stimson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences

Montana State University

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Abstract:

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This cycle can be interpreted as a tidal flat deposit with the above members representing the supratidal, intertidal, and subtidal environments, respectively. The laminated member has been thoroughly dolomitized at Brush Lake and porosity values within the dolomites change rapidly. Evidence from Brush Lake reveals that the porosity distribution is primarily the result of diagenetic controls rather than structural or depositional controls. Textural evidence from the laminated member indicates that porosity has been reduced in some parts of the laminated member by 1) early precipitation of calcite cements, 2) overdolomitization, 3) early precipitation of gypsum, 4) late precipitation of replacive anhydrite, and 5) pressure solution along low amplitude stylolites.

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MONTANA STATE UNIVERSITY

Bozeman, Montana

May, 1985

APPROVAL

of a thesis submitted by

James Roy Stimson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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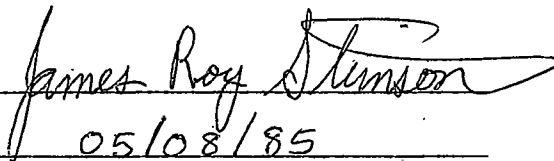
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This thesis is dedicated to the memory of Dr. Don Smith, whose signature of approval would have given me great satisfaction.

ACKNOWLEDGMENTS

I thank Dr. David Mogk, Dr. Stephan Custer, and Dr. Raymond Murray for encouragement, guidance, and constructive criticism. Appreciation is extended to Tom Colligan for conducting the cathodoluminescence examinations. I also gratefully acknowledge Chevron Oil Company (Denver) for making cores from the Brush Lake field available for examination, and the following individuals and companies for their financial support of the thesis project:

Robert L. Nance and Associates (Billings, MT.)

Langdon Williams (Billings, MT.)

Dennis Rehrig and Associates (Billings, MT.)

Al Bloomer and Associates (Billings, MT.)

Anadarko Production Company (Denver, CO.)

ARCO Exploration Company (Denver, CO.)

City Services Oil Company (Denver, CO.)

Gulf Oil and Exploration Company (Casper, WY.)

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1. Stratigraphic Cross Section of the Brush Lake Field.....In Pocket

ABSTRACT

The Red River "C" cycle at the Brush Lake field consists of three distinct informal members; 1) the anhydrite member, 2) the laminated member, and 3) the burrowed member, in descending order. This cycle can be interpreted as a tidal flat deposit with the above members representing the supratidal, intertidal, and subtidal environments, respectively. The laminated member has been thoroughly dolomitized at Brush Lake and porosity values within the dolomites change rapidly. Evidence from Brush Lake reveals that the porosity distribution is primarily the result of diagenetic controls rather than structural or depositional controls. Textural evidence from the laminated member indicates that porosity has been reduced in some parts of the laminated member by 1) early precipitation of calcite cements, 2) overdolomitization, 3) early precipitation of gypsum, 4) late precipitation of replacive anhydrite, and 5) pressure solution along low amplitude stylolites.

INTRODUCTION

Statement of Problem

Drilling activity in the Williston Basin of eastern Montana has in the last 10 to 15 years established the Red River Formation and particularly its "C" laminated member as an important reservoir for hydrocarbons. The "C" laminated member is thoroughly dolomitized in many parts of the basin and produces hydrocarbons where dolomitization has resulted in a substantial increase in the volume of intercrystalline porosity. Determining where porosity is sufficient for hydrocarbon production remains a major difficulty because even within thoroughly dolomitized portions of this member porosity values change rapidly. For example, it is not uncommon for one well penetrating this member to encounter dolomite with economically significant porosity (greater than or equal to 6 percent) while another well, less than a mile away, encounters dolomite with very little porosity (much less than 6 percent) (Plate 1). This is an interesting and important phenomenon because theoretically, complete dolomitization of limestone should result in an increase of porosity (Murray, 1960; Weyl, 1960). The fact that some parts of the "C" laminated member lack significant porosity despite being thoroughly dolomitized suggests other factors, in addition to dolomitization, contributed to the observed porosity distribution. The purpose of this thesis is to identify what other diagenetic processes affected the

"C" laminated member and to determine how these processes affected the distribution of economically significant porosity.

Stratigraphy

The term Red River Formation is applied to the Middle and Upper Ordovician carbonates in the subsurface of the Williston Basin (Fig. 1). The outcrop equivalent of this formation is the Bighorn Dolomite. The Red River Formation was originally described by Dowling (1900) and was defined as the carbonate sequence lying below the Ordovician Stony Mountain Shale and above the Ordovician Winnipeg Formation (Fig. 1). Numerous workers have studied and subdivided this formation; Dowling (1900), Foerste (1928), Ballie (1952), Porter and Fuller (1959), Andrichuk (1959), Sinclair (1959), Fuller (1961), Ballard (1963) and Friestad (1969). The Red River is most often subdivided into two parts; an upper unit composed of several carbonate/evaporite cycles and a lower unit comprised of massive dolomitic limestone (Porter and Fuller, 1959; Sinclair, 1959; Fuller, 1961). The boundary separating the upper and lower parts is placed at the base of the lowest anhydrite bed (the "C" anhydrite in Fig. 2) (Fuller, 1961). Another subdivision employed mainly by workers in the hydrocarbon industry divides the formation on the basis of the carbonate/evaporite cycles and this subdivision is employed in this thesis. According to this subdivision there are three general cycles labeled A, B, and C in descending order (Fig. 2). In the basin interior, each of these cycles is made up of three informal members; an upper anhydrite member, a middle laminated dolomite mudstone member, and

<i>Devonian</i>	<i>Prairie Fm</i>
	<i>Winnipegosis Fm</i>
	<i>Ashern Fm</i>
<i>Silurian</i>	<i>Interlake Fm</i>
	<i>Stonewall Fm</i>
<i>Ordovician</i>	<i>Stony Mountain Shale</i>
	<i>Red River Fm</i>
	<i>Winnipeg Fm</i>
	<i>Deadwood Fm</i>
<i>Cambrian</i>	
<i>Precambrian</i>	

Figure 1. General stratigraphic column for the Williston Basin.

CHEVRON MELBY 4-1
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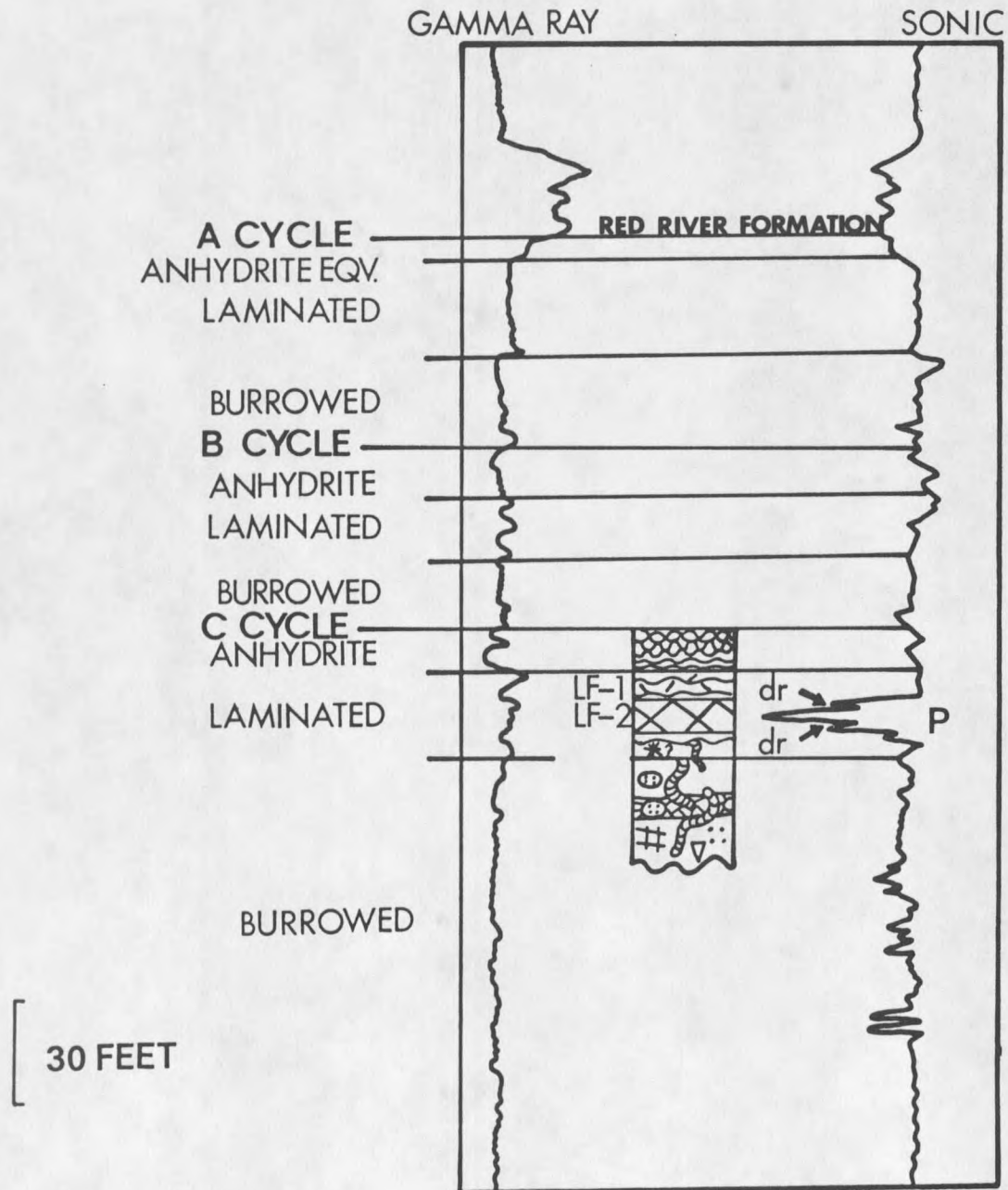


Figure 2. General log characteristics and terminology for the Red River Formation. P = porosity zone and dr = dolomitization resistive beds.

a lower bioturbated mudstone to wackestone member (Fig. 2). In this study, the three members of each cycle are referred to as 1) the anhydrite member, 2) the laminated member, and 3) the burrowed member. An "A", "B", or "C" will precede these member terms to specify the Red River cycle under discussion. This study focuses on the "C" cycle and in particular the "C" laminated member.

To conduct a detailed study of the "C" cycle lithology and porosity distribution requires numerous core samples and mechanical logs. A search was made to locate a field where several wells had been cored. As a result, the Brush Lake field was chosen as the study area.

Study Area

The Brush Lake field located in Sheridan County, Montana (Fig. 3) is well suited for a detailed study of the Red River "C" cycle and to accomplish the thesis objectives. One reason for this is that the "C" laminated member is thoroughly dolomitized throughout the field and porosity values change rapidly over short distances. Another very important reason for choosing this study area is the fact that eight of the ten wells comprising the field have core samples of most, if not all of the "C" cycle. These extensive core samples made it possible to conduct a detailed examination of the entire "C" cycle. From this examination, the depositional environment, diagenetic history, and stratigraphic relations of the various lithologic units present in the "C" zone have been determined. Also, the textural and compositional characteristics of the "porous" and "nonporous" dolomites have been examined and compared. Therefore, the thorough dolomitization, the rapid changes in porosity in the laminated member, and the availability of extensive core samples make the Brush Lake field an ideal study area for this research project.

Brush Lake Structure and Structural Development

Figure 4 shows the present-day structure at the Brush Lake field using the "C" anhydrite base as the datum. From this map the Brush

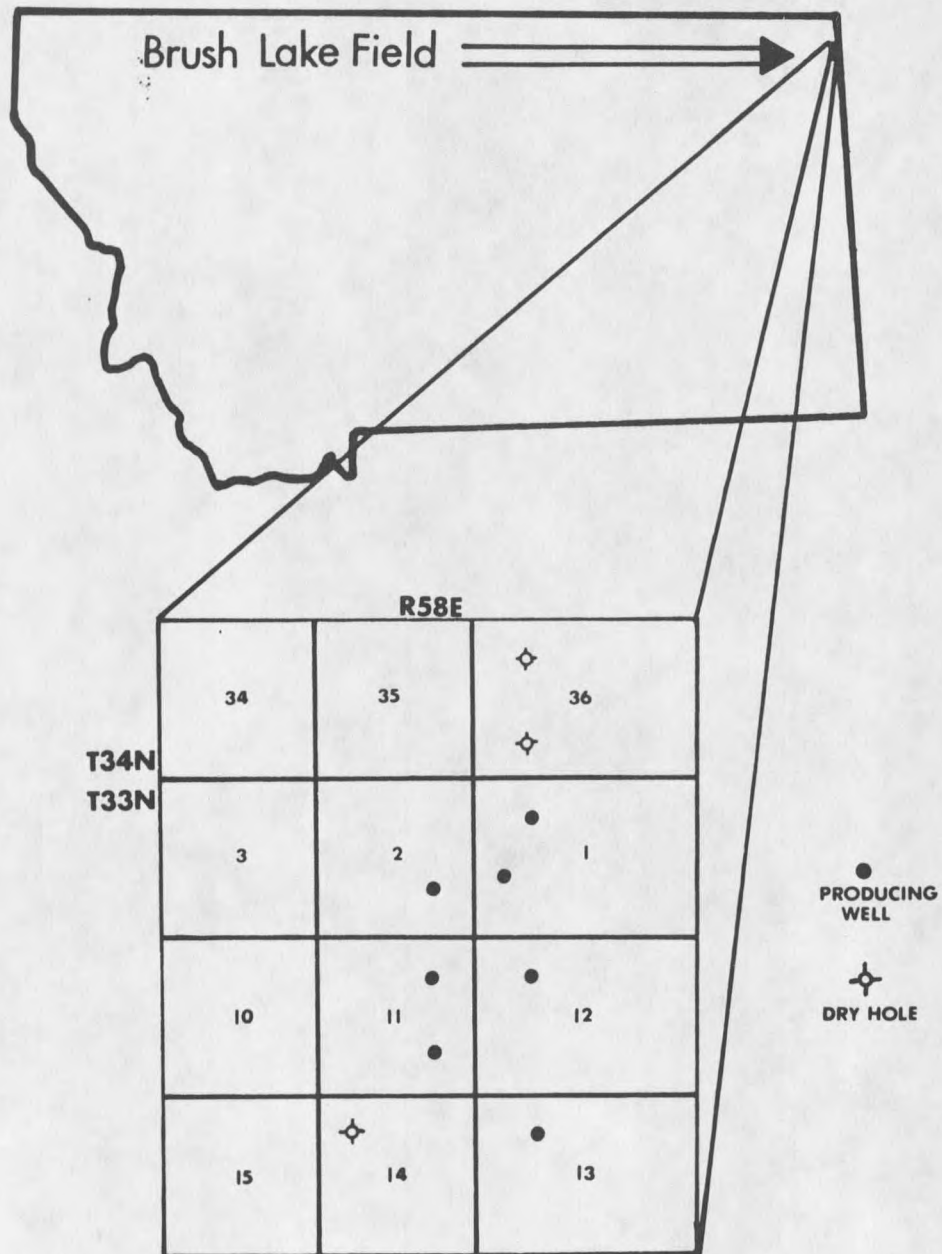


Figure 3. Location of study area and well locations for the Brush Lake Field.

Lake structure is observed to be about 4 miles in length and 2 miles wide. The structural axis trends roughly north-south. In addition, the Brush Lake structure can be seen to consist of two prominent "highs," one to the north and one in the south. The structural closure is approximately 100 feet on the northern high and about 40 feet on the southern part of the structure.

Although the Brush Lake structure has significant closure at present, the isopach maps reveal this was not always the case (Figs. 5 through 7). Figure 5 is an isopach of the "C" laminated member which shows that significant variations in thickness are lacking. The absence of substantial thickness variations within the laminated member indicates that during deposition of this member the Brush Lake structure was a subtle feature with total relief or closure probably not exceeding 4 to 6 feet.

Figures 6 and 7 show somewhat greater thickness variations than Figure 5 and indicate the structure had developed 20 feet of relief by the end of the Red River deposition and about 40 feet of relief by the end of Silurian time. The isopach maps are important because they clearly show that the Brush Lake structure did not become a prominent feature until sometime after Red River time. This means paleostructure could not have influenced penecontemporaneous dolomitization. Consequently, paleostructure did not control the porosity distribution within the "C" laminated member at the Brush Lake field.

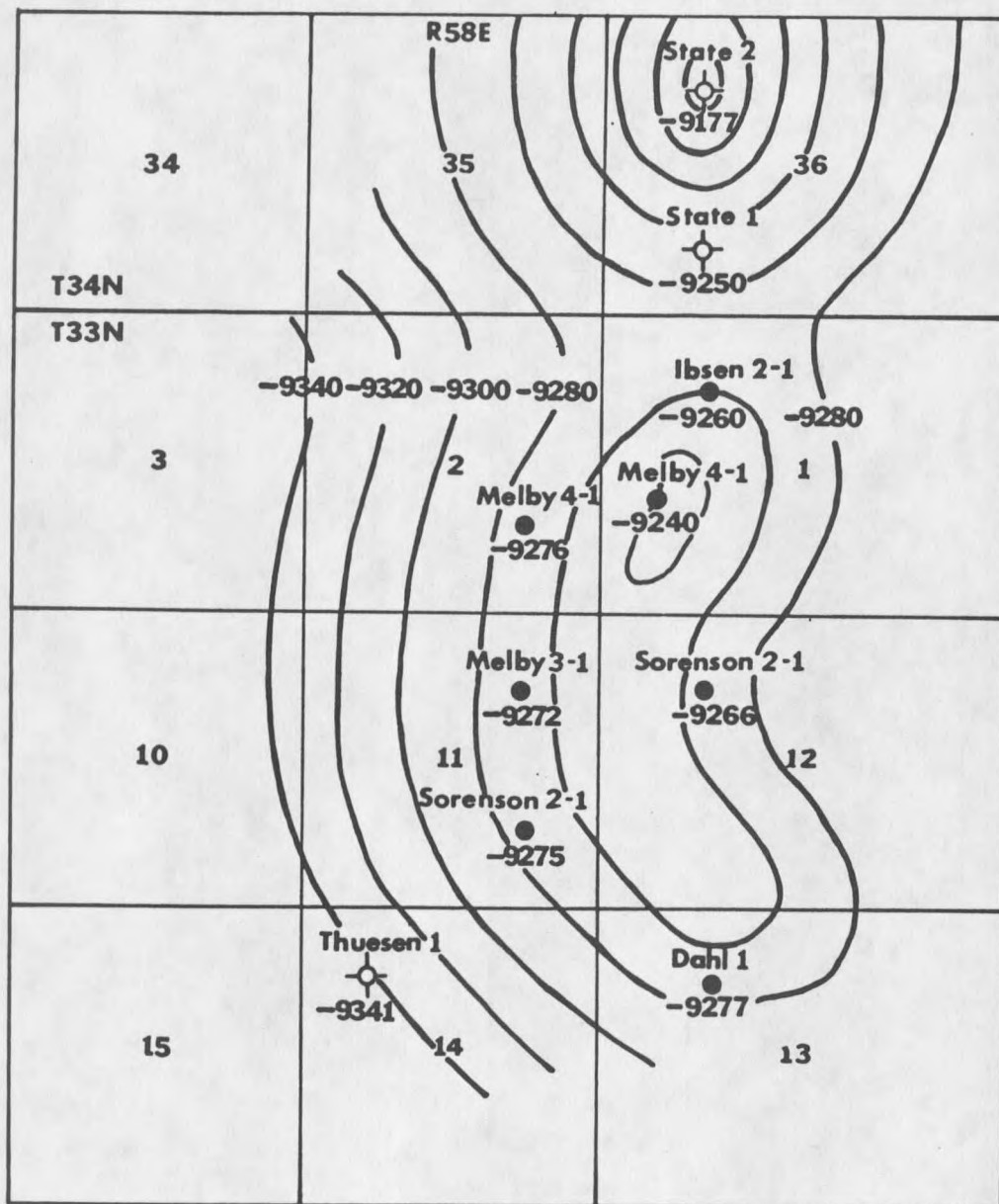


Figure 4. Structure map on the "C" anhydrite base. Contour interval = 20 feet.

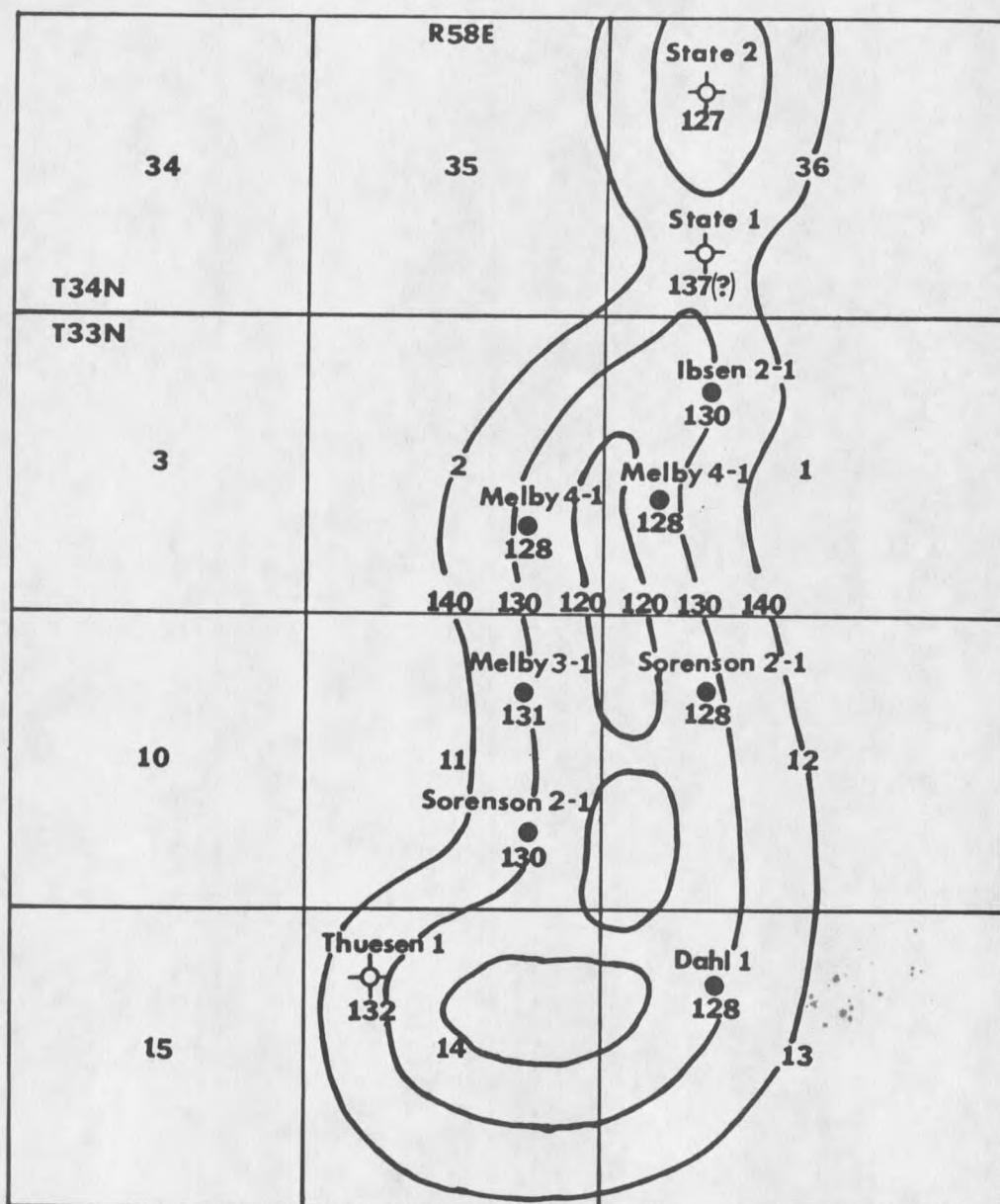


Figure 6. Isopach map of the Red River to "C" anhydrite base interval. Contour interval = 10 feet.

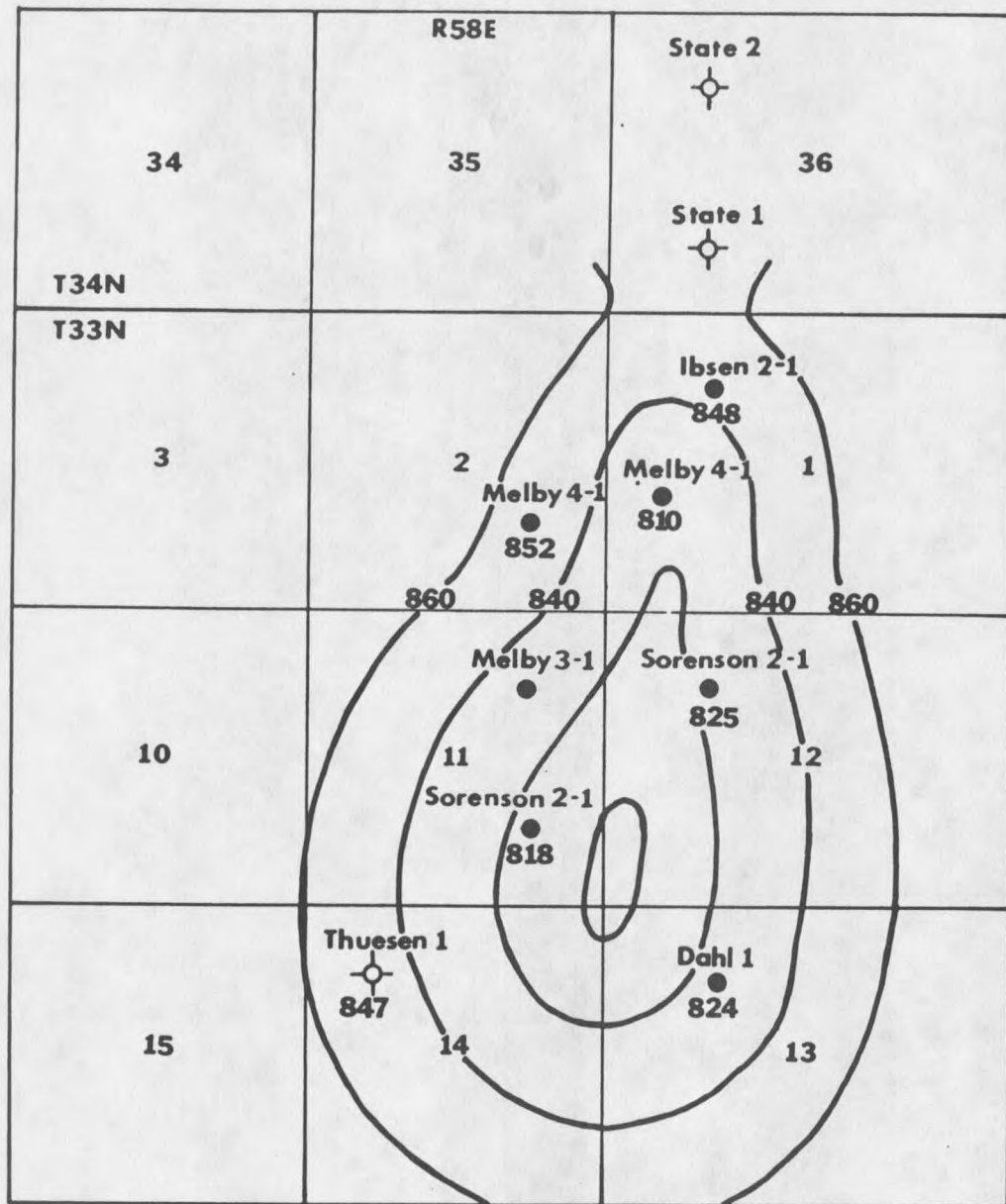


Figure 7. Isopach map of the Devonian Ashern to Red River interval. Contour interval = 20 feet.

Porosity Distribution

In addition to the present-day structural and paleostructural configuration, the distribution of porosity at Brush Lake was also mapped (Fig. 8 and Plate 1). Figure 8 is a fence diagram showing the distribution of porosity in the "C" cycle at Brush Lake. The upper-most horizontal line on the fence represents the "C" anhydrite base. The porosity zone immediately below the anhydrite base represents porosity development within the laminated member and the lower-most porosity zone represents porosity development in the upper burrowed member. Two areas at Brush Lake possess economically significant porosity (Fig. 8 and Plate 1). One occurs to the north near the structures' axis and the other is located in the south, significantly off-structure. If paleostructure had influenced the porosity distribution, the porosity zones should parallel structure contours or the porosity zones should occur consistently on one particular part of the structure. The observed random relationship between porosity and structure is therefore, further evidence that structure did not control porosity development. The fence diagram and stratigraphic cross section also clearly illustrate how rapidly porosity values change within the thoroughly dolomitized laminated member. As can be seen from Plate 1, wells possessing significant porosity are commonly less than a mile from wells lacking the porosity.

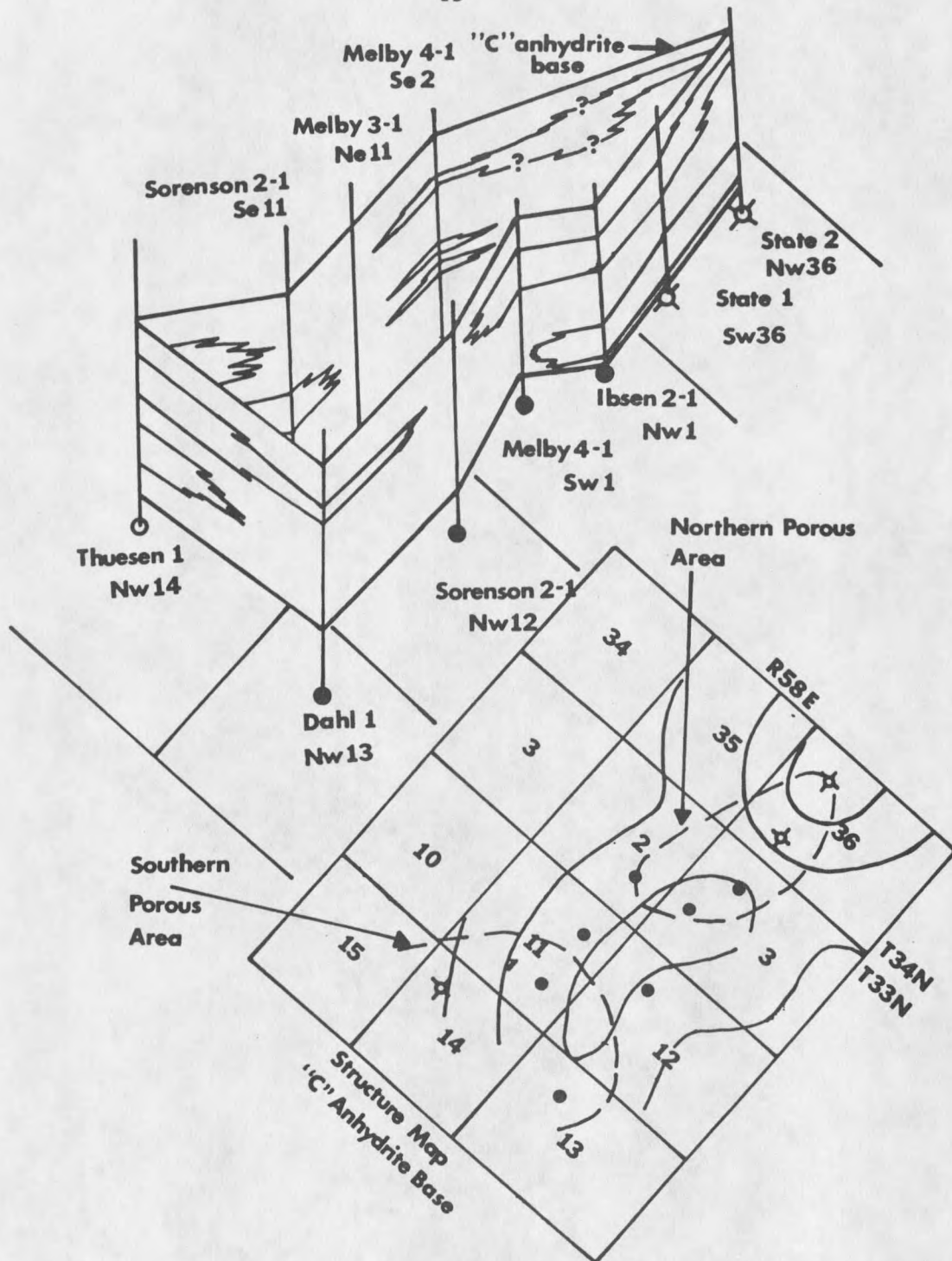


Figure 8. Fence diagram and reference map showing the distribution of porosity in relation to present-day structure. Economically significant porosity is shown for the laminated member (upper zone on diagram) and burrowed member (lower zone). Two areas possess significant porosity; one to the north and one to the south.

LITHOLOGY

The isopach maps and fence diagram shown in the last section indicate the porosity distribution was not controlled by structure. Other factors that could influence the observed distribution are 1) the original distribution of porosity which is largely controlled by depositional energy or depositional environment, and 2) diagenesis. Evidence of what effect either factor had on the porosity distribution is imprinted in the various lithologies comprising the "C" cycle. Therefore, the lithologies of the "C" cycle are described below with emphasis on the laminated member.

Anhydrite Member

The "C" anhydrite is consistently 3.4 to 3.7 meters thick throughout the Brush Lake field and is made up of three distinct units. The upper unit consists of 0.5 to 0.9 meter of dark gray and brown, inter-laminated nodular anhydrite and dolomite (Fig. 9). Individual laminae are 0.5 to 2.5 cm thick. The anhydrite nodules are elongate parallel to bedding and are 5 to 10 cm in length. The nodules are composed of randomly oriented needles and laths of anhydrite. Areas between the nodules contain highly contorted laminae of brown dolomite. Often, the nodules coalesce resulting in nearly continuous undulating laminae of anhydrite.

The middle unit consists of about 0.6 meter of brown, stylolitic, laminated dolomite. This dolomite is very finely crystalline and



Figure 9. Photograph of nodular anhydrite from the "C" anhydrite member. Core width = 8.1 cm.

anhedral. Anhydrite is present as needles and laths which are oriented randomly or parallel to bedding in some cases and as small (2 to 3 mm diameter isolated spherical nodules. The nodules are composed of anhydrite laths and partings of dolomicrite.

The basal unit consists of 2.1 meters of gray to brown, nodular anhydrite which becomes more laminated near the contact with the underlying "C" laminated member. Nodules are 1 to 4 cm in length and 0.25 to 2.0 cm thick. The nodules are also elongate parallel to bedding. In the lower part of this unit there are laminae of anhydrite. Some of these laminae appear to consist of severely distorted nodules. The contact with the underlying laminated member is gradational with the transition taking place over a distance of 0.5 meter.

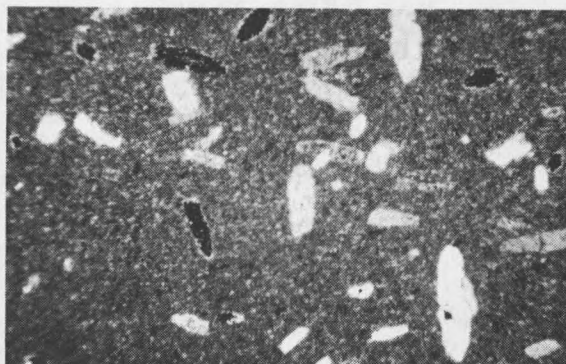
Laminated Member

Within the laminated member rapid changes in porosity have been observed (Fig. 8). Associated with changing porosity are changes in dolomite crystal morphology, relative abundance of anhydrite,

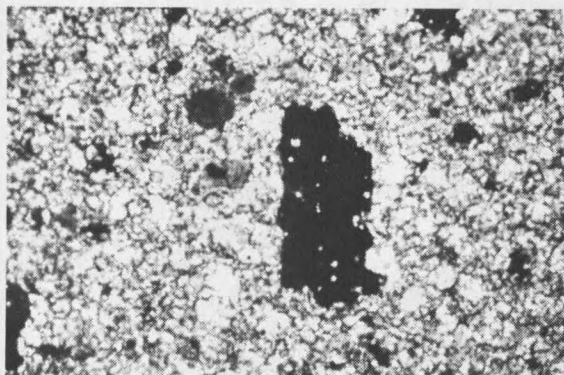
and relative abundance of stylolites. These changes in mineralogy and texture suggest variations in diagenesis and/or variations in the intensity of similar diagenetic processes within the laminated member. For this reason, the laminated member was subdivided into two diagenetic lithofacies (LF) which are discussed below.

Lithofacies 1 possesses very low porosity and is always present in the laminated member. In some wells the entire laminated member, except for the basal 0.6 to 1.2 meters, consists of LF-1 and no reservoir quality porosity (LF-2) is present. In other wells where there is reservoir quality porosity (LF-2), LF-1 is present above the reservoir zone. LF-1 consists of gray to brown, stylolitic, variably laminated, nonfossiliferous, very finely crystalline dolomite. Figures 10A through C show typical LF-1 textures. These figures show the very finely crystalline matrix and numerous larger crystals (porphyrotopes). The matrix consists of micrite (4 to 5 microns) to microspar (5 to 20 microns) sized dolomite. Note in Figures 10A and B that the matrix consists largely of anhedral to subhedral crystals. A matrix of anhedral crystals is referred to in this thesis as having xenotopic texture (after Friedman, 1965), whereas a matrix made up of subhedral crystals is termed hypidiotopic. In thin section, the LF-1 matrix ranges between xenotopic and hypidiotopic. However, in the scanning electron microscope (SEM) photograph the matrix is seen to consist of a substantial number of euhedral crystals (Fig. 10C). Many of these euhedral crystals are surrounded by anhedral dolomite overgrowths which suggest overdolomitization has occurred in LF-1

A
 ———
 400
 Microns



B
 ———
 100
 Microns



C
 ———
 20
 Microns



Figure 10. Typical LF-1 crystal textures. A. Very finely crystalline matrix and discoidal anhydrite. B. Anhydrite lath with parallel extinction. C. SEM photograph. An = anhydrite, D = dolomite. See text for complete descriptions.

(F. J. Lucia, personal communication). Overdolomitization is discussed in greater detail later under the heading Diagenetic Controls on Porosity.

Figures 10A and C show that porphyrotopes are present in varying amounts (0 to 40% by visual estimates). The SEM photograph shows a large rectangular lath shaped crystal as well as several smaller more equant crystals surrounded by the dolomite matrix (Fig. 10C). The larger lath is an anhydrite crystal identifiable by its crystal habit, high birefringence, x-ray spectrum, and pseudocubic cleavage. Throughout LF-1 the anhydrite porphyrotopes occur as needles (200 x 50 microns), laths (600 x 200 microns), and equant and discoidal crystals (Figs. 10A and B). There are two general types of anhydrite porphyrotopes within LF-1. The first type represents anhydrite which replaced gypsum. It can be seen in Figure 10A that this anhydrite possesses a discoidal crystal habit which is characteristic of gypsum. Also note the crystals do not show parallel extinction with respect to the external crystal morphology which suggests the replacement of monoclinic gypsum by orthorhombic anhydrite. This anhydrite has in effect "inherited" the gypsum crystal habit and optical properties. The second type of anhydrite is observed in Figure 10B and exhibits a prismatic crystal habit and parallel extinction, both of which are characteristic of anhydrite (Heinrich, 1965). This indicates the crystal in Figure 10B precipitated originally as anhydrite and did not replace gypsum. This second type of anhydrite could have precipitated only after burial created conditions which made anhydrite the stable evaporite mineral phase (Blatt and others,

1980). In addition to anhydrite, dolomite is also present as porphyrotopes in LF-1. A prominent dolomite porphyrotope is present in Figure 10C. The rhombic crystal habit and cleavage of the dolomite porphyrotopes distinguish them from the anhydrite. In addition to the petrographic and SEM examination of LF-1 dolomite, cathodoluminescence characteristics and stoichiometry were also investigated. LF-1 dolomite was found to be slightly magnesium rich. Compositions are recorded in Table 1. When examined with the luminoscope the matrix and porphyrotope dolomite had dull red luminescence. These two characteristics will be compared with the dolomite of LF-2 and the significance of this comparison will be discussed later.

The amount and content of insoluble residue (IR) for LF-1 was also determined. The results from these determinations are shown in Table 2. The weight percent IR for LF-1 ranges from a low 0.54 to a high 3.03 percent with the mean value of 1.75 percent. From Table 2 there does not appear to be a relationship between the total percent IR and the lithofacies.

Detailed examinations of LF-1 also revealed a variety of sedimentary and diagenetic structures. The most common structures observed in LF-1 are laminations. The laminae are between 3 mm and 1.5 cm thick and are planar concentrations of darker colored dolomite. In thin sections, the laminae consist of concentrations of coarser dolomite and dark brown dolomite matrix. Stylolites commonly occur on or near the laminae boundary making the latter more distinct.

Stylolites are very common to this lithofacies, especially in wells where most or all of the "C" laminated member consists of

Table 1. Dolomite stoichiometry measurements.

WELL NAME	SAMPLE DEPTH (feet)	LF#	DOLOMITE d(104)	PERCENT CALCITE (Standard Deviation)	
				*	**
Melby 4-1 Sw 1	11287.5	1	2.8800	48.9(±1.25)	48.0(±1.3)
Melby 4-1 Sw 1	11289	2	2.8878	51.4(±2.5)	50.6(±2.73)
Melby 3-1	11312	1	2.8823	49.5(±0)	48.8(±0)

*d(104) value taken for 50.0% CaCO_3 = 2.8837 and for 56.97% CaCO_3 = 2.9048 (after Blatt and others, 1980).

**d(104) value taken for 50.0% CaCO_3 = 2.886 and for 55.0% CaCO_3 = 2.901 (after Lumsden and Chimahusky, 1982).

Table 2. The percent insoluble residue for samples of the "C" laminated member.

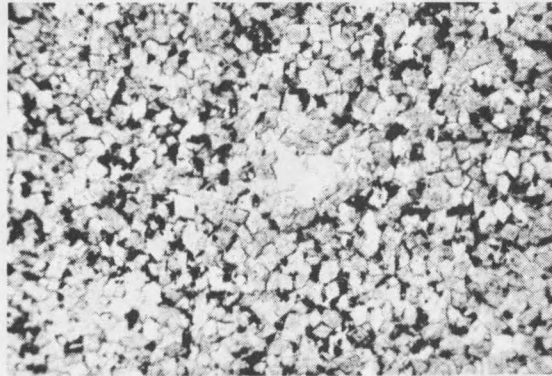
WELL NAME	SAMPLE DEPTH (feet)	LF#	PERCENT INSOLUBLE RESIDUE
Melby 4-1 Sw 1	11280	1	3.03
	11287	2	2.81
Melby 3-1 Ne 11	11301	1	1.87
	11310	1	2.47
	11316	1	1.1
Melby 4-1 Se 2	11308	1	1.5
	11318	1	0.54
	11324	2	3.78

LF-1. These stylolites are most often parallel to bedding although some oblique stylolites do occur. The stylolite amplitude is usually less than 5 mm and the stylolites truncate matrix dolomite and porphyrotopes. Associated with many of the LF-1 stylolites are anhydrite or dead-oil filled fractures. These fractures extend from the stylolite surface. Sometimes these fractures are truncated by other stylolites. The fractures may have originated prior to the stylolites and simply be truncated by the stylolite. It is also possible the fractures represent tension fractures or gashes which are intimately associated with the stylolite and formed under the same stress regime (Nelson, 1982).

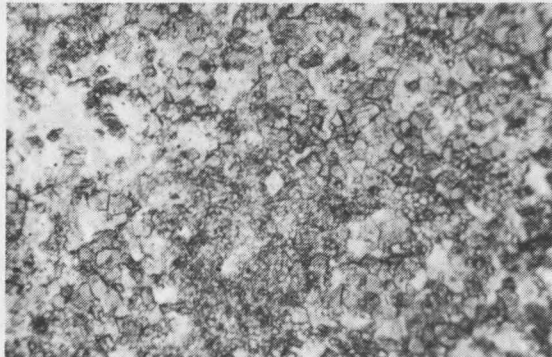
Lithofacies 2 represents dolomite with reservoir quality porosity and is made up of gray to brown, vaguely laminated, non-fossiliferous, finely crystalline dolomite. As can be seen in Figure 11 the dolomite crystals of LF-2 are equigranular compared to LF-1. It should also be noted that these dolomite crystals are euhedral, resulting in an idioblastic texture (Figure 11) (after Friedman, 1965). The dolomite rhombs range in size between 25 and 90 microns although when LF-2 texture is fully developed the size is usually more restricted (30 to 50 microns) (Figs. 11A and C).

Anhydrite is also present but is much less abundant than in LF-1. The anhydrite occupies intercrystalline pore space and former vugs or molds as seen in the center of Figure 11A. The anhydrite exhibits almost exclusively the lath crystal habit and parallel extinction which indicates it precipitated originally as anhydrite and did not replace gypsum. This anhydrite is analogous to the anhydrite in LF-1

A
—
200
Microns



B
—
200
Microns



C
—
10
Microns

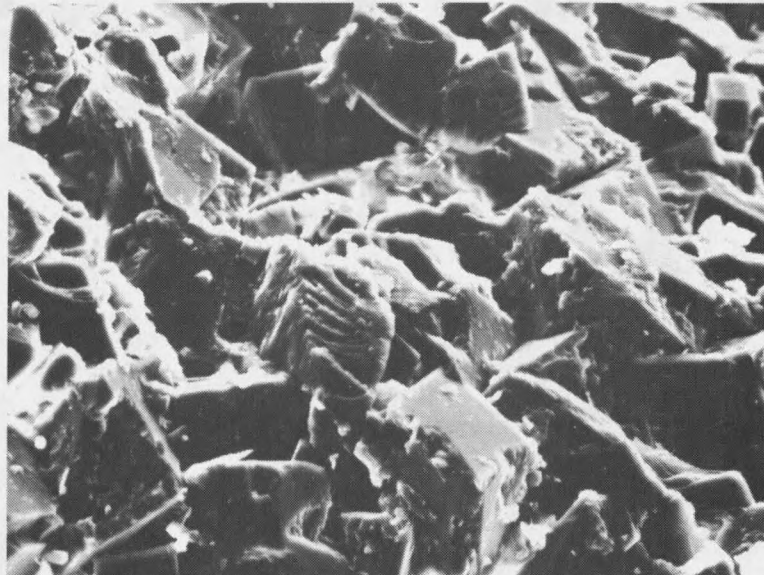


Figure 11. A. Typical LF-2 texture. Anhydrite fills central clear area. B. Sample which resisted dolomitization (compare texture with Figure 10). MC = micritic calcite, D = dolomite. C. SEM photograph. See text for complete description.

with parallel extinction and the rectangular crystal habit. The presence of rhombs within the anhydrite crystals shows the anhydrite enclosed dolomite during precipitation. Such a relationship is common in LF-2 and the term poikilotopic is used to describe this relationship. Often the dolomite within the anhydrite has a corroded appearance suggesting the host dolomite is being replaced by the anhydrite. Therefore, this anhydrite can be referred to as replacive anhydrite.

It is significant to note that some thin beds within LF-2 resisted dolomitization and consist of large amounts of microspar-sized calcite (Fig. 11B). Early cementation probably prevented thorough dolomitization in these beds. These beds are of interest because they represent the preserved texture of the precursor to LF-2. The precursors texture is essentially identical to that of LF-1 except the latter is comprised of dolomite. This similarity in crystal texture suggests LF-2 and LF-1 originated from the same precursor. Dolomitization in LF-1 has preserved this relict texture while dolomitization in LF-2 has largely destroyed the original texture except where early cementation prevented dolomitization. Since the two lithofacies developed from the same precursor, it is likely that the present porosity distribution in the laminated member is not the result of original variations in porosity within the precursor.

Examination of the LF-2 dolomite luminescence character reveals no difference from the dolomite of LF-1. Both dolomite types (LF-1

and 2) have dull red luminescence. The response of cathodoluminescence (CL) is of interest because it provides a means to examine and compare composition of the "nonporous" dolomites (LF-1) and "porous" dolomites (LF-2). The luminescence response in carbonates depends on the Mn/Fe ratio (Frank and others, 1982). Manganese is thought to activate luminescence in carbonates while ferrous iron inhibits the response (Sommers, 1972 from Frank, 1981; Frank, and others, 1982). Dolomite and calcite crystals commonly display distinct bands or zones when examined under cathodoluminescence (Oglesby, 1976 from Frank, 1981; Frank and others, 1982). In addition, it has been shown that individual crystals and zones with similar luminescence characteristics possess similar Mn/Fe ratios while those with dissimilar luminescence response have markedly different Mn/Fe ratios (Frank, 1981; Frank and others, 1982). The compositional zoning is thought to result from changes in fluid chemistry during crystal growth (Katz, 1972; Oglesby, 1976 from Frank, 1981). Consequently, the identical response to CL by the LF-1 and LF-2 dolomites indicates they formed from compositionally similar fluids. This observation shows that crystal morphological differences between LF-1 and 2 dolomites may not be the result of crystallization from fluids with very different concentrations as suggested by Asquith and others (1978). Therefore, another theory to explain the dolomite morphology differences may be applicable. An alternative explanation is discussed later under the heading Diagenetic Controls on Porosity.

LF-2 dolomite was found to be nearly stoichiometric with a composition of Ca51.4 Mg48.6 (Table 1). Dolomite stoichiometry may be in part controlled by the chemistry of the dolomitizing fluids (Lumsden and Chimahusky, 1980). This is supported by the fact that dolomite associated with evaporites is more nearly stoichiometric than dolomite which is not associated with evaporites (Lumsden and Chimahusky, 1980). Therefore, the similarity of stoichiometry between LF-1 and 2 also supports formation from compositionally similar fluids.

LF-2 has only a few structures which were observed. Among these, vague laminae are present in some core samples but absent in others. In addition, stylolites are also present but are much less abundant than in LF-1. However, the stylolites are similar to those of LF-1 in that they truncate all the other fabrics.

The basal 0.6 to 1.2 meters of the laminated member is similar to LF-1 in that it is laminated and has a largely xenotopic texture. However, the basal beds differ from the rest of the laminated member in that they are less thoroughly dolomitized, sparsely fossiliferous, and contain some burrows and distinct allochems. The lower 0.6 to 1.2 meters of the laminated member consists of tan to black, finely crystalline, dolomitic mudstone. It is rarely bioturbated, laminated, and sparsely fossiliferous. The crystal texture for these beds is generally xenotopic, although areas of hypidiotopic texture do exist. This unit is distinguished from the rest of the laminated member by its sparse fossil content and its burrows.

The allochems present include ostracods, crinoids (?), brachiopods, pellets, and small intraclasts. Together, these characteristics indicate the beds represent a transition between the laminated and burrowed members.

A large part of the matrix in these transition beds consists of brown anhedral dolomite. Limpid dolomite rhombs, 20 to 40 microns in sized, are present in the interiors of ostracod tests and small vugs. In addition to the dolomite, the interior of many vugs are occupied by anhydrite and pyrite. A few of the pyrite crystals are subhedral and appear to express a pyritohedron crystal form.

The basal beds have more distinct and varied structures than LF-1 and 2. Laminations are common in the upper part of the transition beds but they are increasingly disrupted by bioturbation in the lower part. There are several types of laminae represented in these beds. Some laminations are produced by alternations of brown and black dolomite. An increase of organic material may be responsible for the color change and could indicate the former presence of algal mats. Other laminations are produced by concentrations of severely altered crinoid parts (?) or by fining upward sequences of small intraclasts and pellets. One sample consists of a flat pebble conglomerate. The pebbles are 3 to 5 mm thick and 1 to 3 cm in length. Most are rectangular in outline and consist of brown dolomite. The matrix of this conglomerate is made up of black dolomite.

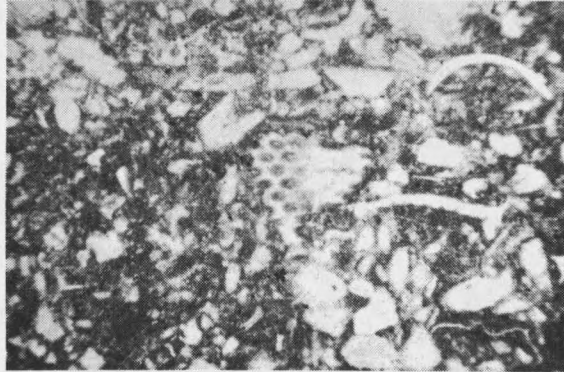
Some intraparticle and solution pore space exists in these beds but much of this porosity has been eliminated by the dolomite and

anhydrite cements. Therefore, the transition beds are usually characterized by noneconomic porosity.

Burrowed Member

This member is made up of tan to dark brown, stylolitic, bioturbated, fossiliferous, dolomitic mudstone to wackestone with occasional thin beds of packstone and grainstone. Calcite occurs as micrite to microspar matrix, as microspar and coarsely crystalline sparry-cement filling fossil molds, vugs, and intraparticle pore space, and as fossil grains (Fig. 12). Two generations of cement are observed in many former voids. Note in Figure 12B that the first generation cement is composed of equant to bladed microspar that completely lines the outer edge of the former void. The second generation of sparry calcite is also made up of equant to bladed crystals which occupy the more interior portion of the void. Figure 12B shows the interparticle cements within an intraclastic grainstone bed near the burrowed members top. This bed is interesting because it contains no dolomite but occurs between dolomitic mudstones and wackestones. The abundant pore filling calcite cement and absence of dolomite illustrates clearly that early cementation has prevented dolomitization from occurring. Therefore, these grainstones are similar to the beds in LF-2 which resisted dolomitization and further illustrate the potential for other diagenetic processes to control dolomitization and influence the distribution of porosity.

A
—
160
Microns



B
—
100
Microns

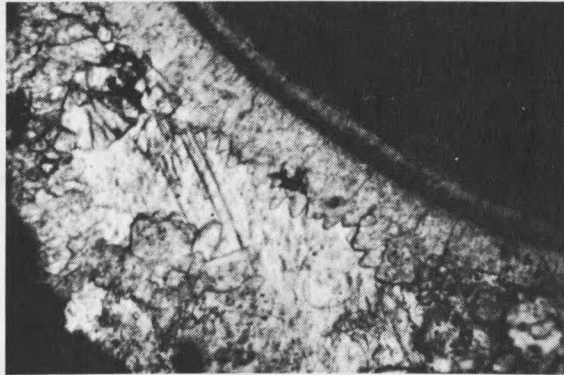


Figure 12. Typical burrowed member textures. A. Wackestone texture with abundant and varied fauna, and micritic calcite matrix. See text for list of fossil types. B. Photograph showing interparticle cements. These cements preceded and prevented dolomitization.

The dolomite of the burrowed member is more coarsely crystalline than those previously described for the laminated member. Rhomb size is normally between 60 to 120 microns. Dolomitization has been largely restricted to the burrows in some samples although dolomite rhombs are present disseminated in the matrix and partially filling some vugs and fossil molds. Several samples of the dolomite were examined with the luminoscope. Dolomite within the burrows has a slightly darker red luminescence than dolomite outside the burrows. This could indicate the dolomite within the burrows formed from fluids which were compositionally distinct from those responsible for the matrix dolomite. This observation could support Kendall's (1976, 1984) theory that dolomite within burrows and in the matrix represent distinct stages of dolomitization. In addition to dolomite, anhydrite is also present in the member and fills fractures and dolomite lined vugs and molds.

This member is moderately to intensively bioturbated. Individual burrows often have fossil grains arranged tangentially around them. The burrows are frequently 2.0 to 5.5 mm in diameter. Often, this member is so intensely burrowed that individual burrows cannot be identified.

Stylolites are common in the burrowed member and frequently occur at the contact between dolomite filled burrows and the micritic matrix. The stylolites are greater in amplitude than those of the laminated member and commonly have fractures associated with them. The cement filled fossil molds are affected by stylolitization but the cement

filled vugs are not. Therefore, the cements filling some vugs may represent carbonate minerals removed by pressure solution along stylolites and reprecipitated within the vugs. The orientation of stylolite surfaces are more variable than those of the laminated member. This is most likely the result of greater anisotropy existing in the burrowed member.

Other diagenetic structures common to this member are solution vugs and molds. These voids are abundant in thin (lm) zones at several stratigraphic horizons. The vugs are 1 mm to 2 cm in diameter. Both vugs and molds frequently contain coarse limpid dolomite and anhydrite. The dolomite may have replaced a precursor calcite cement or precipitated as a cement. However, the fact that dolomite and calcite do not occur together within the former voids may support the original precipitation of dolomite as cement.

Not only does this member contain more distinct sedimentary structures than the rest of the "C" cycle, it also contains abundant and varied fauna. The fossil assemblage consists of echinoderms, brachiopods, trilobites, bryozoans, mollusks, gastropods, ostracods, and small coral (?), in order of decreasing abundance (Fig. 12A). For the most part, fossil grains are disarticulate but unabraded. Selective dissolution created numerous fossil molds, mostly mollusks, which were subsequently filled with sparry calcite. Imbrication of fossil material is commonly observed. The core samples show that the variety and abundance of the fauna increases with increasing depth. Other allochems present are pelloids and intraclasts. The

peloids are best preserved where fossil debris sheltered them from compaction. The intraclasts contain a pelleted matrix with a minor number of disarticulate ostracod tests and other shells. The intraclasts are 0.5 to 2.0 cm in their longest dimension.

Porosity values vary substantially within the burrowed member. Economically significant porosity is directly associated with increasing dolomite content unlike the laminated member, and in some cases with well developed solution porosity.

INTERPRETATIONS

Depositional Environment

The Red River "C" cycle consists of an upper member comprised of nodular anhydrite interbedded with carbonates; an intermediate member of laminated carbonates with abundant discoidal evaporite crystals; and a lower member which became increasingly more fossiliferous and bioturbated with depth. This sequence is very similar to that described by McKenzie and others (1980) for the tidal-flat at Abu Dhabi (Fig. 13). The supratidal facies at Abu Dhabi is composed largely of nodular anhydrite both as isolated nodules and as densely packed nodules which generate a chicken wire mosaic. Discoidal gypsum is also present in some of the supratidal beds (Fig. 13). Directly below the supratidal beds, the upper intertidal facies consists of algal laminations, intensely dolomitized carbonates, and abundant discoidal gypsum crystals. The lower intertidal facies is also intensely dolomitized and possesses laminations and discoidal gypsum. Most distinctive of the lower intertidal facies is the first appearance of marine organisms (Fig. 13). This facies is in turn underlain by the less intensely dolomitized, abundantly fossiliferous subtidal facies.

The striking similarities between the two sequences strongly suggests that the Red River "C" cycle represents an ancient sabkha deposit. Therefore, the composite profile in Figure 13 can be used as a model to interpret the depositional environments for each "C"

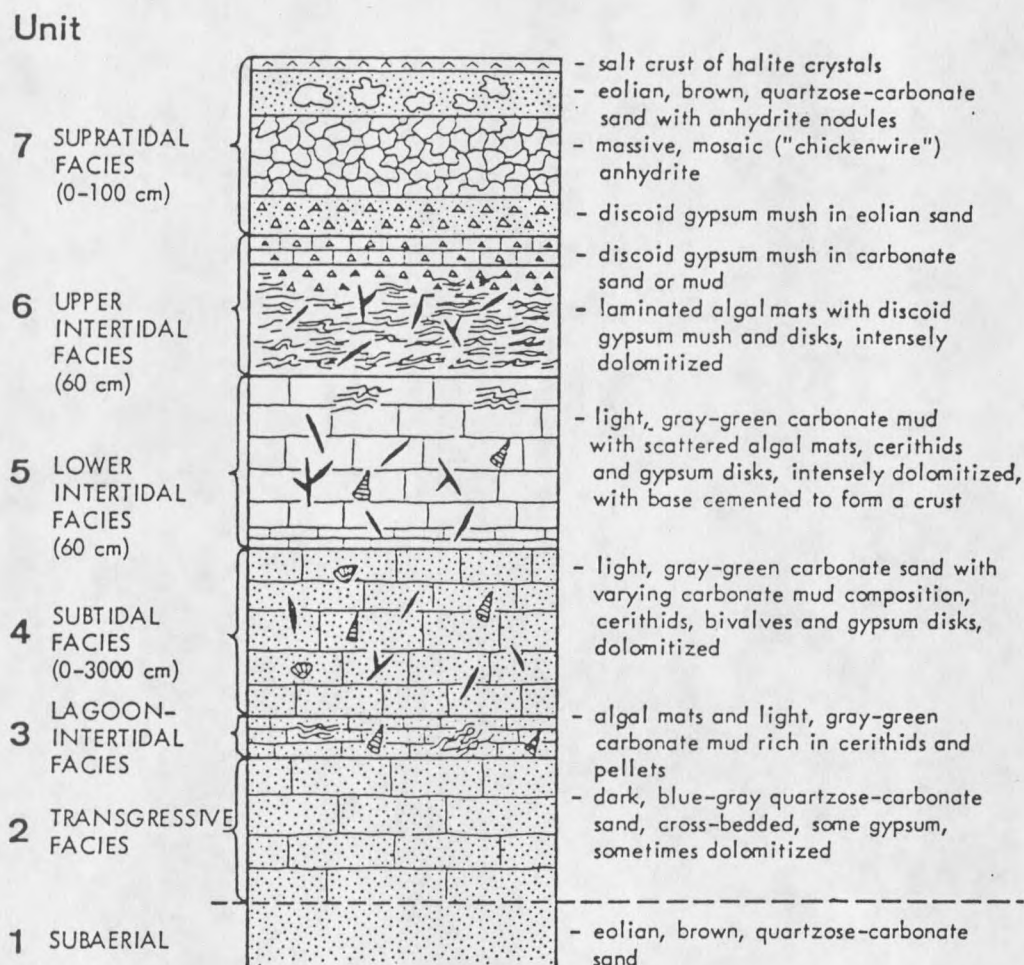


Figure 13. Composite profile showing the characteristics of sabkha sediments at Abu Dhabi (from McKenzie and others, 1980).

cycle member (Fig. 14). In the interpretation of Figure 14, the "C" anhydrite and probably the upper most laminated member represents the supratidal sabkha environment. Most of the remaining laminated member, except for the basal 0.6 to 1.2 meters, represents the upper intertidal zone. The lower intertidal environment is represented by the transition beds as indicated by the first appearance of marine fossils. The burrowed member below the transition originated in the subtidal normal marine environment as suggested by the varied fauna and bioturbation. This interpretation is similar to studies of the Red River by Carroll (1979) and Ruzyla (1980).

Not all who have examined the Red River Formation agree that the "C" cycle represents a tidal flat or sabkha sequence. Some workers interpret the cycle as an entirely subaqueous deposit (Kent, 1960; Fuller, 1961; Kendall, 1976, 1984; Kohm and Loudon, 1978; Longman and others, 1983, 1984). These workers interpret the "C" anhydrite as a bedded evaporite which suggests a subaqueous origin and cite the absence of desiccation structures in the laminated member to support their interpretation. The subaqueous origin for the "C" anhydrite is rejected in this thesis because the texture of the evaporite at the Brush Lake field is definitely nodular and nodular evaporites do not form in subaqueous environments (Blatt and others, 1980). As a result, interpreting the "C" anhydrite as a supratidal deposit is reasonable. In addition, once the supratidal environment is recognized, it can be reasonably assumed that intertidal and subtidal sediments occur below (Lucia, 1968).

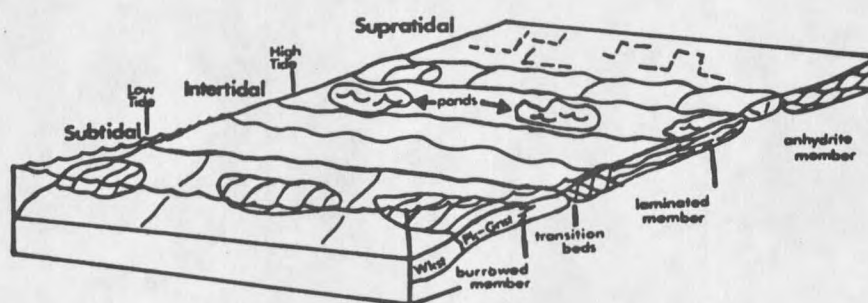
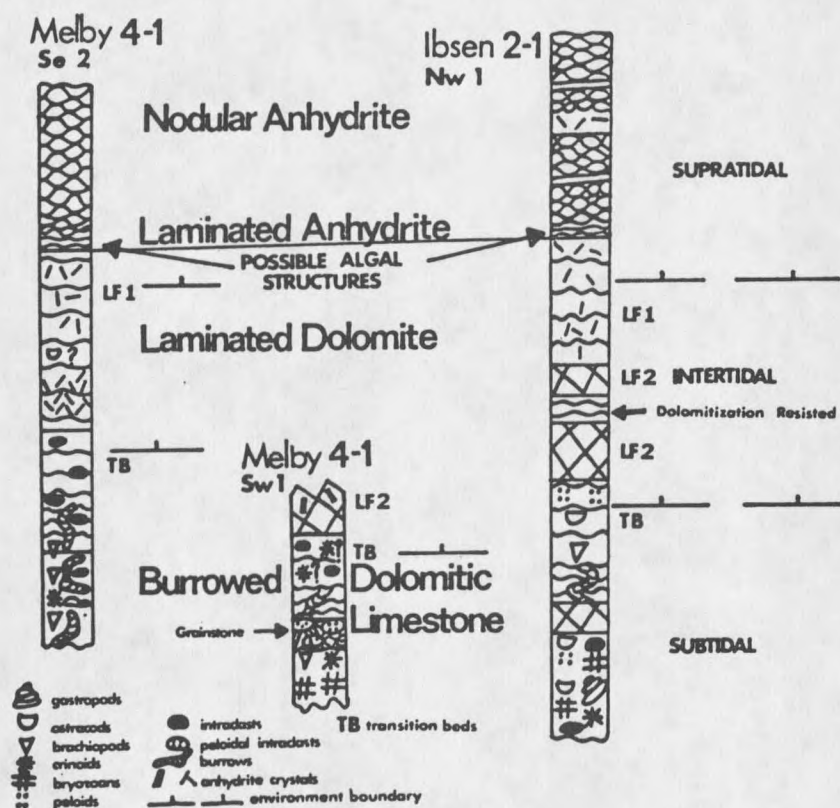


Figure 14. Characteristics of the Red River "C" cycle and environmental interpretations made by comparing the "C" cycle with Figure 13. No scale.

Dolomitization

The interpretation that part of the "C" cycle represents the supratidal environment is central to understanding how dolomitization was accomplished and when it was initiated. Nodular and discoidal anhydrite within the "C" cycle indicates the former existence of gypsum which precipitated within the precursor sediments and grew displacively (Blatt and others, 1980; Kerr and Thomas, 1963). The precipitation of gypsum in modern sabkhas removes calcium from interstitial fluids and increases the fluids Mg/Ca ratio. Such magnesium rich fluids are considered capable of dolomitization (Adams and Rhodes, 1960; Deffreys and others, 1965; Zenger, 1972; Blatt and others, 1980). Figure 15 shows that in the tidal flats of the Persian Gulf brines are generated in the supratidal environment

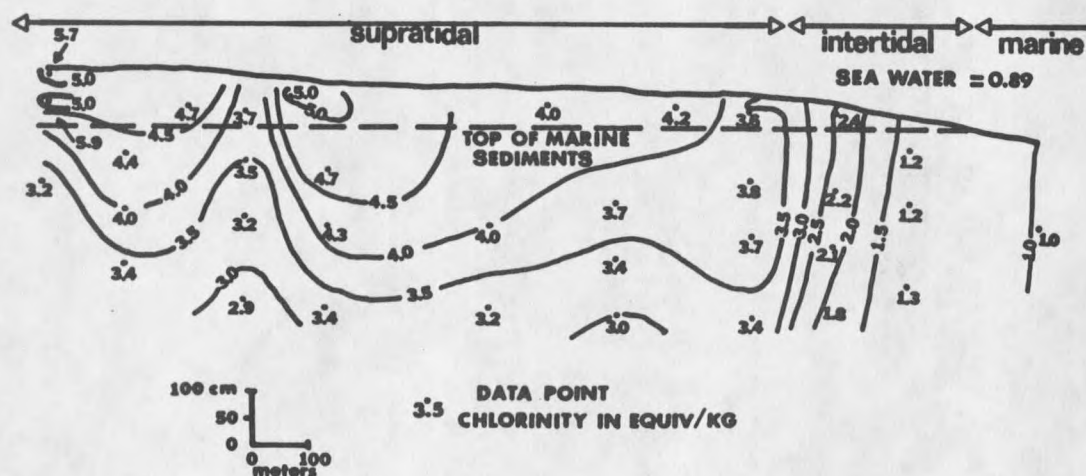


Figure 15. Distribution of hypersaline waters beneath the tidal flat in the Persian Gulf. The presence of hypersaline fluids within the marine sediments shows that seepage refluxion is occurring (modified from Illing and others, 1965).

where the highest chlorinity values are recorded. The presence of hypersaline water in the marine sediments below the sabkha illustrates that brines generated in the supratidal zone are refluxing or sinking and displacing the marine connate waters. As these brines move through the carbonate sediments, dolomitization proceeds. The abundance of anhydrite after gypsum within the Red River "C" cycle suggests that brine generation and dolomitization may have occurred penecontemporaneously with sedimentation in a manner similar to that thought to be taking place in the modern sabkha.

Several mechanisms for dolomitization have been proposed for the modern tidal flats. They are 1) seepage refluxion (Adams and Rhodes, 1960), 2) dorag (Badiozamani, 1973), and 3) evaporative pumping (Hsu and Siegenthaler, 1969) or capillary concentration. Combinations and/or variations of these models have been applied to the Red River Formation to explain dolomitization and in some cases to explain the distribution of porosity. Examples include studies by Kendall (1976, 1984); Asquith and others (1978); Kohm and Loudon (1978); Carroll (1978); Wittstrom and Chimney (1980); Ruyzla (1980); and Longman and others (1983, 1984). While the formal models can be applied to explain dolomitization of ancient carbonates, it is less clear how the models can explain the localized porosity distribution of the Red River "C" cycle. Porosity distribution is not simply a matter of thoroughly dolomitized portions of the laminated member possessing greater porosity than nondolomitized portions. If so, any model which explained how dolomitization could be restricted to operate in some areas preferentially to others

might be adequate to explain the distribution of porosity. Instead, the problem at the Brush Lake field is to explain why thorough dolomitization preserved and enhanced the porosity volume in some parts of the laminated member but not in others. While no totally adequate explanation for the distribution of porous dolomite exists, a comparison of LF-1 (nonporous dolomite) and LF-2 (porous dolomite) does provide some evidence of the factors which contribute to the observed distribution.

Diagenetic Controls on Porosity

Table 3 lists the general differences between LF-1 and LF-2. The major difference between the two lithofacies is that LF-1 possesses xenotopic texture while LF-2 has hypidiotopic to idiotopic texture (compare Figures 10 and 11). The most common explanation for this difference in crystal morphology has been clearly described by Asquith and others (1978). According to this theory, very finely crystalline, xenotopic dolomite is the product of rapid crystallization from a large number of nucleation sites. Rapid reaction rates are thought to result from very concentrated brines. As the brines move through the sediments, dolomitization proceeds and the brine concentration is reduced (brine composition changes). With reduced concentration, dolomitization proceeds more slowly from fewer nucleation sites and is thought to produce a more coarsely crystalline, sucrosic (hypidiotopic to idiotopic) dolomite. This theory predicts substantial changes in fluid composition between the time the xenotopic and idiotopic dolomites are produced. If

Table 3. Comparison of LF-1 and LF-2.

CHARACTERISTICS	LF-1	LF-2
CRYSTAL TEXTURE	Xenotopic	Hypidiotopic to Idiotopic
STOICHIOMETRY (%Ca)	48.9 (± 1.25) 49.5 (± 0)	51.4 (± 2.5)
CATHODOLUMINESCENCE	Dull Red	Dull Red
ANHYDRITE	1. After Gypsum 2. Replacive	1. Replacive
STYLOLITES	Abundant	Rare

this is so, the compositional changes should be passed on to the resulting dolomite. As a result, the xenotopic dolomites should be compositionally distinct from the idiotopic dolomite. However, it was shown previously that cathodoluminescence and stoichiometric data indicate the LF-1 and 2 dolomites are very similar if not identical in composition. Therefore, differential rates of dolomitization resulting from changing fluid composition (concentration) appears to be inadequate to explain the differences in crystal morphology observed in the two lithofacies.

The morphological differences between the "nonporous" (LF-1) and "porous" (LF-2) dolomites may be the result of overdolomitization. F. J. Lucia (personal communication) has observed a decrease in porosity in the upper part of the section as a result of overgrowths on euhedral dolomite and has termed the phenomenon "overdolomitization." Overdolomitization occurs after the precursor limestone has been completely dolomitized as a result of the

continued influx of Mg-rich brines which contain sufficient carbonate to allow dolomite to precipitate as a cement (distant carbonate source dolomitization of Murray, 1960). In the laminated member at Brush Lake, it was observed that LF-1 always occurs above LF-2 when both lithofacies are present in the same well. Therefore, as Lucia observed, porosity values are lower in the upper part of the section. In addition, the SEM photograph of LF-1 reveals a surprisingly high number of subhedral and euhedral dolomite crystals in the matrix. Some of these crystals appear to be surrounded or "incased" by anhedral dolomite (Fig. 10C). This relationship suggests the LF-1 dolomite originated as subhedral and euhedral crystals and a later precipitation of dolomite as overgrowths and pore filling cement obscured the hypidiotopic to idiotopic texture and reduced porosity. Therefore, the stratigraphic relations of LF-1 and 2 when they occur together in the same well, as well as the LF-1 crystal texture, suggest overdolomitization has occurred at the Brush Lake field.

Although overdolomitization played an important role in producing the LF-1 texture, it is not clear why in some areas the entire laminated member was overdolomitized while in other areas the same stratigraphic horizon retained the hypidiotopic to idiotopic texture. The remaining evidence shown in Table 3 suggests several other diagenetic processes also contributed to the observed porosity distribution. From Table 3 it can be seen that LF-1 experienced two phases of anhydrite precipitation. The first phase is represented by anhydrite after gypsum. The precipitation of

gypsum represents one of the earliest phases of diagenesis in modern sabkha sediments (Bathurst, 1975). Growth of the gypsum crystals also results in reduction of the sabkha sediments primary porosity. In addition, gypsum precipitation is commonly preceded by the precipitation of other authigenic minerals (Bathurst, 1975). Bathurst listed nine such authigenic minerals currently found in modern sabkhas. Some of these minerals are easily removed by dissolution during flooding by meteoric waters or more commonly, by normal marine waters. However, other authigenic minerals such as aragonite, calcite, dolomite, and magnesite are less vulnerable to dissolution. Once formed, these minerals also represent early cements which reduce the host sediments porosity volume. The anhydrite after gypsum in LF-1 therefore represents an early porosity-reducing event.

LF-2 lacks anhydrite after gypsum. This could indicate either 1) no gypsum and other authigenic minerals were precipitated originally, or 2) all authigenic minerals were replaced by dolomite. It is not possible to determine which of these possibilities actually occurred. However, if the gypsum and other minerals were absent from the precursor of LF-2, it would mean an important porosity-reducing event did not take place in those sediments. Therefore, it is possible that initial porosity differences existed between the precursors of LF-1 and 2 and, although these differences would not have been as pronounced as those currently observed, they would have caused the two precursors (those of LF-1 and 2) to be affected differently by later diagenetic events.

The second phase of anhydrite precipitation resulted in replacement of dolomite by anhydrite in both LF-1 and 2. The reaction involved in dolomite replacement is:



Mineral products of such a process include magnesite (MgCO_3) and/or dolomite. Whether these minerals are removed in solution or precipitated within the pore system of the host rock largely depends on the host's ability to transmit fluids. The precipitation of magnesite and/or dolomite as pore filling cements or as overgrowths (for dolomite) on existing dolomite is therefore favored in the proto-LF-1. If the replacement anhydrite represents $\frac{1}{4}$ to $\frac{1}{2}$ the total volume of anhydrite, porosity reduction would be significant at some horizons in the laminated member. For example, in the laminated member of the Melby 3-1 (Ne 11) and the Sorenson 1 (Nw 12) there are several horizons where anhydrite represents 30 to 40 percent of the total rock volume (by visual estimates). If $\frac{1}{4}$ of the anhydrite was replacive, the original porosity could be reduced by as much as 7.5 to 10 percent, which is significant. In contrast, the amount of anhydrite in LF-2 was always much less than 5 percent. The effect on the total porosity of LF-2 by this replacive anhydrite has been minor.

It can be seen from Table 3 that LF-1 and 2 responded very differently to pressure solution. Very low amplitude stylolites are common in LF-1 and they are especially abundant where the laminated member consists almost entirely of LF-1, namely in sections 2, 11, and 12 (Fig. 8 and Plate 1). Several characteristics of LF-1 may be responsible for

its greater susceptibility to pressure solution. First, the distribution of insoluble material within a host rock may determine where pressure solution will occur (Heald, 1959 from Park and Schot, 1968). The greater concentration of insoluble residue along laminae may have encouraged and localized stylolitization in LF-1. This could explain why the stylolites of LF-1 tend to occur on or near the laminations. Secondly, the fine crystal size of LF-1 may have also aided stylolitization. Small crystals are somewhat more soluble than larger crystals because of their larger surface area to volume ratio (Bathurst, 1975). Consequently, under a given stress, a framework of small crystals would be more susceptible to dissolution than a framework of larger crystals. Together, these factors may account for the greater abundance of stylolites in LF-1. In contrast to LF-1, LF-2 would resist pressure solution more effectively as a result of its more coarsely crystalline texture. Such a framework of crystals would tend to form sutured contacts rather than stylolites in response to compressive stresses.

The stylolites of LF-1 have played an important role in reducing the porosity and permeability. Stylolites have been found to be associated with low porosity and permeability values in carbonate rocks (Harms and Choquette, 1965; Dunnington, 1967; both from Bathurst, 1975). Both porosity and permeability properties increase away from the stylolites surface. This suggests the material removed by pressure solution is reprecipitated adjacent to the stylolite surface. In addition to this, the concentration of insoluble residue along stylolite surfaces also act as permeability barriers. By the sheer

abundance of stylolites in LF-1 as compared to LF-2, it is clear that porosity reduction due to pressure solution has had a greater impact on LF-1.

From the above evidence, it can be seen that LF-1 experienced several porosity reducing diagenetic events while LF-2 did not or was less severely affected by them. As a result the porosity distribution within the laminated member is the result of several diagenetic processes namely: 1) early cementation by calcite as exemplified by the beds in LF-2 which resisted dolomitization and the intraclastic grainstones of the upper burrowed member, 2) overdolomitization, 3) early precipitation of gypsum, 4) late precipitation of replacive anhydrite, and 5) pressure solution along stylolites.

SUMMARY

At the Brush Lake field, the Red River "C" zone consists of three informal members; 1) the anhydrite member, 2) the laminated member, and 3) the burrowed member. The "C" zone is interpreted as a tidal flat deposit based on its stratigraphic sequence of lithologies which are strikingly similar to those observed in modern sabkhas. The anhydrite member and the upper-most laminated member are interpreted to represent the high supratidal environment. The remainder of the laminated member except for the basal part represents the high intertidal zone. A transition between the laminated and burrowed members occurs in the lower-most laminated member. The first occurrence of marine fossils and burrowing suggest these beds represent the lower intertidal environment. The burrowed member is clearly a normal marine subtidal deposit.

The Brush Lake structure currently has about 20 to 40 feet of closure on its southern part and about 100 feet of closure on its northern part. During Red River deposition, however, the structure was a subtle feature and possessed low relief. This being the case, early structural configuration could not have influenced early dolomitization by determining where brines would migrate and where brine residency time would be maximized.

Porosity values change rapidly within the laminated member dolomites. This could be the result of original porosity variations

which were essentially preserved by thorough dolomitization. However, the fact that thin nondolomitized beds within LF-2 are texturally identical to LF-1 (except they are composed of calcite) suggests LF-1 and 2 originated from a similar precursor sediment. This in turn indicates the variations in dolomite texture do not result from primary textural variations caused by different depositional energies.

The observed porosity distribution at Brush Lake has resulted from diagenesis. The stratigraphic relations of LF-1 and 2 when both coexist in the laminated member, and LF-1 crystal fabric suggests the differences in porosity between LF-1 and LF-2 dolomites are largely the result of overdolomitization. In addition to this, textural differences between the two lithofacies indicate they experienced slightly different diagenetic sequences or different intensities of the same diagenetic processes. Throughout diagenesis LF-1 was more susceptible to porosity occlusion than LF-2. This greater vulnerability to porosity occlusion appears to result from LF-1 retaining a more finely crystalline texture. Such a texture inherently possesses low permeability which favors the precipitation of authigenic minerals within the lithofacies. The finely crystalline texture also is more susceptible to pressure solution than a more coarsely crystalline texture. Stylolites are as a result, more abundant in LF-1 than LF-2 and represent an important porosity reducing event in LF-1.

In conclusion, the present distribution of dolomite porosity within the laminated member is not simply the result of a single

diagenetic process as some recent studies imply. Instead, it is the product of several diagenetic processes. Some of these processes may have occurred early in the laminated members diagenetic history and to a significant extent determined how different parts of the member would respond to later diagenetic events. The complex history of diagenesis makes prediction of porosity trends very difficult.

REFERENCES CITED

References Cited

- Adams, J. E., and Rhodes, M. L., 1960, Dolomitization by seepage refluxion: American Association of Petroleum Geologists Bulletin, v. 44, p. 1912-1921.
- Andrichuk, J. M., 1959, Ordovician and Silurian stratigraphy and sedimentation in southern Manitoba, Canada: American Association of Petroleum Geologists Bulletin, v. 43, p. 2333-2398.
- Asquith, G. B., Parker, R. L., Gibson, C. R., and Root, J. R., 1978, Depositional history of the Ordovician Red River C and D zones, Big Muddy Creek field, Roosevelt County, Montana: Montana Geological Society Guidebook, 1978 Williston Basin Symposium, p. 71-76.
- Badiozamani, K., 1973, The dorag dolomitization model-application to the Middle Ordovician of Wisconsin: Journal of Sedimentary Petrology, v. 43, p. 965-984.
- Ballard, F. V., 1963, Structural and stratigraphic relationships in the upper Paleozoic rocks of North Dakota: North Dakota Geological Survey Bulletin, v. 40, 42 p.
- Ballie, A. D., 1952, Ordovician geology of the Lake Winnipeg and adjacent areas, Manitoba: Manitoba Mines Branch Publication 51-6, 64 p.
- Bathurst, R. G. C., 1975, Carbonate sediments and their diagenesis: Amsterdam-London-New York, Elsevier, 620 p.
- Blatt, H., Middleton, G., and Murray, R., 1980, Origin of sedimentary rocks: Englewood Cliffs, Prentice-Hall, 782 p.
- Carroll, W. K., 1979, Depositional environment and paragenetic porosity controls, Upper Red River Formation, North Dakota: North Dakota Geological Survey, Report of Investigation Number 66, 51 p.
- Deffeyes, K. S., Lucia, F. J., and Weyl, P. K., 1965, Dolomitization of Recent and Plio-Pleistocene sediments by marine evaporation waters on Bonaire, Netherlands, Antilles: in Pray, L. C., and Murray, R. C., eds., Dolomitization and Limestone Diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication 13, p. 71-87.

- Dowling, D. B., 1900, Report on the geology of the west shore and islands of Lake Winnipeg: Geological Survey of Canada Annual report Part F, 100 p.
- Dunnington, H. V., 1967, Aspects of diagenesis and shape change on stylolitic limestone reservoirs: 7th World Petroleum Congress Production, v. 2, p. 457-458.
- Ellingboe, J., and Wilson, J., 1964, A quantitative separation of non-carbonate minerals from carbonate minerals: Journal of Sedimentary Petrology, v. 34, p. 412-418.
- Foerste, A. F., 1929, The cephalopods of the Red River Formation of southern Manitoba: Denison University Bulletin, Scientific Laboratory Journal, v. 24, p. 129-235.
- Frank, J. R., 1981, Dedolomitization in the Taum Sauk Limestone (Upper Cambrian), southeast Missouri: Journal of Sedimentary Petrology, v. 51, p. 7-18.
- Frank, J. R., Carpenter, A. B., and Oglesby, T. W., 1982, Cathodoluminescence and composition of calcite cement in the Taum Sauk Limestone (Upper Cambrian), southeast Missouri: Journal of Sedimentary Petrology, v. 52, p. 631-638.
- Friedman, G. M., 1959, Identification of carbonate minerals by staining methods: Journal of Sedimentary Petrology, v. 29, p. 87-97.
- Friestad, H. K., 1969, The Upper Red River Formation (Ordovician) in western North Dakota: Master's Thesis, University of North Dakota, Grand Forks, 82 p.
- Fuller, J. G. C. M., 1961, Ordovician and contiguous formations in North Dakota, South Dakota, Montana, and adjoining areas of Canada and United States: American Association of Petroleum Geologists Bulletin, v. 45, p. 1334-1363.
- Harms, J. C., and Choquette, P. W., 1965, Geologic evaluation of a gamma-ray device: Society of Professional Well Log Analysts, 6th Annual Logging Symposium Transcripts, paper C, p. 1-37.
- Heald, M. T., 1969, Significance of stylolites in permeable sandstones: Journal of Sedimentary Petrology, v. 29, p. 251-253.
- Heirich, E. Wm., 1965, Microscopic identification of minerals: New York, McGraw-Hill, 414 p.
- Hsu, K. J., and Siegenthaler, C., 1969, Preliminary experiments and hydrodynamic movement induced by evaporation and their bearing on the dolomite problem: Sedimentology, v. 12, p. 11-25.

- Katz, A., 1971, Zoned dolomite Crystals: *Journal of Geology*, v. 79, p. 38-51.
- Kendall, A. C., 1976, The Ordovician carbonate succession (Bighorn Group) of southeastern Saskatchewan: Department of Mineral Resources, Saskatchewan Geological Survey Report 180, 185 p.
- Kendall, A. C., 1984, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: Discussion: *American Association of Petroleum Geologists Bulletin*, v. 68, p. 776-779.
- Kent, D. M., 1960, The evaporites of the Upper Ordovician strata in the northern part of the Williston Basin: Saskatchewan Department of Mineral Resources Report 46, 46 p.
- Kerr, S. D., and Thomson, A., 1963, Origin of nodular and bedded anhydrite in Permian shelf sediments, Texas and New Mexico: *American Association of Petroleum Geologists Bulletin*, v. 47, p. 1726-1732.
- Kohm, J. A., and Loudon, R. O., 1978, Ordovician Red River of eastern Montana and western North Dakota: Relationships between lithofacies and production: *Montana Geological Society Guidebook, Williston Basin Symposium*, p. 99-117.
- Longman, M. W., Fertal, T. G., and Glennie, J. S., 1983, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: *American Association of Petroleum Geologists Bulletin*, v. 67, p. 744-771.
- Longman, M. W., Fertal, T. G., and Glennie, J. S., 1984, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: Reply: *American Association of Petroleum Geologists Bulletin*, v. 68, p. 780-784.
- Lucia, F. J., 1972, Recognition of evaporite-carbonate shoreline sedimentation, in Rigby, J. K., Hamblin, W. K., (eds.), *Society of Economic Paleontologists and Mineralogists Special Publication 16*, p. 160-191.
- Lumsden, D. N., and Chimahusky, J. S., 1980, Relationship between non-stoichiometry and carbonate facies parameters, in Zenger, D. H., Dunham, J. B., Ethington, R. L., eds., *Concepts and Models of Dolomitization: Society of Economic Paleontologists and Mineralogists Special Publication 28*, p. 123-138.
- Mckenzie, J. A., Hsu, K. J., and Schneider, J. F., 1980, Movement of subsurface waters under the sabkha, Abu Dhabi, UAE, and its relation to evaporative dolomite genesis, in Zenger, D. H., Dunham, J. B., Ethington, R. L., eds., *Concepts and Models of dolomitization: Society of Economic Paleontologists and Mineralogists Special Publication 28*, p. 11-30.

- Murray, R. C., 1960, Origin of porosity in carbonate rocks: *Journal of Sedimentary Petrology*, v. 30, p. 59-84.
- Nelson, R. A., 1981, Significance of fracture sets associated with stylolite zones: *American Association of Petroleum Geologists Bulletin*, v. 65, p. 2417-2425.
- Oglesby, R. W., 1976, A model for the distribution of manganese, iron, and magnesium in authigenic calcite and dolomite cements in the Upper Smackover Formation in eastern Mississippi (M. A. thesis): Columbia, Missouri, University of Missouri, 122 p.
- Park, W. C., and Schot, E. H., 1968, Stylolites: their nature and origin: *Journal of Sedimentary Petrology*, v. 38, p. 175-191.
- Porter, J. W., and Fuller, J. G. C. M., 1959, Lower Paleozoic rocks of the Williston Basin and adjacent areas: *American Association of Petroleum Geologists Bulletin*, v. 43, p. 124-189.
- Ruzyla, K., 1980, The relationship of diagenesis to porosity development and pore geometry in the Red River Formation (Upper Ordovician) Cabin Creek field, Montana (Ph. D. thesis): Troy, New York, Rensselaer Polytechnic Institute, 200 p.
- Sinclair, G. W., 1959, Succession of Ordovician rocks in southern Manitoba: *Geological Survey of Canada Paper* 59-5, 9 p.
- Sommer, S. E., 1972, Cathodoluminescence of carbonates, I. Characteristics of cathodoluminescence from carbonate solid solution: *Chemical Geology*, v. 9, p. 257-273.
- Weyl, P. K., 1960, Porosity through dolomitization-conservation-of-mass-requirements: *Journal of Sedimentary Petrology*, v. 30, p. 85-90.
- Wittstrom, M. D., and Chimney, P. C., 1980, Proposed model for development of Red River (Ordovician) porosity, eastern Montana and western North Dakota (abs): *American Association of Petroleum Geologists Bulletin*, v. 64, p. 804-805.
- Zenger, D. H., 1972, Dolomitization and uniformitarianism: *Journal of Geological Education*, v. XX, p. 107-124.

APPENDICES

APPENDIX A

EXPERIMENTAL PROCEDURES

APPENDIX A

Evaluation of the impact of depositional environment, original porosity and permeability, diagenetic history, and paleostructure on the porosity distribution in the "C" laminated member necessitated demonstrating a relationship between these processes or factors and porosity variations within the above member. To determine if such relationships existed in the "C" cycle, research was focused on 1) detailed lithologic examination and 2) subsurface mapping.

Lithologic Examination

Eight core from the "C" cycle were examined to determine gross lithology for each "C" cycle member. In addition to the initial examination, each core was sampled in order to make thin sections which were examined with the petrographic microscope. The laminated member was sampled at 0.6 meter intervals in three well preserved core and at 0.9 to 1.5 meter intervals in the remaining cored wells. The anhydrite and burrowed members were selectively sampled. Thin section analysis was used in conjunction with the initial core examination to place each sample into a textural category using the Dunham classification system and to aid in interpreting the depositional environment and diagenetic history. To determine the extent of dolomitization, one half of each slide was stained with Alizarine Red S using the procedures described by Friedman (1959) (Appendix B). The stain was very effective on the more coarsely crystalline samples from the burrowed member but was ineffective in distinguishing between calcite and dolomite in the finely crystalline samples from the

laminated member. Alternative methods for determining the extent of dolomitization were 1) observing the relative reaction rate of 10% HCL on each sample, and 2) etching each sample and thin section in 10% HCL. There are two reasons for determining the amount of dolomite present in each sample; 1) to identify beds within the "C" cycle which resisted dolomitization so as to determine why they are more resistive and 2) to discern general trends in dolomitization.

To supplement the petrographic analysis, a select number of thin sections and rock samples were examined with the scanning electron microscope (SEM). This allowed the submicroscopic textures of "porous" and "nonporous" dolomite to be observed and used in comparing the dolomite textures.

Cathodoluminescence (CL) was also used to further compare low porosity dolomite with high porosity dolomite. If compositional differences exist between the dolomites, CL is useful to demonstrate the differences. The operating conditions for the luminoscope are listed in Appendix C.

Another characteristic of the dolomite types investigated was the content (weight percent) of insoluble residue (IR). Ten samples from the laminated member were digested in 12% HCL and the percent IR by weight was determined for each sample. The procedure used to digest the samples and to determine the percent IR is listed in Appendix B.

Dolomite stoichiometry was determined for several samples of the "porous" and "nonporous" dolomites using the x-ray diffraction techniques given by Blatt and others (1980) and Lumsden and Chimahusky

(1980). The operating conditions for the x-ray diffractometer are given in Appendix C.

Subsurface Mapping

Mechanical logs from the Brush Lake field were used to obtain elevations for formation tops which were required to generate structure and isopach maps. The logs were also used to construct a stratigraphic cross section. Collectively these maps and the cross section were used to determine 1) the fields present day structural configuration, 2) the paleostructural development for the field, and 3) the distribution of economically significant porosity. From these determinations it could be established whether a relationship exists between present day or paleostructure and the distribution of porosity.

APPENDIX B

PROCEDURE FOR STAINING

AND

EXTRACTING INSOLUBLE RESIDUE

APPENDIX B

- A) Recipe for alizarine red S (after Friedman, 1959).
- 1) 0.1 gram of alizarine red dissolved in 100 cc of 0.2% cold hydrochloric acid.
- B) Staining Procedure.
- 1) One half of each thin section immersed in stain for 2 minutes.
 - 2) Excess stain rinsed from the thin section with deionized water.
- C) Procedure used to determine percent insoluble residue (IR). (modified from Ellingbow and Wilson, 1964).
- 1) Sample is crushed.
 - 2) Sample is soaked in Tetrahydrofloran (THF) for 12 to 24 hours to remove excess hydrocarbons.
 - 3) THF plus excess hydrocarbons are decanted.
 - 4) Sample is air dried to evaporate the remaining THF.
 - 5) Sample is dried for 2 hours at 105 degrees centigrade.
 - 6) Sample is weighed.
 - 7) Sample is immersed in 12% hydrochloric acid (HCL) until carbonate minerals are completely digested.
 - 8) The spent HCL is decanted and the remaining residue is rinsed with deionized water.
 - 9) Insoluble residue is removed by filtration (using predried and preweighed filter paper).
 - 10) Insoluble residue and filter paper are dried for 2 hours at 105 degrees centigrade.
 - 11) Insoluble residue and filter paper are weighed (IR) and filter weight - filter = insoluble weight).
 - 12) Percent insoluble residue calculated using the following equation:
$$\%IR = \text{Weight IR} / \text{Weight of original sample} \times 100.$$

APPENDIX C

OPERATING CONDITIONS

FOR THE

LUMINOSCOPE AND X-RAY DIFFRACTOMETER

APPENDIX C

- A) Cathodoluminescence operating conditions. (Instrument: Nuclide Corporation Luminoscope)
- 1) Chamber pressure = 50 millitor.
 - 2) Bean size = 5 to 20 millimeters.
 - 3) Accelerating voltage = 20 kilovolts.
 - 4) Beam current = 0.6 to 1.0 milliamps.
- B) X-Ray Diffractometer operating conditions.
- 1) 18 Ma.
 - 2) 45 KVP.
 - 3) Range 1000, 2000, 5000 CPS.
 - 4) Time constant 2.0.
 - 5) Angle Range (~~20~~) = 28 to 32 degrees.
 - 6) Copper target.

APPENDIX D

WELL DATA

APPENDIX D

WELL LOCATION	WELL	KB	Cgh	Mb	Dp top	Da base
------------------	------	----	-----	----	-----------	------------

T.33N R. 58E

Sw Nw 1	Ibsen 2-1	2056	3685	8654	9911	10190	10338
Nw Sw 1	Melby 4-1	2038	3685	8647	9906	10190	10340
Se 2	Melby 4-1	2028	3667	8638	9896	10180	10324
Ne 11	Melby 3-1	2022	3664	8646	9898	10183	10332
Se 11	Sorenson 1	2039	3692	8680	9932	10220	10366
Nw 12	Sorenson 1	2041	3696	8666	9920	10212	10354
Nw 13	Dahl 1	2028	3710	8686	9930	10210	10352
Nw 14	Thuesen 1	2029	3710	8720	9964	10246	10391

T.34N R. 58E

Sw 36	State 1	(1983)
Nw 36	State 2	(2046)

WELL LOCATION	WELL	Orr top	Orr "C" An base	Orr "C" Lam base
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T.33N R. 58E

Sw Nw 1	Ibsen 2-1	11186	11316	11341
Nw Sw 1	Melby 4-1	11150	11275	11300
Se 2	Melby 4-1	11176	11304	11330
Ne 11	Melby 3-1	11163	11294	11318
Se 11	Sorenson 1	11184	11314	11338
Nw 12	Sorenson 1	11179	11307	11332
Nw 13	Dahl 1	11176	11304	11328
Nw 14	Thuesen 1	11238	11370	11395

T.34N R. 58E

Sw 36	State 1		11283	11310
Nw 36	State 2	11096	11223	11245

LEGEND

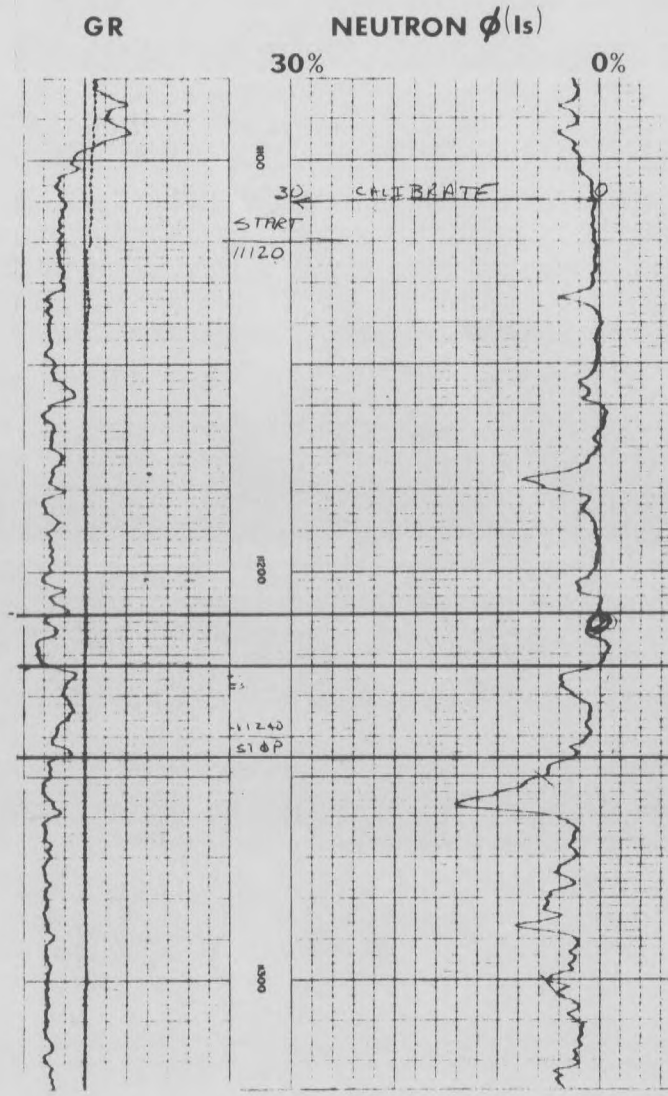
KB = Kelly Bushing Elevation
 Cgh = Cretaceous Greenhorn Fm.
 Mb = Mississippian Bakken Fm.
 Dp = Devonian Prairie Evaporite
 Da = Devonian Ashern Fm.
 Orr = Ordovician Red River Fm.

"C" An = "C" Anhydrite Member
 "C" Lam = "C" Laminated Member

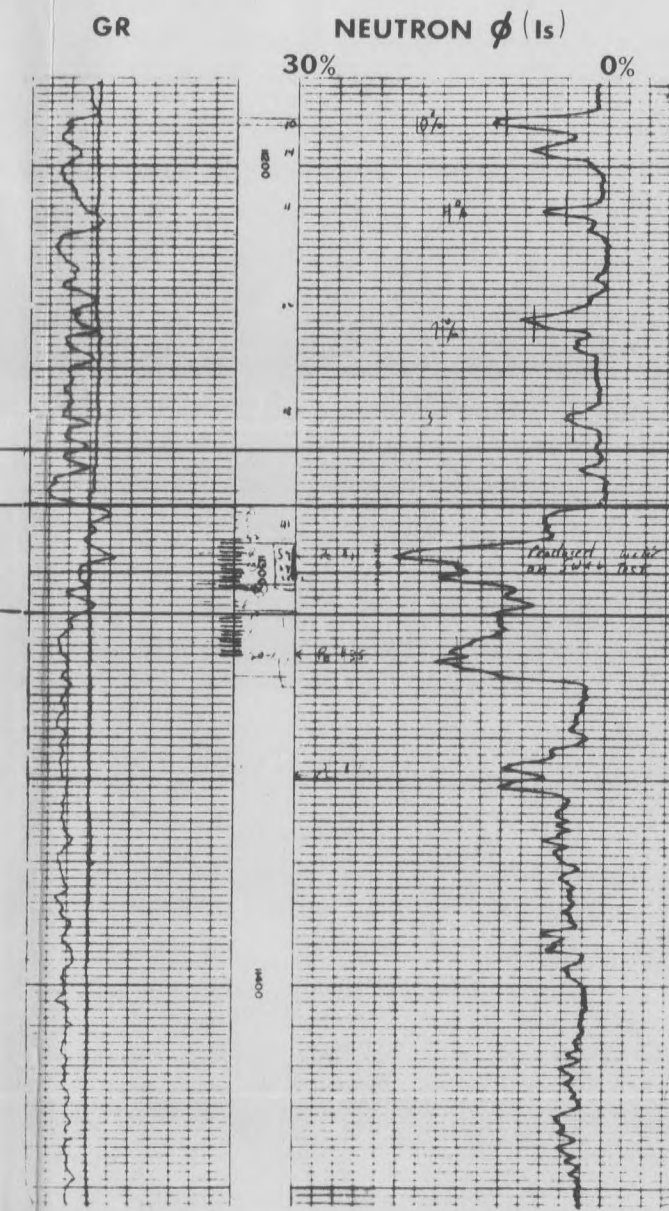
NOTE: All elevation measured
 in feet.

NORTH

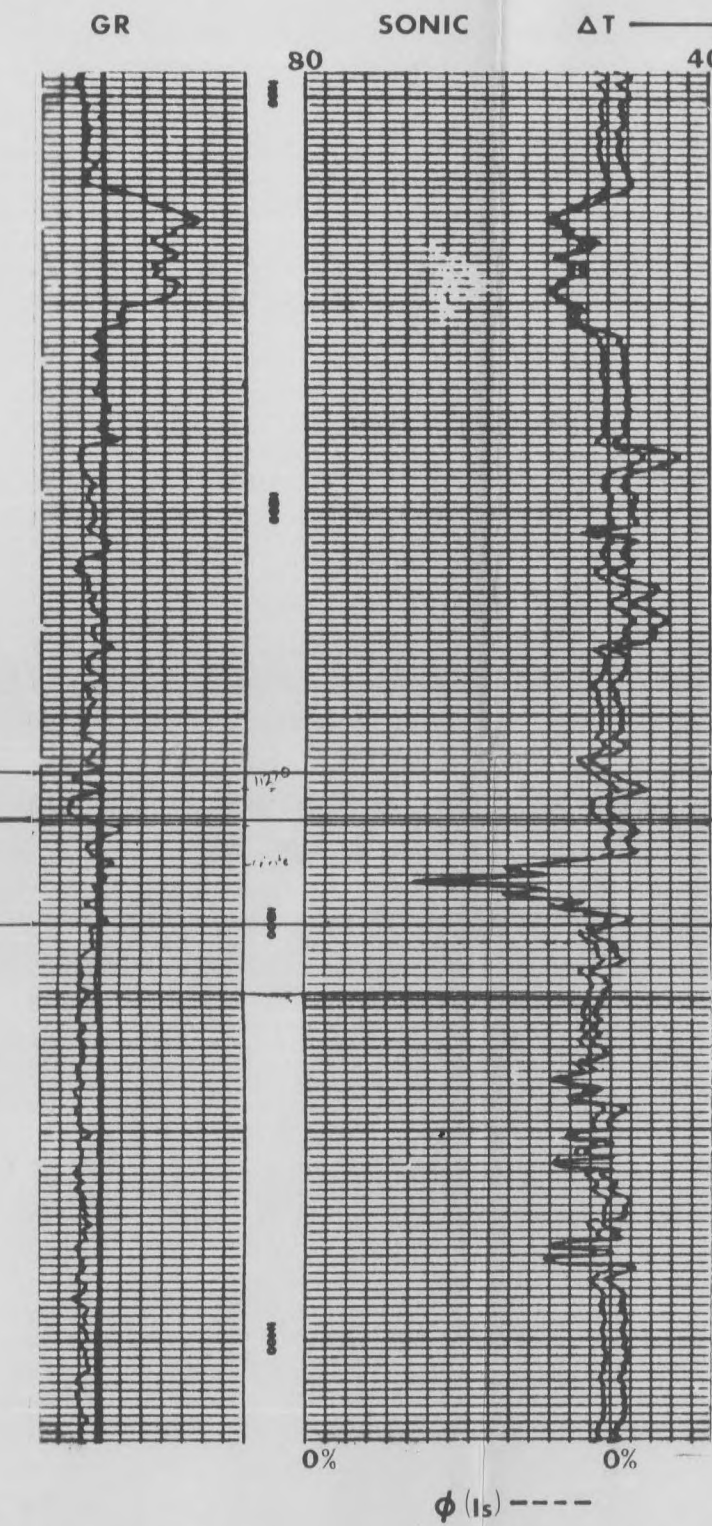
Chevron
STATE 2
NW 36 T34N R58E
SIDEWALL NEUTRON



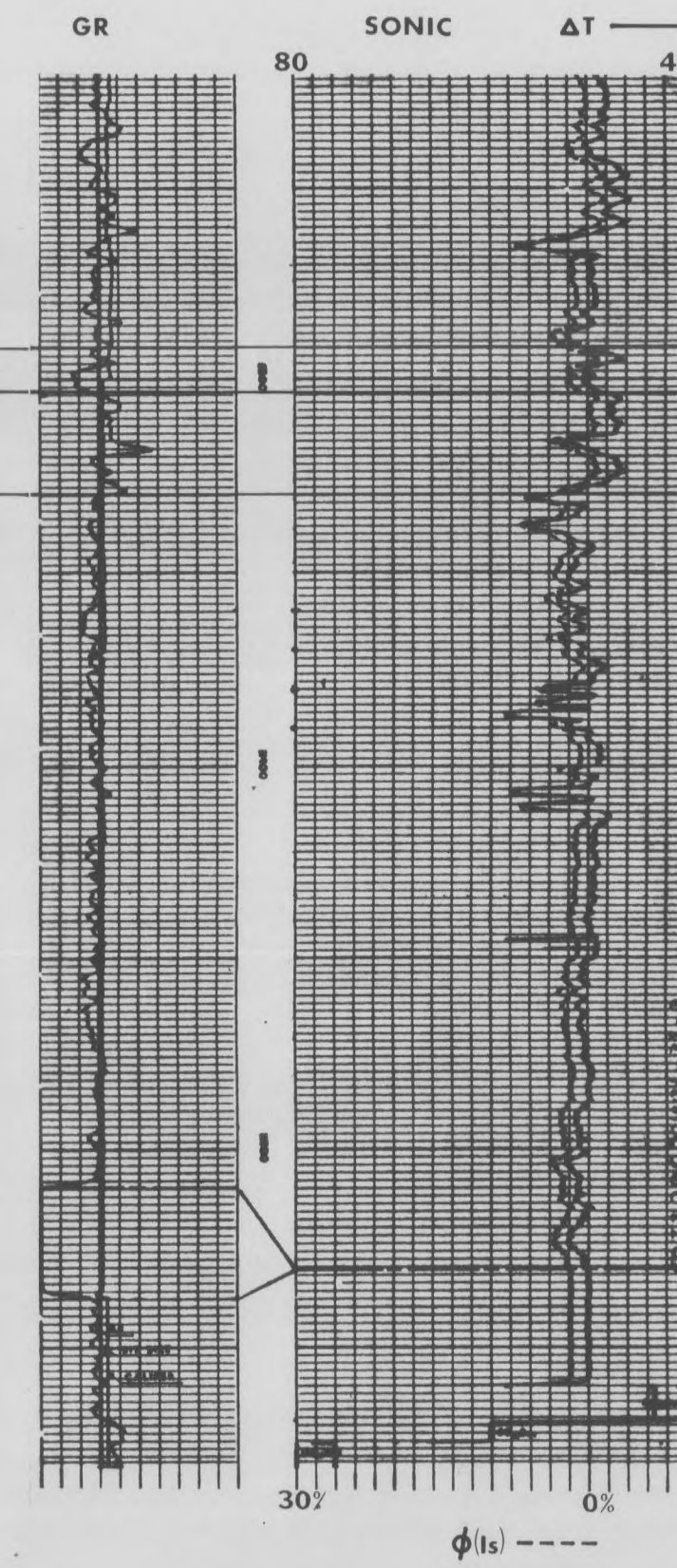
Chevron
STATE 1
SW 36 T34N R58E
SIDEWALL NEUTRON



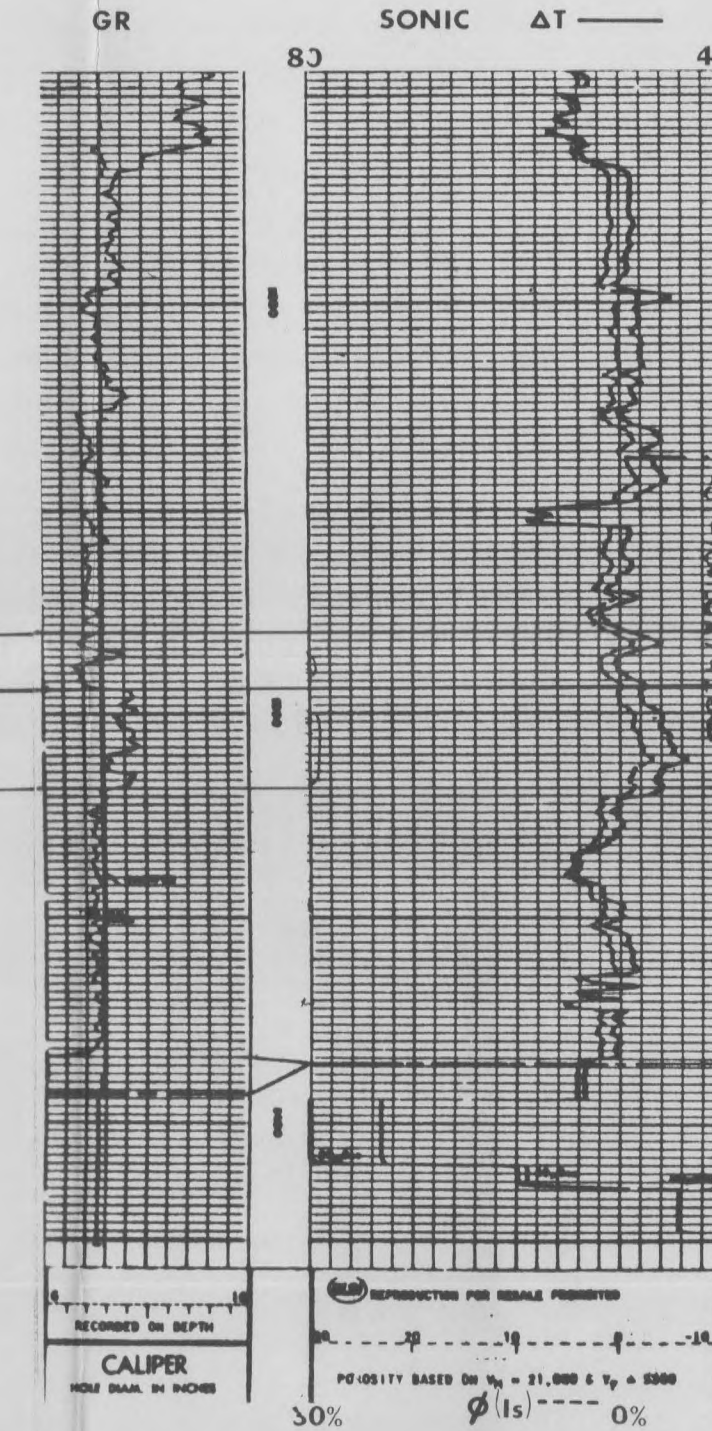
Chevron
MELBY 4-1
NW 5W 1 T33N R58E
SONIC



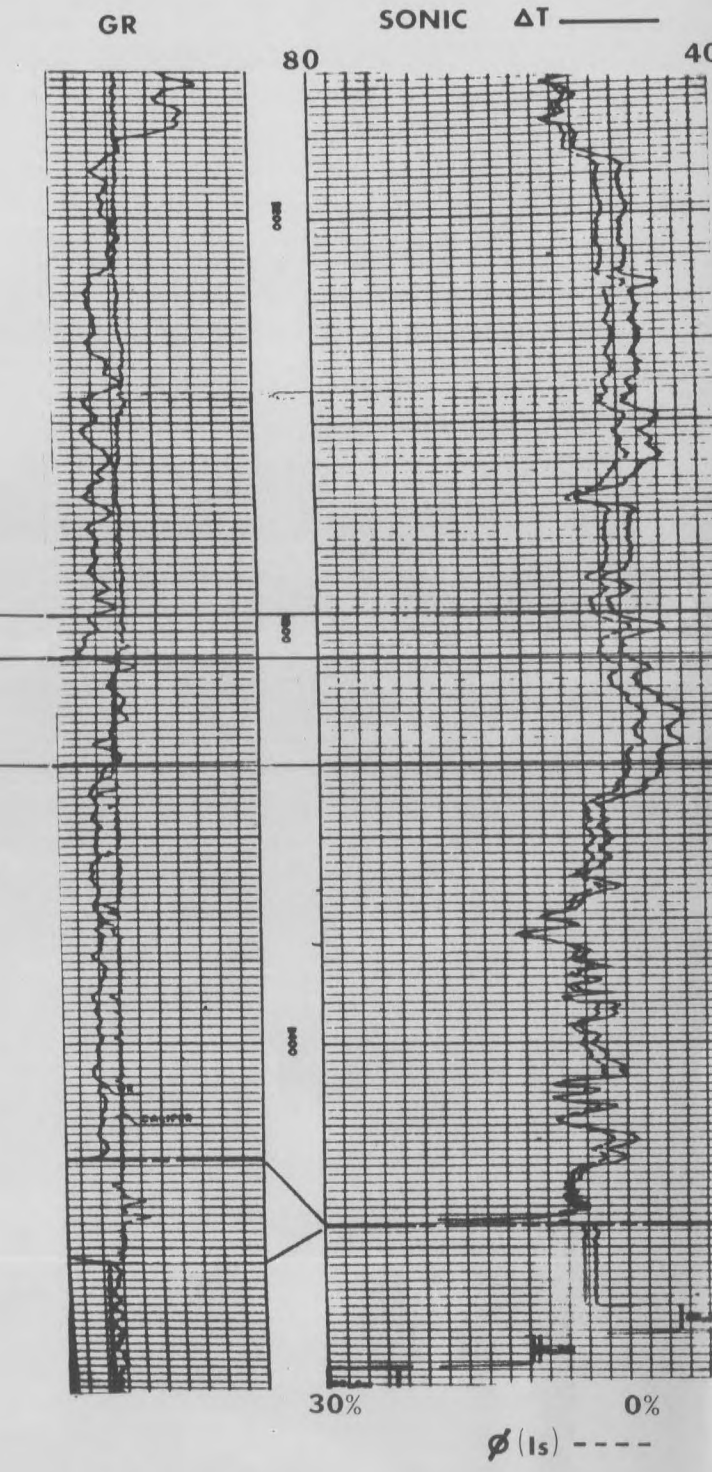
Chevron
MELBY 4-1
SE 2 T33N R58E
SONIC



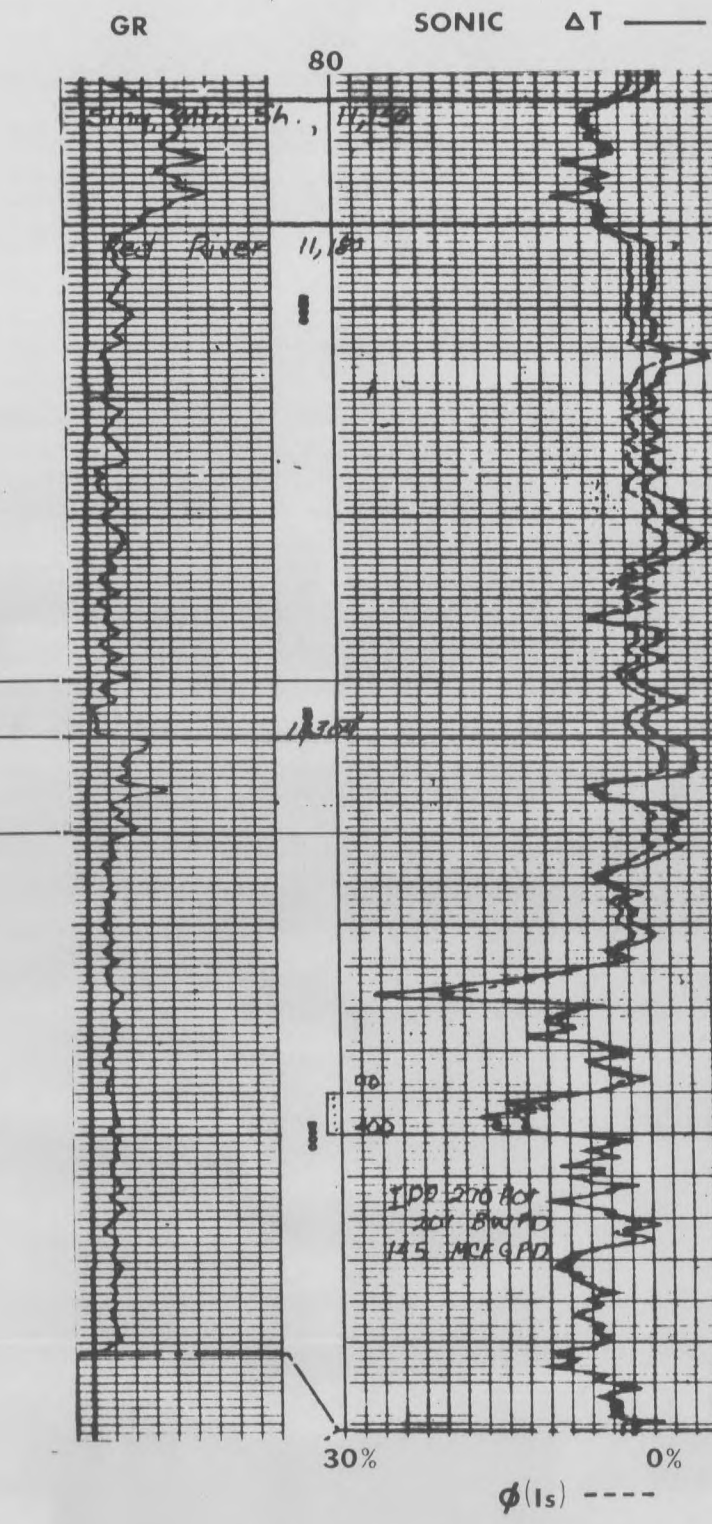
Chevron
MELBY 3-1
NE 11 T33N R58E
SONIC



Chevron
SORENSEN 2-1
NW 12 T33N R58E
SONIC

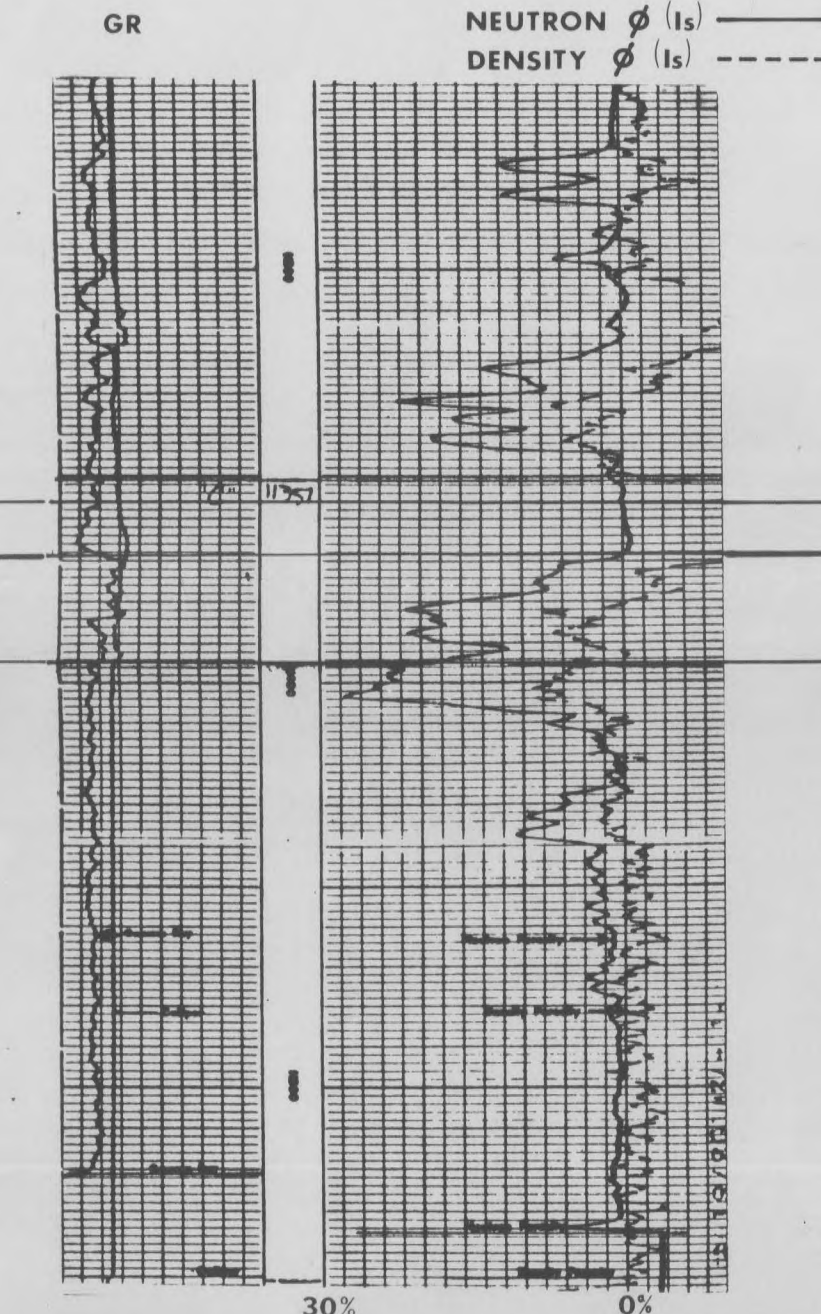


Chevron
DAHL 1
NW 13 T33N R58E
SONIC



SOUTH

Chevron
THUESSEN 1
NW 14 T33N R58E
CNFD

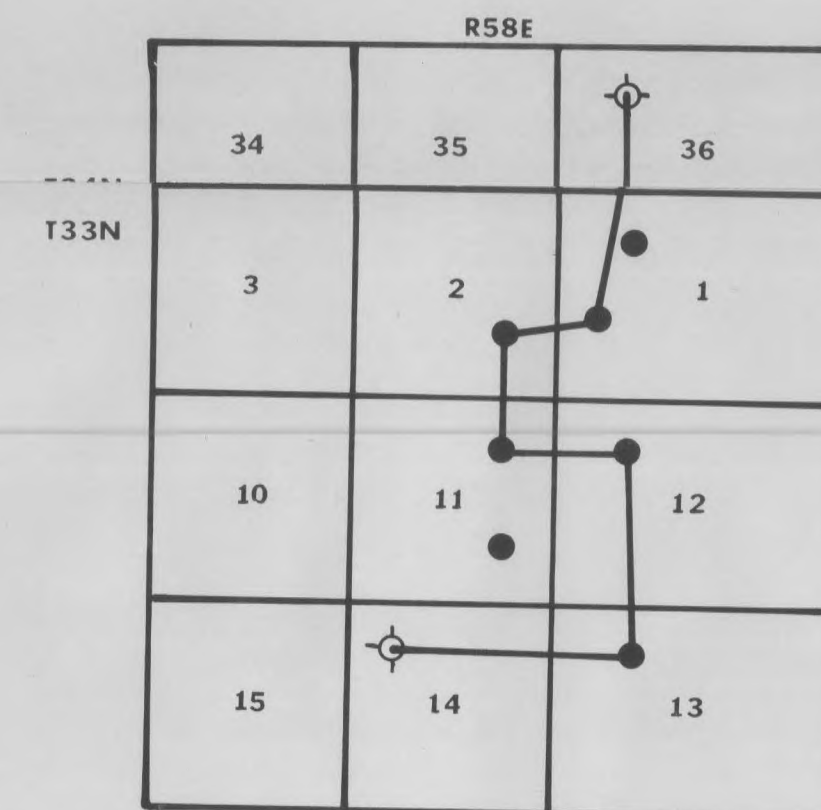


C Anhydrite Member
C Laminated Member
C Burrowed Member

VERTICAL SCALE
50 FEET

HORIZONTAL SCALE
0 1/2 MILE 1

PLATE 1
STATIGRAPHIC CROSS SECTION
DATUM: "C" ANHYDRITE BASE



A standard 1D barcode with vertical black bars of varying widths on a white background, used for library identification and tracking.

3 1762 10015571 0

N378
St55
c.2

Stimson, J. R.
Control and distribution of porosity...

[illegible]