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STRATIGRAPHY, FACIES, EVOLUTION AND DIAGENESIS
OF PRODUCTIVE NIAGARAN GUELPH REEFS AND CAYUGAN
SABKHA DEPOSITS, THE BELLE RIVER MILLS GAS
FIELD, MICHIGAN BASIN.

The University of Michigan, Ph.D., 1973
Geology

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**STRATIGRAPHY, FACIES, EVOLUTION AND DIAGENESIS OF
PRODUCTIVE NIAGARAN GUELPH REEFS AND CAYUGAN SABKHA
DEPOSITS, THE BELLE RIVER MILLS GAS FIELD, MICHIGAN BASIN**

**by
Dan Gill**

**A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Geology)
in The University of Michigan
1973**

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In memory of my father,
Baruch M. Gill (1902-1970),
and Yaakov ("Hubi") Eilam
who fell in the battle for Jerusalem,
June 1967.

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INTRODUCTION

Purpose of Investigation

Silurian formations contribute a significant and increasing amount to the production of hydrocarbons in Michigan. Since 1962 they accounted for over half of the state's natural gas production. With the continuous exploitation and depletion of the prolific Devonian oil reserves and the Mississippian gas fields, and the decline in their future development potential, the role of the largely unexplored Silurian resources becomes all the more important. To date, more than 60 Silurian oil and gas fields have been discovered. Most of the fields are associated with reef buildups of Niagaran (Middle Silurian) age. St. Clair and Macomb counties, in the southeastern part of the state, are the most heavily drilled areas, where most of the productive structures have been found. Their proximity to large urban and industrial centres, their shallow depth (2000 to 3000 ft.) and their effective petroleum seal by overlying and flanking impervious evaporites make the reefs ideal for underground gas storage. In recent years, similar reefs have been the target for an extensive exploration program in the northern part of the Lower Peninsula of Michigan. Since August 1969, several new fields have been discovered in this area (Ells, 1970; Ells and Champion, 1972).

The need for adequate reservoir data prompted an extensive coring program which entails the entire reef section as well as potential pay zones within the flank-off-reef carbonates. Full diameter petrophysical core analysis and well surveying by radioactive logging methods in potential gas reservoirs are a standard procedure. A wealth of stratigraphic, lithologic and reservoir engineering data is thus provided for detailed integrated studies of individual reef complexes.

In addition to their economic importance, the Niagaran reefs afford material for exploring questions and concepts of general geological interest. These include such topics as reef evolution and paleoecology, interpretation of ancient carbonate and evaporite environment, modes of dolomitization and diagenesis of carbonates, as well as of petroleum origin, migration and entrapment and reservoir modeling.

The juxtaposition of organic reefs with off-reef evaporite sediments, as it exists in the Silurian of Michigan, is known from other areas and other parts of the geologic column. This association of incompatible sedimentary facies presents an enigmatic stratigraphic and sedimentologic problem which is widely debated in the literature.

The present study is an attempt to provide a detailed account of the geology of a typical Niagaran reef in the subsurface of the southeastern part of the Michigan basin represented by the Belle River Mills reef gas field. Its prime objective is to reconstruct the growth and depositional history of the reef and its surrounding strata by means of lithofacies analysis. Within this framework more specific objectives include identification of discrete growth stages in the reef's evolution, reconstruction of the environmental interpretation of the off-reef formations, stressing sedimentary fabrics and textures in anhydrite and in laminated carbonates and their environmental significance. Additional objectives include the time of, and stratigraphic relationships between, the organic buildup and its flanking carbonate-anhydrite cycles, diagenesis of the reef and its stratigraphic significance, and the petroleum geology aspects of the structure.

Despite their economic importance, comprehensive lithofacies studies of the reefs and their surrounding strata have thus far not been emphasized. Of the numerous studies devoted to the Silurian of the subsurface of Michigan and Ontario, only two (Felber, 1964; Hill, 1968) contain detailed illustrated petrographic data. One of the purposes of the present study is to provide a pictorially documented lithofacies "atlas" which will serve as a reference for future studies.

The evaluation of the spatial distribution of reservoir properties, as based on data available from core analysis, presents an analytical and methodological problem. Part of this study was devoted to the development of a quantitative method for the zonation of ordered data sets as a means for data reduction in multi-well studies, in order to facilitate the use of core analysis data in three-dimensional reservoir modeling (Gill, 1969, 1970).

The Belle River Mills Field

Regional Setting

Geographically, the Michigan basin, roughly circular in shape and covering an area of 122,000 square miles, encompasses the lower and upper peninsulas of Michigan and the adjacent parts of the bordering states of Wisconsin, Illinois, Indiana, Ohio and the province of Ontario, Canada. Tectonically, it is an intracratonic depression bounded by the following positive tectonic elements (King, 1957; Cohee and Landes, 1958, Fig. 1): on the north and northeast by the Canadian Shield in Ontario; on the east by the Algonquin Arch in Ontario; on the southeast by the Findlay Arch in northwestern Ohio; on the southwest by the Kanikakee Arch in Indiana and northeastern Illinois and on the west by the Wisconsin Arch in eastern Wisconsin. The stratigraphic column, ranging in age from Cambrian to Pennsylvanian, reaches an estimated total thickness of about 14,000 feet in the central part of the basin (Clare County west of Saginaw Bay).

Surface exposures of Silurian rocks appear all around the Michigan basin (Lowenstam, 1950, Fig. 11). The reefoid nature of much of these outcrops has been extensively discussed and documented in the literature.¹ In fact, it is of interest to note that Chamberlin's (1877) description of Silurian reefs in Wisconsin is probably one of the first detailed accounts of ancient reefs in North America (Ingels, 1963, p. 405). Reefs, bioherms, biostromal beds and inter-reef and related facies are present at various stratigraphic levels within the Niagaran series. The rock units displaying these facies have been assigned different names in different areas, and their exact time correlation is somewhat controversial. However, the Guelph dolomite of Ohio, the Huntington dolomite of Indiana, the Fort Byron and Racine dolomite of Illinois,

¹Only selected, more recent or "classical" references are listed below. Each should be consulted for a more extensive bibliography. In Indiana: Sangree, 1960; Pinsak and Shaver, 1964; Carozzi, 1962; Textoris and Carozzi, 1964; Textoris, 1966; Cumings and Shrock, 1928. In Ohio: Summerson, 1963; Textoris and Carozzi, 1966; Kahle and Floyd, 1968. In Ontario: Liberty and Bolton, 1956; Liberty, 1968. In Illinois: Willman, 1962; Ingels, 1963; Lowenstam, 1948. In Wisconsin: Shrock, 1969; Soderman and Carozzi, 1963; Chamberlin, 1877. In Michigan: Sheldon, 1961, 1963; Ehlers and Kesling, 1957, 1962. General, regional papers: Lowenstam, 1950, 1957.

the Guelph and Racine dolomite of Wisconsin, the Guelph-Lockport of Ontario, and the Engadine dolomite of northern Michigan (Pinsak and Shaver, 1964, Fig. 3; Sharma, 1966, Fig. 1b) represent the correlative development of an intricate carbonate bank and reef complex during Middle Silurian times. This reefal buildup resulted in the formation of a physiographic barrier along the entire circumference of the Michigan Basin (Fig. 1-1) which controlled the sedimentary framework during the subsequent deposition of the Cayugan (Upper Silurian) evaporite and carbonate cycles (Alling and Briggs, 1961).

With reference to the economic importance of the Niagaran carbonates, oil seeps are known to this author at three localities, and heavy asphalt staining can be observed in the outcrop. Seeps and stains occur at Maumee, Ohio (Maumee Stone Company Quarry) where a well-developed algal stromatolite mound is exposed. The lowermost two units (Textoris and Carozzi, 1966) are practically saturated with heavy oil which seeps out from between algal laminae, vugs and open karstic cavities, some up to several inches and even feet in diameter, which coat the quarry walls like a black paint. Similar features can be observed in the Monon Quarry (Crushed Stone Company, Inc.), northwestern Indiana, and to a lesser extent in Logansport Quarry (Cass County Stone Company), Indiana.

In the subsurface, Silurian rocks are present throughout most of the Michigan basin. They dip gently towards the basin center where they attain an estimated thickness of 4000 feet. In contrast to the general isopach pattern which shows consistent thickening of rock units towards the basin center throughout the stratigraphic column, rocks of Middle Silurian age are thickest along the basin margin (Ells, 1967, p. 4; Burgess and Benson, 1969, section 2, Fig. 2; Cohee, 1948, Fig. 9). These fringing arcuate belts of thick Niagaran sections² represent the subsurface extension of the

²The Niagaran (Middle Silurian, time-stratigraphic series name) section is composed of interfingering non-reef and reefal carbonates. No satisfactory or uniformly used rock-stratigraphic nomenclature has been established to accommodate these facies variations. In the subsurface of southeastern Michigan, the carbonate section between the Clinton shale and the A-1 evaporite is commonly referred to as Niagara Group (following Cohee, 1948) or "Niagaran" and this terminology is used here. A further discussion of stratigraphic nomenclature is offered in Chapter II.

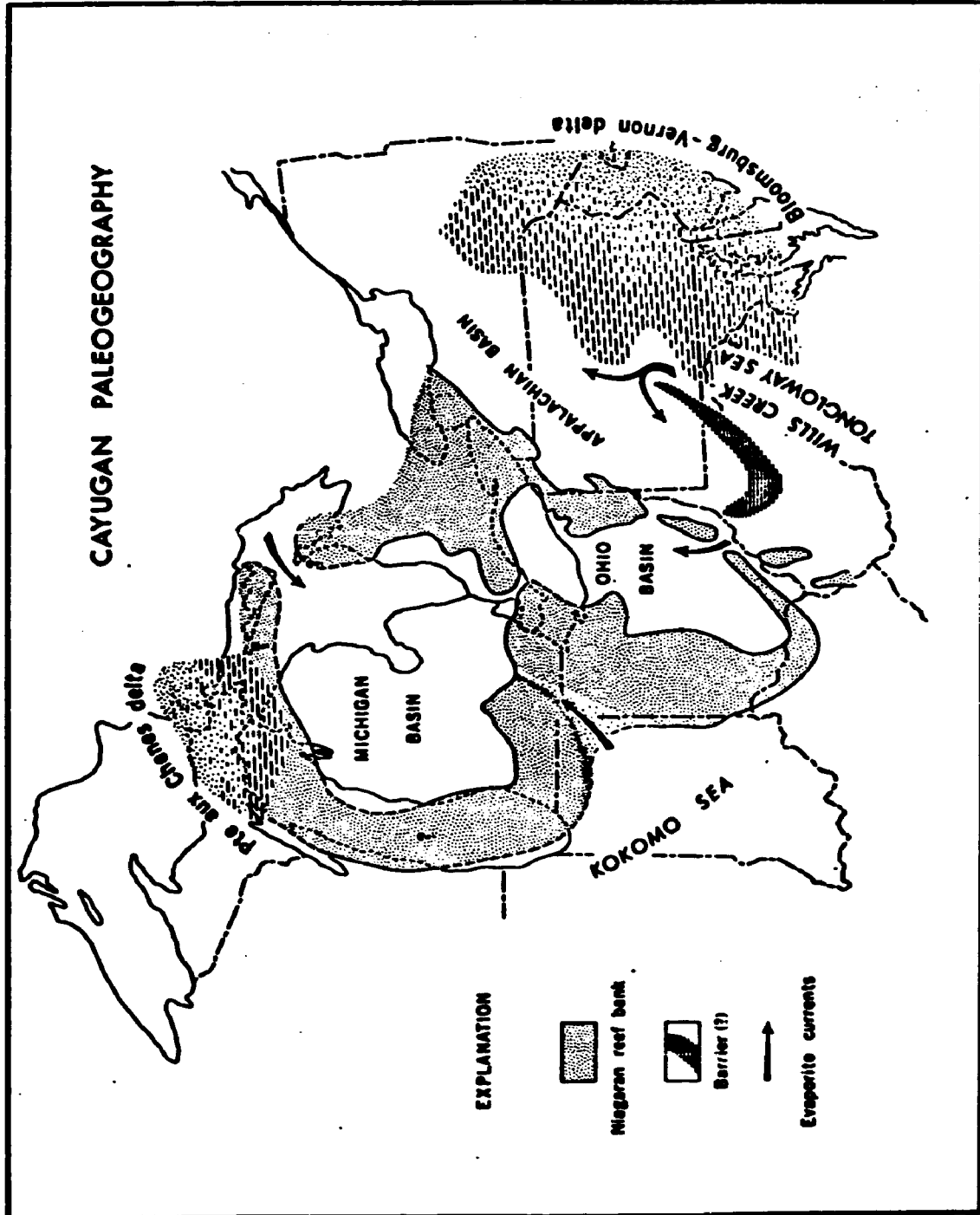


Fig. 1-1. Michigan basin Cayugan (Upper Silurian) paleogeography (after Alling and Briggs, 1961).

exposed reef complexes described earlier.

The progressive, gradual deepening basinward is expressed in both the thickness and the lithologic aspects of the Niagaran carbonates. From the basin center outward three broad circumjacent depositional belts, arranged in an almost concentric pattern, can be recognized (Figs. 1-2 and 1-3; Burgess and Benson, 1969; Pounder, 1962):

A. deeper basin area - 80' to 100' of light gray and brown, dense crinoidal biomicritic limestones and dolomites with reddish and pink mottling and some shaly parting;

B. shelf area - the section thickens gradually outwards from 100' to 300'. It consists of skeletal (crinoidal, bryozoan, and brachiopod) dolomitized wackestones, grading in places to limestone basinward. On the basis of color changes the section is divisible into a lower "white Niagaran", middle, more argillaceous and locally cherty "gray Niagaran" and upper "brown Niagaran". Localized small scale biohermal masses are recognized throughout the section and are most prominent in the upper part. Based on their size and on the thickness of the underlying Niagaran section, the area is further divisible into an inner minor shoal belt, central pinnacle reef belt and outer transitional patch reef belt (Fig. 1-3; Koepke and Sanford, 1966, Fig. 45), which coincides peripherally with part of the carbonate bank area;

C. carbonate bank area - the Niagaran section reaches its maximum thickness (500') in Ontario (Evans, 1950) and an estimated 900' in the Northern Peninsula (Cobee, 1948). It is characterized by biostromal beds in the lower part and by a continuous biohermal growth activity through the rest of the section.

The three-fold division into a concentric arrangement of depositional belts is a reflection of a continuous increase in the rate of tectonic subsidence basinward. The carbonate bank and part of the patch reef belt coincide with the more stable tectonic arches defining the basin periphery. Here, rate of subsidence is slow and organic activity can spread laterally resulting in buildups of relatively large areal, rather than vertical, extent. The upper shelf, characterized by moderate rates of subsidence, develops small patch reefs whereas in the lower shelf, organic activity has to compete with accelerated subsidence, thereby forming "pinnacles" - very tall but areally small reefs. Ellis observed (1967, p. 18) that reefs farthest in the basin tend to be taller and have smaller areal extent. Subsidence was fastest in the basin center which was too deep to permit reefal development.

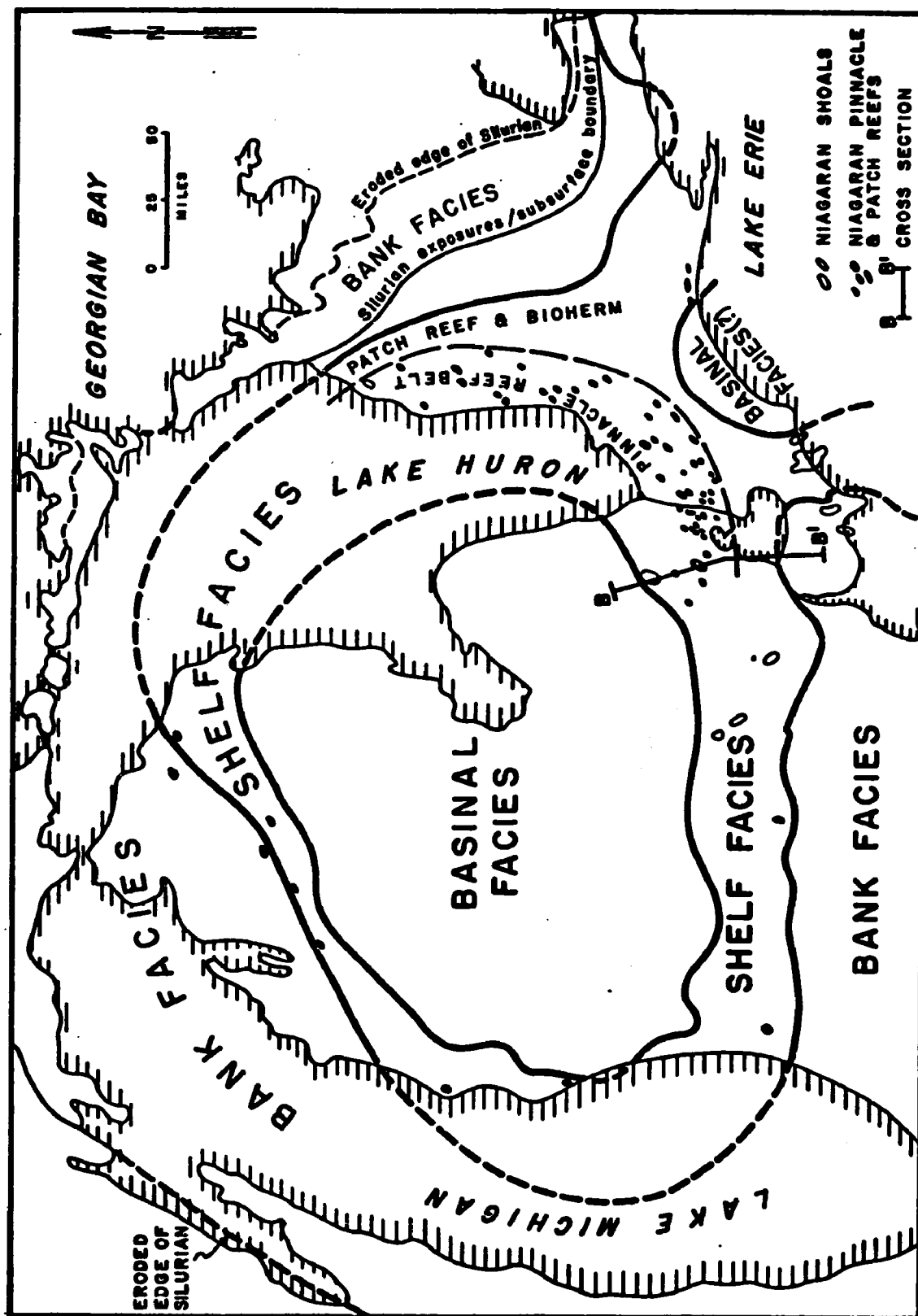


Fig. 1-2. Distribution of major Niagaran carbonate facies in the subsurface of the Michigan basin (modified from Burgess and Benson, 1969).

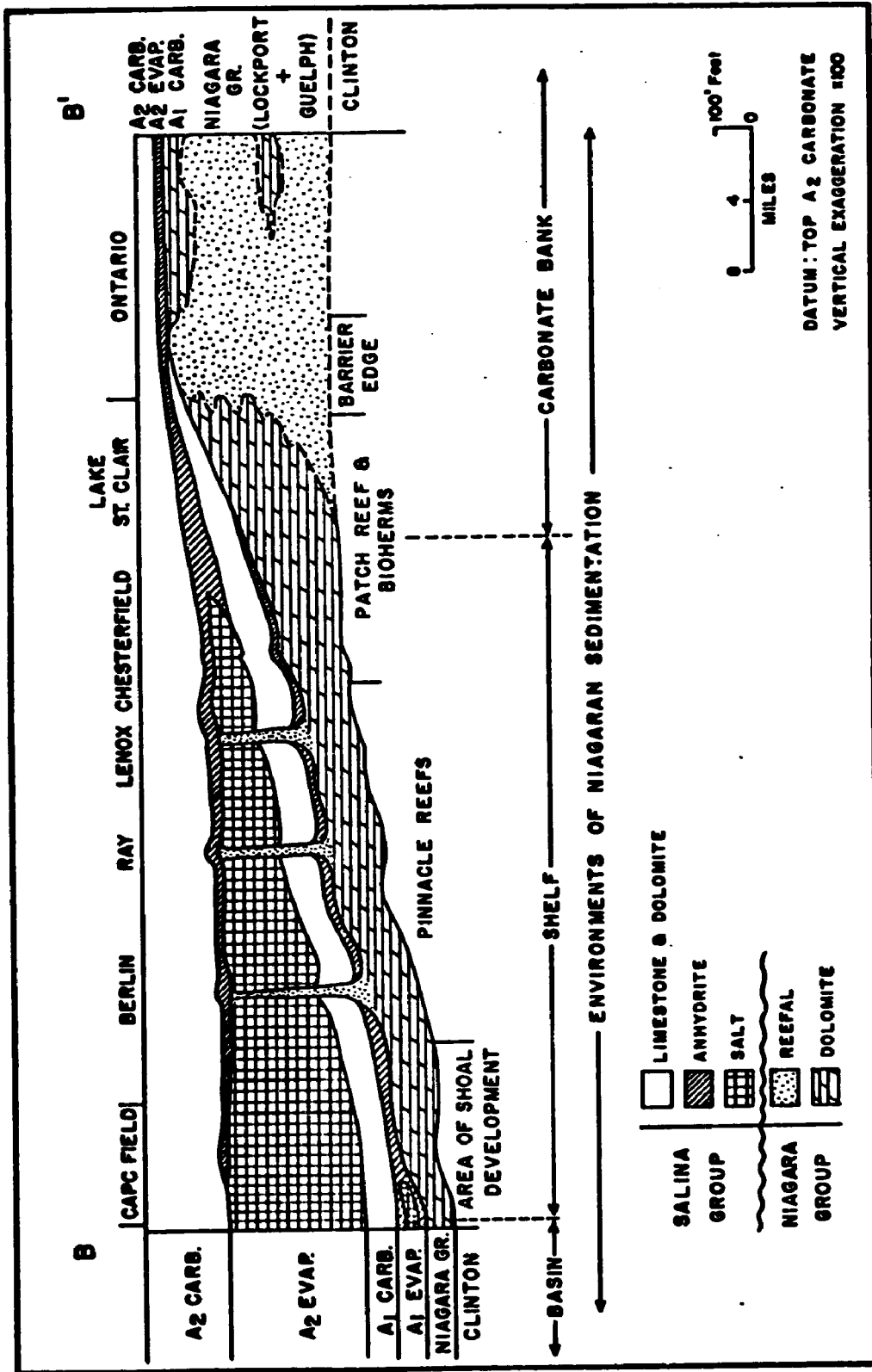


Fig. 1-3. North-south stratigraphic and facies section of the Niagara and Lower Cayuga Formations across pinnacle reefs area showing the environments of Niagaran sedimentation (line B-B', Fig. 1-1; modified from Burgess and Benson, 1969).

Unique to the shelf area is the development of isolated "pinnacle" reef masses which rise to a height of up to 500' above the regional Niagaran surface. The reefs vary in size from less than 100 acres to over 1200 acres, and most have a basal area of less than 500 acres. A predominant number are elliptical in outline and elongated northeasterly, although some smaller reefs are roughly circular in shape. The term "pinnacle" was applied to the reefs owing to their isolation, high relief and small areal extent³ (Fig. 1-3). Our knowledge of the distribution of this type of reef depends largely on density of wells. The close spacing of wells in southeastern Michigan and southwestern Ontario has led to a better understanding of the distribution of the reefs (by the end of 1967, a total of 1104 wells were drilled in St. Clair County, which amounts to about one well per square mile (Ells, 1968)). In this region, pinnacle reefs are localized within a relatively narrow arcuate belt which extends along the Canadian shores of Lake Huron and westward into Michigan (Fig. 1-2). Over 80 reefs are scattered along this trend, 40 of them in Ontario, 23 productive (Koeple and Sanford, 1966, p. 2) and 40 in St. Clair and Macomb Counties, Michigan, 34 productive (Fig. 1-4). The Belle River Mills reef is among the larger in this area. On the basis of geological considerations, the scattered presence of additional reefs outside the two counties mentioned⁴, very likely favorable conditions existed for the development of similar reefs farther westward along the entire southern rim of the basin. The shelf belt along the northern part of the southern peninsula as well as its extensions into the water-covered areas in Lakes Michigan and Huron (Fig. 1-2) are additional potential prospects for reefs of this type. Recent drilling in this area found production in what might be considered the northern analog of both the bank and patch reef environments and the pinnacle reef belt of the southern rim.⁵ However, the regional Niagaran surface

³Shouldice (1955) defines pinnacle reefs as those structures having a height of over 250' and a length of less than two miles.

⁴Leonard, Okland Co.; Northville, Washtenaw Co.; Patello and the four one-well Cal-lee reefs, Calhoun Co.; Fowlerville, Livingston Co.; Romulus, Wayne Co.; East Pullman, Allegan County.

⁵The Onaway field, Presque Isle County and the Tecon Lake field, Otsego County, are situated on the edge of the bank. In the shelf belt basinward, from east to west (Fig. 1-2) the following six pinnacle reefs have so far been discovered: McClure Ristow no. 1; Murrell Welch et al. Otsego-Chester state no. 1; Cold Springs; South Boardman; Hamlin (Maslin County) and Montague (Muskegon County). All but the first are productive (Burgess and Benson, 1969; Ells, 1970).

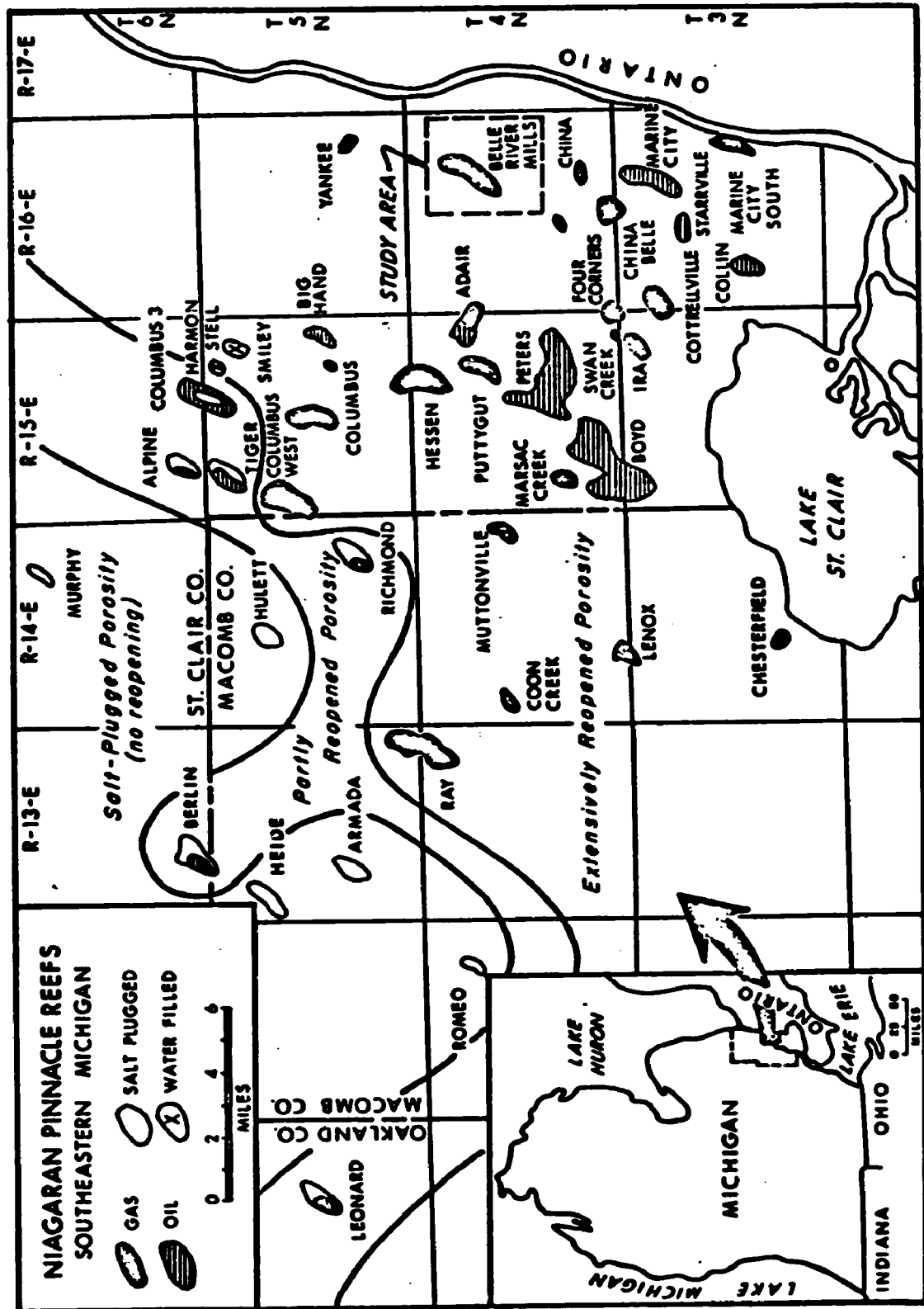


Fig. 1-4. Niagaran Pinnacle Reefs in Southeastern Michigan.

seems to dip at a higher angle and the transition to a basinal facies is more abrupt than along the southern shelf belt. Consequently, a narrower shelf zone with areally small but vertically tall reefs can be anticipated to develop in this area.

Location

The Belle River Mills field is located in sections 11, 14, 15, China township (T4N, R16E), St. Clair County, about 3 miles southwest of St. Clair and 5 miles northwest of Marine City (Fig. 1-5). Indian Trail Road runs along the field's crest. It can be reached through King Road and Division Road which branches from Interstate I-94 connecting Detroit with Port Huron. Smith Creek River in the north and Belle River in the south drain the area to the east into the St. Clair River. The field was named after the small settlement of Belle River Mills, on the Belle River, to the south of the field. The area is covered by 130'-250' of glacial drift, which is underlaid by the Berea Sandstone and Bedford Shale of Mississippian age.

Discovery and Development

The discovery of the Boyd gas field (Fig. 1-4) in 1952 set the stage for the Niagaran pinnacle reef activity in southeastern Michigan. It was followed by intensive drilling with a remarkably high success ratio. In the five townships of Cottrellville, Ira, China, Casco and Columbus comprising the southern portion of St. Clair County, drilling density reached 4 wells to a square mile by the end of 1964 (Corden, 1964) and the overall success ratio for the county through 1967 was 35.9% (390 productive wells out of a total of 1086 drilled; Ellis, 1968). In St. Clair and Macomb Counties 42 reefs were discovered, 36 of which are oil or gas producers (Fig. 1-4; W. Mantek, personal communication).

Gravity prospecting has been extremely successful in locating reefs in this area (Dyer, 1956). Most reefs are expressed as a small positive residual anomaly with a closure of 0.2-0.5 milligals (Kiddoo, 1962). The density contrast between the reef carbonates and the overlying thick Cayugan salt units, and the effects of differential compaction as well as the isolation, high relief and shallow depth (1500'-2000' in Ontario; 2200' in Belle River Mills) of the reefs are the main contributing factors responsible

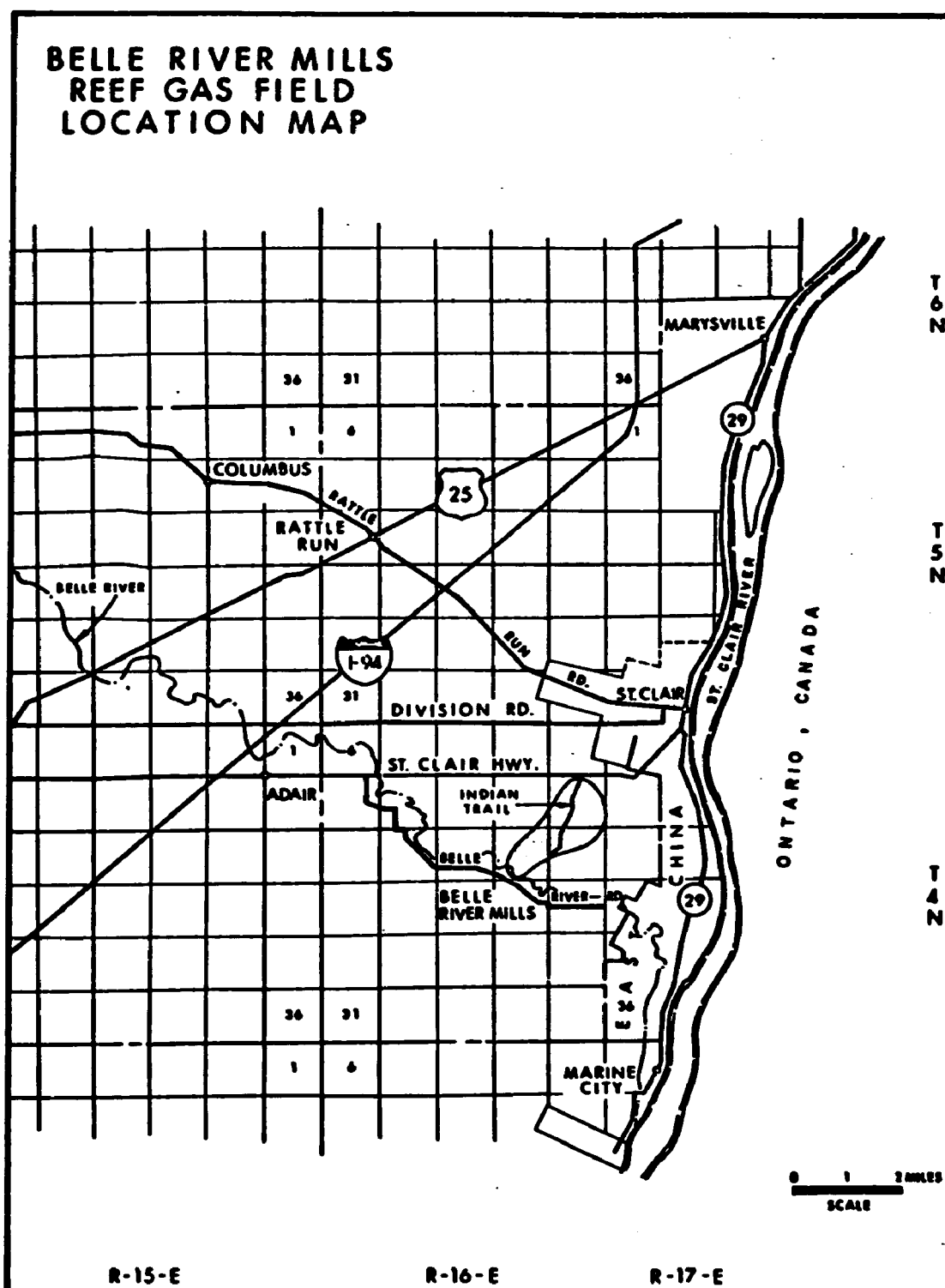


Fig. 1-5. The Belle River Mills gas field, St. Clair County, Michigan. Location map.

for the gravitational anomaly. Unfortunately, variations in the composition and thickness of the glacial drift, salt solution and infill by denser material and basement irregularities have given rise to similar anomalies which are unrelated to reefs (Geyer, 1963). Despite these limitations and other potential ambiguities inherent in the method, gravity surveys have proven to be the most precise exploratory tool in this area.

The Belle River Mills gas field was found on the basis of gravity information. The Bouger gravity map shows an inconspicuous saddle situated in a regionally negative area, but the residual map outlines a closed high area which coincides fairly accurately with the reef's position (Pohly, 1968; Figs. 4 and 5).

The field was discovered on January 21, 1961, with the completion of the Hartman and McClure Urban-Douglas no. 1 (well no. 12 on the following field maps). The development history of the field can be traced with the aid of tables 1-1 and 1-2 and figure 1-6. Table 1-1 identifies the wells in the field as to name, location and other pertinent information. For convenience in mapping and reference, wells have been assigned identifying sequential numbers, ascending from west to east and from south to north. In Table 1-2 wells are arranged into the order in which they were drilled and classified as to their position relative to the reef (off-reef; flank; reef); their status at the time of completion (dry or productive, and from what formation) and their subsequent utility as related to gas storage operations (observation or facility wells). The table also provides data on the drilling pattern and the open flow potential of producing wells. The order of drilling is plotted in figure 1-6 which also provides a well location base map. The (-1900) contour line, traced off the reef configuration map and coinciding with the water level which was encountered at (-1898), outlines the limits of the productive part of the reef. At this elevation, some 50' above its base, the reef covers about 650 acres.

Development drilling proceeded through 1964. The first 25 wells, completed through 1962, closely delineated the field, except for its northern edge which was not defined until the end of 1964 (wells 42-47). They were all drilled according to a prescribed "40 acre pattern," with wells located in the center of the northwest 10-acre corner of each quarter-quarter unit. Subsequent off-pattern wells were located on a 20-acre basis, diagonally opposite to the original pattern site. A total of 43 development wells

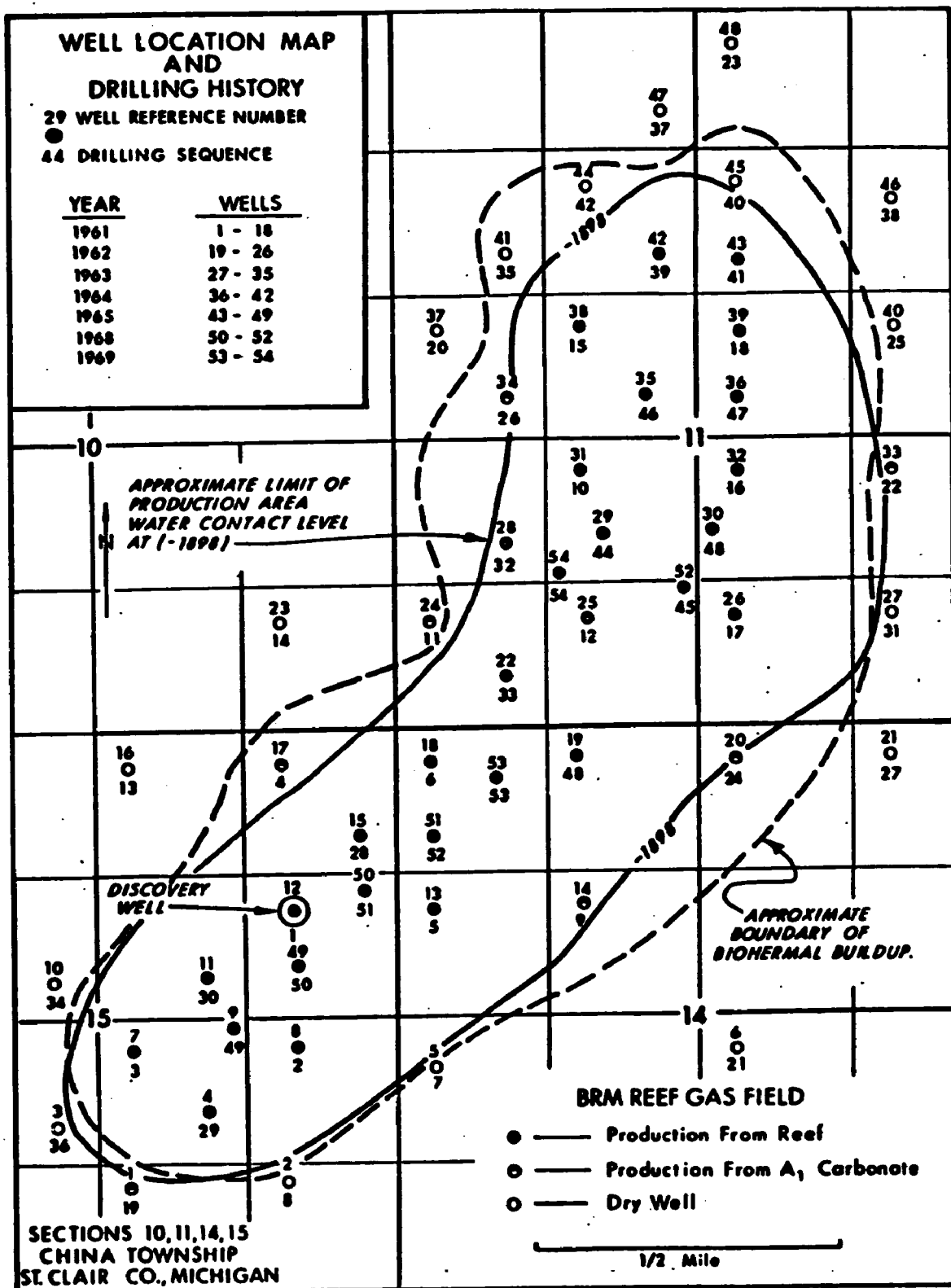


Fig. 1-6. The BRM field-well location map and drilling history.

Well no.	Permit No.	Location	Section	Coordinates		KB elevation	T.D.	Formation at T.D.	Cored interval	
				East	North					
1	Schnack E. Unit 1	23797	NW SW SE	15	063	066	022	2535	A-1 Anhy	2395 - 2522
2	Stager - Frahm - Schunck 1	23303	NW SE SE	15	100	059	019	2523	A-1 Anhy	
3	Radlike 1	25217	SE NE SW	15	050	000	023	2607	Clinton	2406 - 2544
4	Douglas - Schunck 2	24097	SE NW SE	15	110	003	010	2543	BRM Wack.	2347 - 2539
5	Schorat - Schunck 1	23304	NW NW SW	14	220	113	013	2546	BRM Congl.	2403 - 2546
6	Senger 1-14	23066	NW NW SE	14	350	121	001	2549	Lockport	
7	Douglas - Schunck 1	23306	NW NW SE	15	004	121	022	2570	BRM Wack.	
8	Douglas - Frahm 1	23146	NW NE SE	15	156	123	010	2500	Lockport	
9	BR-7	26206	NE NW SE	15	129	132	010	2563	BRM Wack.	
10	Raschinski R. 1	25120	SE SE NW	15	040	104	023	2604	Clinton	2418 - 2513
11	Douglas 1	24094	SE NW NE	15	110	166	022	2526	BRM Wack.	2223 - 2523
12	Urban-Douglas 1	22014	NW SE NE	15	157	100	010	2607	Lockport	
13	Road 3	23043	NW SW NW	14	220	100	010	2534	BRM Wack.	
14	McIntyre - Voll Unit 1	23400	NW SE NW	14	200	100	004	2510	BRM Congl.	
15	Wolser - Man 2	24095	SE NE NE	15	100	223	020	2521	BRM Wack.	2207 - 2521
16	Wolser 1	23641	NW NW NE	15	003	256	010	2623	A-1 Carb.	2442 - 2532
17	Wolser-Man 1	23234	NW NE NE	15	153	257	010	2560	BRM Congl.	2411 - 2550
18	Wolser-Straub Unit 1	23227	NW NW NW	14	219	258	000	2531	BRM Wack.	2210 - 2530
19	Beter 1	25179	NW NE NW	14	205	260	014	2579	Lockport	2200 - 2579
20	Wilson 2	24086	NW NW NE	14	350	250	004	2493	A-1 Carb.	
21	Wilson - Schunck 1	24534	NW NE NE	14	425	259	000	2561	Lockport	
22	Dietlin Comm. 1	25082	SE SW SW	11	254	200	010	2517	BRM Wack.	2206 - 2517
23	Wolser 2	23642	NW SE SE	10	152	225	010	2527	A-1 Carb.	2436 - 2526
24	Dietlin Comm. 1	23656	NW SW SW	11	219	225	010	2531	A-1 Carb.	2449 - 2521
25	Dietlin M.C. 1	23643	NW SE SW	11	200	225	012	2516	BRM Wack.	2153 - 2516
26	Wilson 1	23707	NW SW SE	11	350	226	005	2500	BRM Wack.	2232 - 2306
27	Kochum 1	24007	NW SE SE	11	430	227	000	2671	Clinton	2400 - 2536
28	Merkel 1	24094	SE NW SW	11	254	261	010	2705	Clinton	2377 - 2525
29	BR-3	26117	SN NE SW	11	297	205	016	2542	BRM Wack.	
30	BR-2	26173	SN NW SE	11	247	207	000	2534	BRM Wack.	
31	Buchowski 1	23625	NW NE SW	11	200	205	015	2525	BRM Wack.	2101 - 2525
32	Scott Comm. 1	23671	NW NW SE	11	350	205	005	2507	BRM Wack.	2204 - 2500
33	Gwin Comm. 1	23000	NW NE SE	11	437	205	005	2564	Lockport	
34	Dietlath 2	24303	SE SW NW	11	255	430	020	2535	A-1 Anhy.	2424 - 2535
35	BR-5	26153	SE SE NW	11	217	431	010	2549	BRM Wack.	
36	BR-6	26154	SW SW NE	11	350	429	000	2537	BRM Wack.	
37	Dietlath 1	23021	NW SW NW	11	223	402	001	2523	A-1 Carb.	2402 - 2523
38	Buchowski 2	23672	NW SE NW	11	200	403	014	2513	BRM Wack.	2229 - 2512
39	Saxe Comm. 1	23720	NW SW SE	11	200	401	017	2510	BRM Wack.	2256 - 2517
40	Sayer Comm. 1	24372	NW SE NE	11	420	403	007	2540	A-1 Anhy.	2420 - 2540
41	BRM-1	26123	SE NW NW	11	255	400	001	2723	Clinton	2457 - 2601
42	Jahn 1	26000	SE NE NW	11	226	400	000	2540	BRM Wack.	2215 - 2530
43	Jahn 2	26044	SW NW NE	11	200	405	010	2503	BRM Wack.	
44	Jahn 4	26720	NW NE NW	11	202	520	021	2723	Clinton	2447 - 2553
45	Jahn 3	26305	NW NW NE	11	250	522	010	2542	A-1 Carb.	
46	Carlton - Mose 1	26220	NW NE NE	11	427	523	005	2608	Clinton	2420 - 2616
47	Moseck - Schroeppel	26216	SE SE SW	2	225	504	010	2725	Clinton	2455 - 2573
48	Carlton Comm. 1	23094	NW SW SE	2	266	500	010	2637	Lockport	2470 - 2510
49	BR-12	27300	SW SE NE	15	150	101	013	2547	BRM Wack.	
50	BR-11	27307	NE SE NE	15	100	104	020	2540	BRM Wack.	
51	BR-10	27306	SW NW NW	14	210	226	000	2540	BRM Wack.	
52	BR-4	26142	NE SE SW	11	226	241	004	2520	BRM Wack.	
53	BR-9	27305	NE NW NW	14	253	253	017	2562	BRM Wack.	
54	BR-8	27264	Con SW	11	200	246	022	2508	BRM Wack.	

Table 1-1. Well Identification List, Belle River Mills Gas Field, China Township (RGE, T4N), St. Clair County, Michigan.
(Coordinates are distances in millimeters on a 1:6000 scale map with reference to an arbitrary (0,0) point
at the SW corner of section 15 SE-SW quarter quarter).

Order of drilling	Date		Position and Status						Observation Well	Drilling Pattern		AOF (McF)
	Year	Month	Off-reef		Reef-Flank		Reef-crest			on	off	
			dry	A-1 Gas	dry	A-1 or BRM Congl. Gas	Quelph Gas	Gas Facility				
1	1961	1					13		A-1	+		354,000
2		4					8			+		496,000
3		5				7				+		
4		5				17			A-1	+		
5		6					13			+		164,000+
6		6					18			+		155,000
7		7	5						A-1	+		
8		7	2							+		
9		7				14			A-2	+		262+
10		9					31			+		218,000+
11		9			24				A-1	+		
12		10					25			+		312,000
13		10	16							+		
14		10	23							+		
15		10					36			+		144,000+
16		11					22			+		114,000
17		11					26			+		145,300
18		11					30			+		148,300
19	1962	1		1					A-1	+		975+
20		1	37							+		
21		2	6							+		
22		3		33					A-1	+		
23		5	48							+		
24		5				20			A-1	+		950+
25	10	40							+			
26	10					34			A-1		+	9,000
27	1963	3	31							+		
28		8					15				+	205,700
29		8				4					+	
30		9					11				+	77,800
31		9	37						A-1	+		
32		9				28			A-1		+	7,700
33	10					23				+	367,000	
34	12	10								+		
35	12				41				A-1		+	
36	1964	1	3								+	
37		1	47								+	
38		2	46							+		
39		2					42				+	300,000+
40		2				45				+		
41		10					43				+	49,750+
42	11				44			A-2	+			
43	1965	1					19			+		163,000+
44		9						29			+	
45		9						52			+	
46		9						35			+	
47		10						36			+	
48		10						39			+	
49	10						9			+		
50	1966	7					40				+	
51		8						50			+	
52		8						51			+	
53	1968	7					53				+	
54		7						54			+	
Totals for field			14	3	3	7	16	11	13	31	23	
				17		10		27		54		

Table 1-2. Belle River Mills Gas field, drilling history and production data.

were drilled. In terms of their position relative to the reef, 17 were off-reef, 10 were on the reef flank, and 27 were reef-crest wells. Seven of the reef-flank wells and seven of the off-reef wells encountered gas in the A-1 Carbonate Unit. The flank wells produce also from the underlying BRM conglomerate member. All the reef-crest and flank wells produce gas from the reef (Table 1-2; Fig. 1-6).

Until 1963, when the Michigan Public Service Commission's proration regulations were amended to give net-pay-thickness some weight in determining production allotments, gas well sales were determined solely on the basis of Absolute Open Flow (AOF) potentials. Consequently, completion programs emphasized the maximization of gas deliverabilities. Different completion schemes resulted in extreme variations in original AOF potentials. Corden (1964) discussed in detail the various practices employed in the field. The Michigan Consolidated Gas Company carried out an extensive re-completion program which resulted in significant improvements in well deliverabilities (MCGS, 1965). The utilization of "perf-balls" to seal off more permeable zones in order to selectively open and treat more impervious ones, resulted in some cases in up to a 3-fold increase in production. A particularly successful innovation was the use of what is now referred to as "dynamic well control" or "through tubing perforating" methods (Schlumberger, 1970, p. 5; p. 16). Perforations were shot after the production tubing string was set, in a clean, gas filled, hole in which a positive pressure differential between the formation and the bore hole was maintained. With this method, most of the formation damaging and perforation plugging inherent in the mud or water-filled hole perforation practice is prevented; flow through all perforations is guaranteed and a much improved formation to bore hole communication is established. In the case of the Douglas-Frahm no. 1 well (Well no. 8) it resulted in a 660% increase in production (Corden, 1964, p. 13). This well, with an AOF rating of half a billion cubic feet of gas per day, is probably the best gas well on record in the United States east of the Mississippi River (C. Lundy, personal communication, 1969).

Flow potential data for the rest of the field are provided in Table 1-2. (Figures followed by a (+) sign designate wells in which open flow was gauged with field pressure at 760 psig well head. All the rest are original potentials measured at a reservoir pressure of 1132 psia.) Until its conversion into an underground gas storage facility

the field produced 21,395,142 mcf of its estimated 52,466,000 mcf original gas in place (Lundy, 1968).

Gas storage operations commenced on July 7, 1965. Since then 11 more storage facility wells were added to the field. The subeconomical A-1 Carbonate gas wells, which produced at rates lower by three orders of magnitude than the reef wells (Table 1-2) are utilized as observation wells for spotting potential leakages. The reservoir has a working storage capacity of 42.8 billion cubic feet (Lundy, personal communication, 1969). Gas, supplied from the Gulf Coast area, is injected between April and October at an average daily rate of 400 million cubic feet. During the winter months (November through March) it supplies gas to the Michigan Consolidated Gas Company Detroit distribution system through a 40 mile 24-inch pipeline, at an average volume of 450-500 MMcf per day (a record volume for a single day of 862,393 Mcf was withdrawn on January 20, 1970).

Method of Study

This study is based on the evaluation and integration of information obtained from radioactive logs, core lithologies and petrophysical core analysis data from 54 wells in the field and around its immediate vicinity. The wells are listed and identified in Table 1-1 and shown on the well location base map, figure 1-6. With reference to their position relative to the reef, the wells can be divided into 3 groups: reef wells, reef-flank wells and off-reef wells (Table 1-2, see also Figure 3-14). For all the wells gamma-ray and neutron logs were available. Several wells had in addition sonic or density logs. The radioactive logs were used to identify correlative stratigraphic tops in sections not covered by core material.

A total of 5879 feet of 4 inch core was available from 31 wells in the field (Tables 1-1, 3-4). This includes 3640 feet from 12 reef wells; 1899 feet from 17 off-reef wells and 340 feet from 2 reef-flank wells. Within cored intervals, coverage by the available core was close to 100%. The entire available core was longitudinally slabbed. A substantial part of the core material was sawed more than once, into slices of rectangular blocks, in order to enable the examination of the spatial distribution of the recorded properties. In many samples of rather opaque and superficially featureless

anhydrite sections, the preparation of very thin transparent slices and their examination with transmitted light proved useful in appraising their true fabric. Water wetted core slabs were examined with binocular microscope. For each well a continuous core log was prepared. Logged attributes included petrography, textural and fabric elements, sedimentary structures, fauna, diagenetic features, porosity and fractures and hydrocarbon saturation. Abundance data for the various rock constituents were based on visual estimates. Representative samples were retained for reference, comparison and for more detailed petrographic examinations. The detailed microscopic properties of the various rock types and lithofacies were obtained from the study of more than 500 thin sections (all cut perpendicular to the bedding). Virtually all of the core consists of dolomite. Mineralogical checks for calcite and dolomite, other than routine tests by diluted HCl acid, included staining by Alizarine Red (Friedman, 1959) and X-ray diffraction. In order to investigate the source rock attributes of the A-1 Carbonate, a limited number of samples were analyzed for organic carbon and hydrocarbon content.

Petrophysical measurements, obtained from full-diameter core analysis, were available for a total of 5225 feet of core from 34 wells in the field. The analysis was performed by the Manass Petroleum Laboratory, Mt. Pleasant, Michigan, and was made available through the courtesy of the Michigan Consolidated Gas Company, Detroit, Michigan.

Field work, conducted specifically for the purpose of gaining familiarity and better understanding of the geological aspects of some of the problems dealt with in the subsurface study, included a reconnaissance investigation of Niagaran reefs exposed in quarries in northern Ohio (at Maumee; Textons and Carozzi, 1966) and in northern Indiana (at Fort Wayne, Bluffton, Huntington, Wabash, Logansport, Delphi and Monon; Sangree, 1960, Shaver, 1961). In addition, field experience with modern carbonate reefs was gained in a two month field seminar conducted during the summer of 1969 by the Department of Geology, Indiana University, Bloomington, Indiana. The seminar was devoted to the detailed investigation of the recent shallow marine (including supratidal and reef) carbonate environments of the Florida Keys, Southern Florida. Some of the results of these investigations were published in abstract form (Gill, 1971; Fowler et al., 1970).

Data analysis utilizing digital computer techniques was employed in two phases of this study. The General Purpose Contouring Program, a commercially available package (Calcomp Inc., 1968), was used to evaluate the structural framework of the various Salina units overlying the reef. Processing and evaluation of the petrophysical core analysis data was accomplished by means of a computer oriented, statistical data reduction method, which was developed by the author (Gill, 1969).

Previous Investigations

Aspects of the stratigraphy, sedimentology and paleogeography of the Silurian in the sedimentary basins of the Mid-continent have been the subject of extensive research. Many of these studies are frequently referred to in the body of the dissertation. Only those studies which are of more direct relevance and their major findings and conclusions which are pertinent to questions investigated in the present study are briefly reviewed below.

Felber's (1964) Ph. D. dissertation is the most comprehensive published study on Silurian reefs in southeastern Michigan. Some of the major conclusions of his study are:

- 1) the reef developed in three growth stages (biosomes) in response to increasing salinities; reef growth terminated in A-2 Evaporite Time;
- 2) the deposition of the off-reef A-1 Anhydrite Unit was contemporaneous with the upper algal biosome in the reef (thus implying that the A-1 unit was deposited in deep water);
- 3) no depositional break separates the Salina from the Niagara group (hence their lumping into his "Sanilac" Group); and
- 4) dolomitization and porosity plugging in the two lower biosomes happened very early, before the deposition of the A-1 Anhydrite.

Sharma (1961, 1966) in his study of the Peters Reef (St. Clair County), concludes that the reef grew during both late Niagara and early Salina time and that reef growth was interrupted intermittently by the regressing seas and the development of evaporitic environments in the Michigan basin. During the low sea stands the reef was subject to subaerial weathering. He suggests that the dolomitization of the reef is due in part to seepage refluxion during A-1 Anhydrite times and in part to the subsequent

exposure period. As potential source beds for the hydrocarbons contained in the reef mass, he proposes the Clinton Shale and the A-1 Carbonate Unit.

Jodry (1969) is the strongest proponent for the penecontemporaneity of the reef and the flanking off-reef evaporite sequence. As in the two previous studies mentioned above, he also concludes that reef growth continued during early Salina times. According to Jodry "the reefs never stood more than a few feet or tens of feet above the surrounding sediments" (Jodry, 1969, p. 960). Following Illing (1959), Jodry attributes the dolomitization of the reefs to the effects of large quantities of connate water expelled by compaction into the reef from the surrounding A-1 Carbonate. Unlike the seepage refluxion model, his mechanism calls for an upward migration of fluids and requires that dolomitization be accomplished prior to the reef's burial.

G. D. Ellis' studies (1960, 1962, 1967) are important contributions to the literature on the Silurian oil and gas pools in Michigan. His 1967 paper is a comprehensive compilation in which the stratigraphy, reef geology, diagenesis and production aspects of the Silurian in the subsurface of the Michigan basin are discussed in detail.

Since its inauguration in 1962, the annual conference (and the published proceedings thereof) of the Ontario Petroleum Institute has become the forum in which much of the developments in the exploration for Silurian oil and gas fields in Michigan and in Ontario have been reported (Pounder, 1962; Kiddoo, 1962; Corden, 1964; Adams, 1965; Hill, 1966; and Burgess and Benson, 1969).

The more general and regional aspects of the stratigraphy, facies and paleogeography of the Middle and Upper Silurian in the Michigan basin have been treated in studies by Landes (1945), Cobee (1948), Evans (1950), Alling and Briggs (1961), Ehlers and Kesling (1962), Pounder (1962) and Burgess and Benson (1969).

Many of the publications cited thus far include data on individual reefs. Additional papers in which individual reefs are analyzed include those by Alguire (1962) on the Marine City Field, and by Koepke and Stanford (1966) who include maps and cross sections of 61 reefs in Ontario. Technical reports on the Belle River Mills field have been published by Lundy (1969), Pohly (1968) and Corden (1964).

STRATIGRAPHY

General

The subsurface stratigraphy of the Middle and Upper Silurian section in southeastern Michigan has been discussed in detail by several authors (Landes, 1945; Cohee, 1948; Evans, 1950; Alling and Briggs, 1961; Felber, 1964; Sharma, 1966; Ellis, 1967; Beards, 1967). The stratigraphic section investigated in the present study includes lithostratigraphic units belonging to the Niagara and the Salina Groups. Representative logs of the investigated section are presented in Figure 2-1 and Figures 2-10 to 2-12. The stratigraphic interval of concern to this study includes those rocks contained between the top of the Clinton formation and the Bass Islands formation. The Bass Islands were not included in the stratigraphic analysis since an erosional unconformity separates the upper part of the Bass Islands formation in the Belle River Mills area from the overlying Bois Blanc formation of Early Devonian age.

The present study stresses the geology of the Niagaran and A-1 Salinan rocks. The upper Salina section is lithologically uniform and areally persistent regardless of the presence of underlying Niagaran pinnacle reefs. On the other hand, the lower Salina and Niagara intervals present interesting and controversial stratigraphic problems related to the growth and evolution of reefal buildups, which this study attempts to resolve. Furthermore, the post A-1 Carbonate section is of little economic interest whereas the Guelph formation and the Salina A-1 Carbonate Unit are targets for oil and gas exploration. Consequently, the well cores which afford material for detailed lithofacial studies are generally available for only the lower interval. Therefore, the present study places heavier emphasis on the Pre-A-2 Evaporite section. The post A-1 Carbonate section has been only examined cursorily, to provide some general insight into the framework of the post-reef Silurian stratigraphy of the study area.

Post A-1 Carbonate Stratigraphy and Structure

The stratigraphic terminology for the Salina Group was proposed by Landes (1945) who divided the group into eight units to which he assigned the alphabetic designation "A" through "H" (ascending). Evans (1950) further subdivided the A unit into four

subunits, the "A-1" and "A-2", each with its lower evaporite and upper carbonate member. It has already been pointed out by Felber (1964) and Sharma (1966) that the order in which minerals precipitate out of saline brines (carbonates followed by sulfates) does not correspond to the numerical order of the stratigraphic subdivision created by Evans. Both authors proposed to approach the stratigraphy of the Salina from the standpoint of evaporite cycles. Felber subdivided the section into eight "evaporite megacycles" to which he assigned five new formal formation names (Felber, 1964, Fig. 3). Sharma retained the widely used terminology of Landes and Evans but regrouped their various subunits into five evaporite cycles (Sharma, 1966, Table 2).

In this study the stratigraphic subdivision and the representative gamma-ray-neutron log of the interval top A-1 Carbonate to top Bass Islands Formation (Fig. 2-1) accord to the lithostratigraphic subdivision and nomenclature of type logs of the Michigan basin presented by Ellis (1967, Figs. 4 and 5) and by Beards (1967, Fig. 6). The section consists of alternating carbonate, evaporite and shale units that are readily identified in gamma-ray-neutron logs (Beards, 1967). In each well, sixteen log markers (markers 7 through 22, Fig. 2-1) have been identified. The section is remarkably consistent over the study area and no difficulties were encountered in recognizing the markers and correlating them between wells (Tables 2-1, 2-2).

The problem of determining what is the highest stratigraphic horizon which still reflects accurately the presence of underlying Niagaran reefs is of practical significance as structural maps drawn on this horizon prove to be a valuable reef exploration tool.

Compaction induced structures can be expected to develop whenever buried rigid bodies, such as carbonate reefs, cause their overlying sediments to be differentially compacted (Labute and Gretener, 1969). Spatially the resulting structures develop over the rigid body and conform to its configuration in both shape and areal extent. The size and relief of the closures thus generated decreases systematically upwards as the effects of differential compaction dissipate and diminish away from the source which causes them. Furthermore, the resultant structures constitute additional potential hydrocarbon traps and therefore, information about their size, location and distribution is of economic importance. In order to explore these questions, structure contour maps of all the stratigraphic tops listed in Table 2-2 were constructed using the

**MIDDLE AND UPPER SILURIAN FORMATIONS
SUBSURFACE OF SOUTHEASTERN MICHIGAN
LITHOSTRATIGRAPHIC SUBDIVISION AND REPRESENTATIVE
GAMMA RAY - NEUTRON LOG
Mich. Cons. Gas Co. - Carleton et al., no. 1
(well no. 46, interval 1347'-2692')**

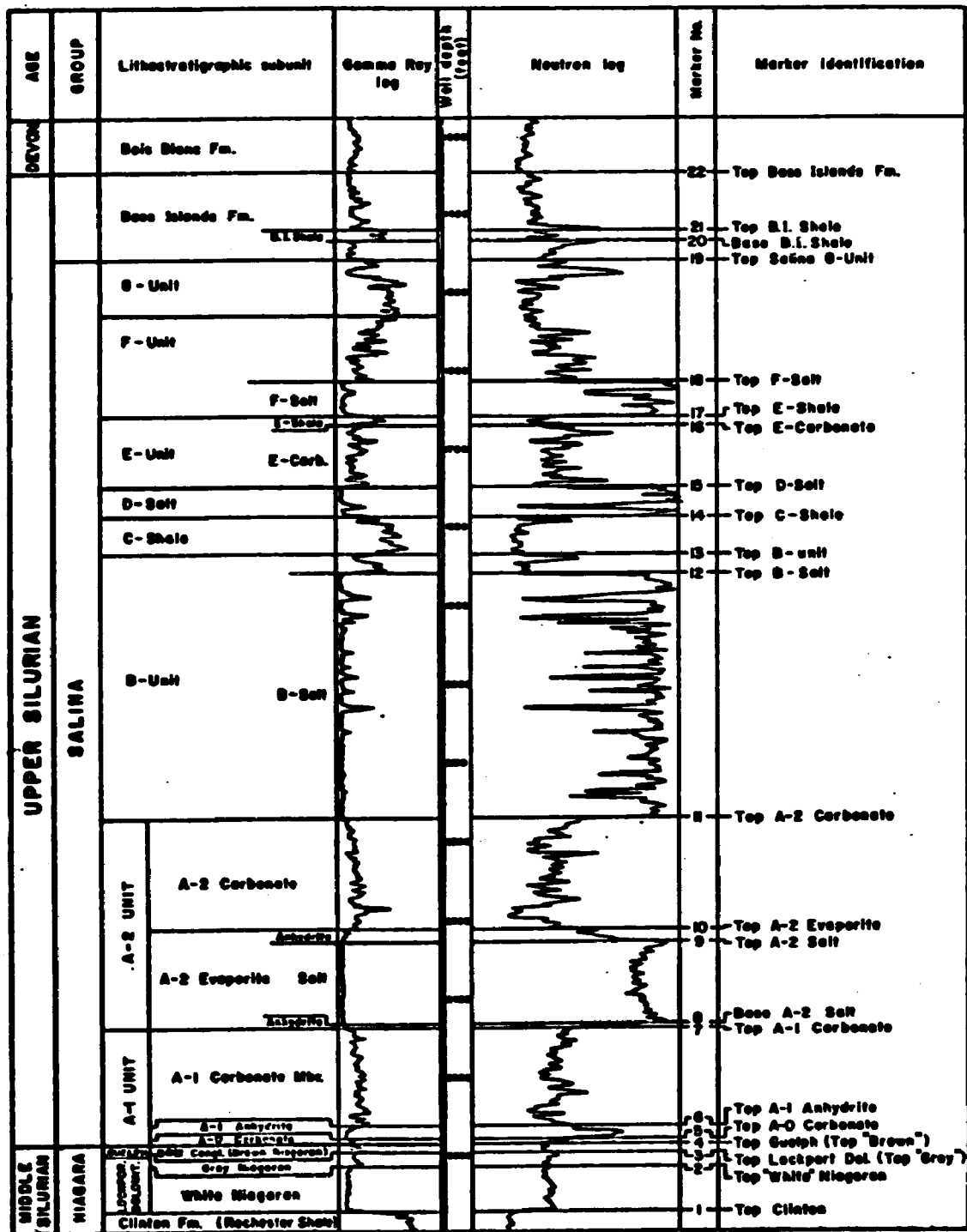


Fig. 2-1. Middle and Upper Silurian stratigraphic nomenclature, subsurface of southeastern Michigan.

Well	marker	(***)	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1		2403	-	2330	2309	2168	1860	1836	1786	1738	1657	1645	1632	1470	1445	1430	1365	
2		2396	2392	2316	2290	2155	1843	1820	1779	1726	1646	1634	1624	1457	1433	1416	1338	
3		2403	2401	2330	2310	2171	1884	1860	1818	1758	1672	1659	1642	1472	1447	1432	1358	
4		2343	-	2316	2305	2156	1835	1812	1763	1725	1648	1636	1630	1468	1441	1425	1352	
5		2398	-	2315	2303	2152	1848	1818	1766	1724	1639	1628	1625	1456	1432	1420	1342	
6		2394	2392	2300	2285	2142	1822	1798	1744	1702	1623	1618	-	1437	1411	1396	1321	
7		2396	-	-	2320	2178	1864	1840	1790	1745	1666	1656	1646	1480	1455	1440	1368	
8		2184	-	-	2157	2072	1809	1787	1745	1710	1633	1626	-	1460	1435	1422	1346	
10		2425	2421	2347	2328	2183	1895	1870	1818	1771	1684	1671	1644	1474	1449	1436	1355	
11		2221	-	-	2187	2065	1835	1811	1770	1736	1659	1647	1634	1472	1448	1434	1370	
12		2195	-	-	2159	2067	1812	1788	1749	1716	1636	1622	-	1455	1429	1424	1344	
13		2175	-	-	2157	2057	1810	1786	1740	1720	1644	1636	1620	1458	1433	1419	1347	
14		2378	-	-	2299	2154	1813	1790	1746	1710	1633	1624	1594	1441	1417	1404	1326	
15		2203	-	-	2166	2072	1822	1800	1762	1731	1652	1643	1629	1462	1437	1424	1352	
16		2440	-	2336	2326	2184	1898	1872	1824	1780	1698	1682	1634	1472	1446	1432	1358	
17		2416	-	2338	2320	2178	1873	1850	1802	1762	1678	1665	1650	1475	1450	1437	1366	
18		2207	-	-	2170	2073	1828	1806	1772	1735	1658	1649	1638	1462	1447	1434	1360	
19		2200	-	-	2177	2065	1829	1806	1770	1739	1654	1645	1604	1470	1444	1432	1354	
20		2390	2387	2340	2322	2179	1819	1795	1748	1714	1637	1630	1615	1450	1427	1413	1338	
21		2405	-	2307	2289	2141	1816	1790	1744	1707	1626	1616	1610	1443	1418	1403	1332	
22		2374	-	-	2224	2157	1843	1817	1780	1746	1667	1657	1636	1470	1445	1432	1358	
23		2435	-	2353	2336	2193	1897	1871	1822	1778	1692	1679	1623	1461	1439	1422	1348	

Table 2-1. Stratigraphic data, (well depth in feet to top of Unit), Base A-2 Evaporite to Top Base Islands Formation.
(Refer to Figure 2-1 for marker identification; dashes denote missing units; (***) denotes Base A-2 Evaporite in reef-wells).

Well	marker (feet)	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
24		2441	2437	2348	2338	2183	1884	1859	1812	1722	1688	1676	1645	1467	1442	1427	1353
25	2147	-	-	-	2130	2041	1809	1787	1750	1720	1642	1637	1622	1455	1430	1416	1344
26	2231	-	-	-	2196	2097	1807	1783	1747	1720	1638	1629	1622	1454	1429	1418	1344
27		2396	-	2328	2318	2167	1825	1792	1744	1713	1634	1626	1622	1457	1434	1422	1344
28		2375	2372	2334	2301	2168	1862	1834	1784	1760	1681	1670	1638	1469	1445	1430	1357
31	2176	-	-	-	2153	2062	1820	1798	1765	1738	1655	1648	1635	1468	1443	1431	1358
32	2257	-	-	-	2218	2115	1818	1794	1757	1724	1646	1639	1626	1456	1433	1420	1342
33		2403	-	2378	2367	2220	1853	1806	1751	1721	1644	1637	1628	1459	1436	1423	1348
34		2423	-	2348	2327	2190	1882	1856	1810	1772	1692	1682	1653	1480	1456	1441	1364
37		2463	2458	2361	2344	2200	1905	1879	1829	1785	1709	1695	1643	1479	1453	1436	1360
38	2227	-	-	-	2197	2108	1849	1826	1785	1754	1676	1666	1625	1465	1440	1427	1350
39	2252	-	-	-	2201	2101	1833	1808	1768	1743	1663	1655	1633	1472	1448	1433	1360
40		2418	-	2316	2302	2158	1834	1810	1768	1734	1655	1646	1622	1459	1434	1420	1349
41		2454	-	2353	2339	2196	1904	1876	1826	1791	1708	1700	1644	1480	1455	1439	1364
42	2213	-	-	-	2167	2083	1843	1819	1782	1752	1677	1669	1626	1471	1446	1433	1360
43	2265	-	-	-	2234	2123	1860	1835	1794	1764	1687	1678	1638	1480	1454	1440	1366
44		2450	2445	2365	2346	2201	1900	1874	1825	1787	1703	1693	1641	1476	1450	1437	1360
45		2442	2436	2357	2338	2192	1875	1848	1803	1767	1687	1676	1647	1478	1453	1439	1362
46		2438	-	2328	2312	2171	1860	1836	1788	1750	1669	1658	1616	1460	1434	1421	1346
47		2454	2448	2358	2340	2200	1898	1871	1820	1784	1702	1689	1636	1472	1447	1434	1357
48		2468	-	2363	2346	2202	1901	1876	1822	1786	1700	1687	1642	1478	1454	1441	1364

Table 2-1 (Continued).

Well	Marker (***)	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1		1781	-	1708	1687	1546	1238	1214	1164	1116	1035	1023	1010	848	823	808	743
2		1777	1773	1697	1679	1536	1224	1201	1160	1107	1027	1015	1005	838	814	797	719
3		1784	1779	1708	1688	1549	1263	1238	1196	1136	1050	1037	1020	850	825	810	736
4		1725	-	1698	1687	1538	1217	1194	1147	1107	1030	1018	1012	850	823	807	734
5		1785	-	1702	1690	1539	1235	1205	1153	1111	1026	1015	1012	843	819	807	729
6		1793	1791	1701	1694	1541	1221	1197	1143	1101	1022	1017	-	836	810	795	720
7		1776	-	-	1698	1556	1242	1218	1168	1123	1044	1034	1024	858	833	818	746
8	1866	-	-	-	1539	1444	1191	1179	1127	1092	1015	1006	-	842	817	804	728
10		1802	1798	1724	1705	1580	1272	1247	1195	1148	1061	1048	1021	851	826	813	732
11	1899	-	-	-	1505	1463	1213	1189	1148	1114	1036	1025	1012	850	826	812	748
12	1885	-	-	-	1349	1457	1202	1178	1139	1106	1028	1018	-	845	819	814	734
13	1857	-	-	-	1529	1439	1192	1168	1122	1102	1026	1018	1002	840	815	801	729
14	1774	-	-	-	1695	1550	1209	1186	1142	1106	1029	1020	990	837	813	800	722
15	1883	-	-	-	1546	1452	1202	1180	1142	1111	1032	1023	1009	842	817	804	732
16	1821	-	1717	1707	1565	1279	1253	1233	1205	1161	1079	1063	1015	853	827	813	739
17	1800	-	1722	1704	1582	1257	1234	1204	1166	1146	1062	1049	1034	859	834	821	740
18	1887	-	-	-	1550	1483	1208	1186	1152	1115	1038	1029	1018	852	827	814	740
19	1886	-	-	-	1563	1471	1215	1192	1156	1125	1040	1031	990	856	830	818	740
20	1786	1783	1736	1718	1576	1215	1191	1161	1144	1110	1033	1026	1011	846	823	809	734
21	1806	-	1708	1690	1542	1217	1191	1161	1145	1108	1027	1017	1011	844	819	804	733
22	1656	-	-	-	1606	1539	1225	1199	1162	1128	1049	1039	1018	852	827	814	740
23	1819	-	1737	1720	1577	1261	1255	1206	1162	1122	1076	1063	1007	845	823	806	732

Table 2-2. Structural data (feet below sea level to top of Unit), Base A-2 Evaporite to Top Bass Islands Formation.
(Refer to Figure 2-1 for marker identification; dashes denote missing units; (***) denotes Base A-2 Evaporite in reef-walls).

Well	(⁰⁰⁰)	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
24	1822	1818	1729	1719	1564	1265	1240	1193	1103	1069	1057	1026	848	823	808	734	
25	1535	-	-	1518	1429	1197	1175	1138	1106	1030	1025	1010	843	818	804	732	
26	1626	-	-	1591	1492	1202	1178	1142	1115	1053	1024	1017	849	824	813	739	
27	1793	-	1725	1715	1564	1222	1189	1141	1110	1031	1023	1019	854	831	819	741	
28	1756	1753	1715	1692	1549	1243	1215	1175	1141	1062	1051	1019	850	826	811	736	
31	1561	-	-	1538	1447	1205	1183	1150	1123	1040	1033	1020	853	828	816	743	
32	1652	-	-	1613	1510	1213	1189	1152	1119	1041	1034	1021	853	828	815	737	
33	1798	-	1773	1762	1615	1248	1201	1146	1116	1039	1032	1023	854	831	818	743	
34	1803	-	1728	1707	1570	1262	1236	1190	1152	1072	1062	1033	860	836	821	744	
37	1841	1837	1740	1723	1579	1284	1258	1208	1164	1088	1074	1022	858	832	817	739	
38	1613	-	-	1583	1494	1235	1212	1171	1140	1062	1052	1011	851	826	813	736	
39	1635	-	-	1584	1484	1216	1191	1151	1126	1046	1038	1016	855	831	816	743	
40	1811	-	1709	1695	1551	1227	1203	1159	1127	1048	1039	1015	852	827	813	741	
41	1833	-	1732	1718	1575	1283	1255	1205	1170	1087	1079	1023	859	834	818	743	
42	1593	-	-	1547	1463	1223	1199	1162	1132	1057	1049	1006	851	826	813	740	
43	1647	-	-	1616	1505	1242	1217	1176	1146	1069	1061	1020	862	836	821	748	
44	1829	1824	1744	1725	1580	1279	1253	1204	1166	1082	1072	1020	855	829	816	739	
45	1824	1817	1739	1720	1574	1257	1230	1185	1149	1069	1058	1029	860	835	821	744	
46	1833	-	1723	1707	1566	1255	1231	1193	1145	1064	1053	1011	855	829	816	741	
47	1836	1830	1740	1722	1582	1280	1253	1202	1166	1084	1071	1018	854	829	816	739	
48	1850	-	1745	1728	1584	1283	1258	1204	1172	1082	1069	1024	860	836	823	746	

Table 2-2 (Continued).

General Purpose Contouring Program, developed and marketed by the California Computer Products, Inc. (Calcomp, 1968). Machine contouring is particularly applicable to the situation at hand because of several reasons:

1) The available control points are fairly evenly distributed (Fig. 1-6), thus providing a data base well suited for the contouring algorithm and alleviating some of the interpolation and extrapolation difficulties inherent to contouring unevenly spaced data (Walters, 1969).

2) Objective contouring and avoidance of personal bias is crucial to the specific problem investigated and,

3) Although in some respects only preliminary and unpolished, the results obtained are nevertheless sufficiently refined to provide adequate answers to the problem at hand.

The structure maps (Figs. 2-2 to 2-8¹) reveal that the highest horizon which shows closure above the reef is the top of the E-Carbonate. Figure 2-3 shows two small local closures, the northern one of which (around well no. 25) coincides with the highest part of the reef. The structure maps on top of the E-Shale and those on stratigraphically higher units do not indicate the existence of an underlying reef. In this regard, it is noteworthy that in other parts of Michigan, horizons as high as the Devonian Traverse Limestone and Sunbury Shale still accurately delineate the outline of buried reefs (Ells, 1967, Fig 11). As can be expected, resolution improves with depth. The reef structure becomes better defined in maps of successively lower markers. The top of the A-2 Carbonate (Fig. 2-6) fairly accurately delineates the configuration of the reef mass and shows a closure of 175 feet. Additional refinement is obtained in the top A-2 Evaporite

¹The program first superimposes a uniform square grid over the map and assigns map values to each mesh point. The choice of the density of the grid is optional. In Figs. 2-2 to 2-7, 80 grid points were used whereas in Fig. 2-8, 750 points were used (every 60 map coordinate units vs. every 20 respectively). A denser grid system yields more accurate results (Fig. 2-8) but requires longer processing time. Fewer grid points result in smoother contour lines at the expense of map detail and some loss of accuracy. In Figs. 2-2 to 2-7 some contours are actually in error by several feet on the map scale, as they leave control points on the wrong side of the line. However, for the purpose of this general stratigraphic survey, accuracy was not crucial and smoothness and economy were preferred.

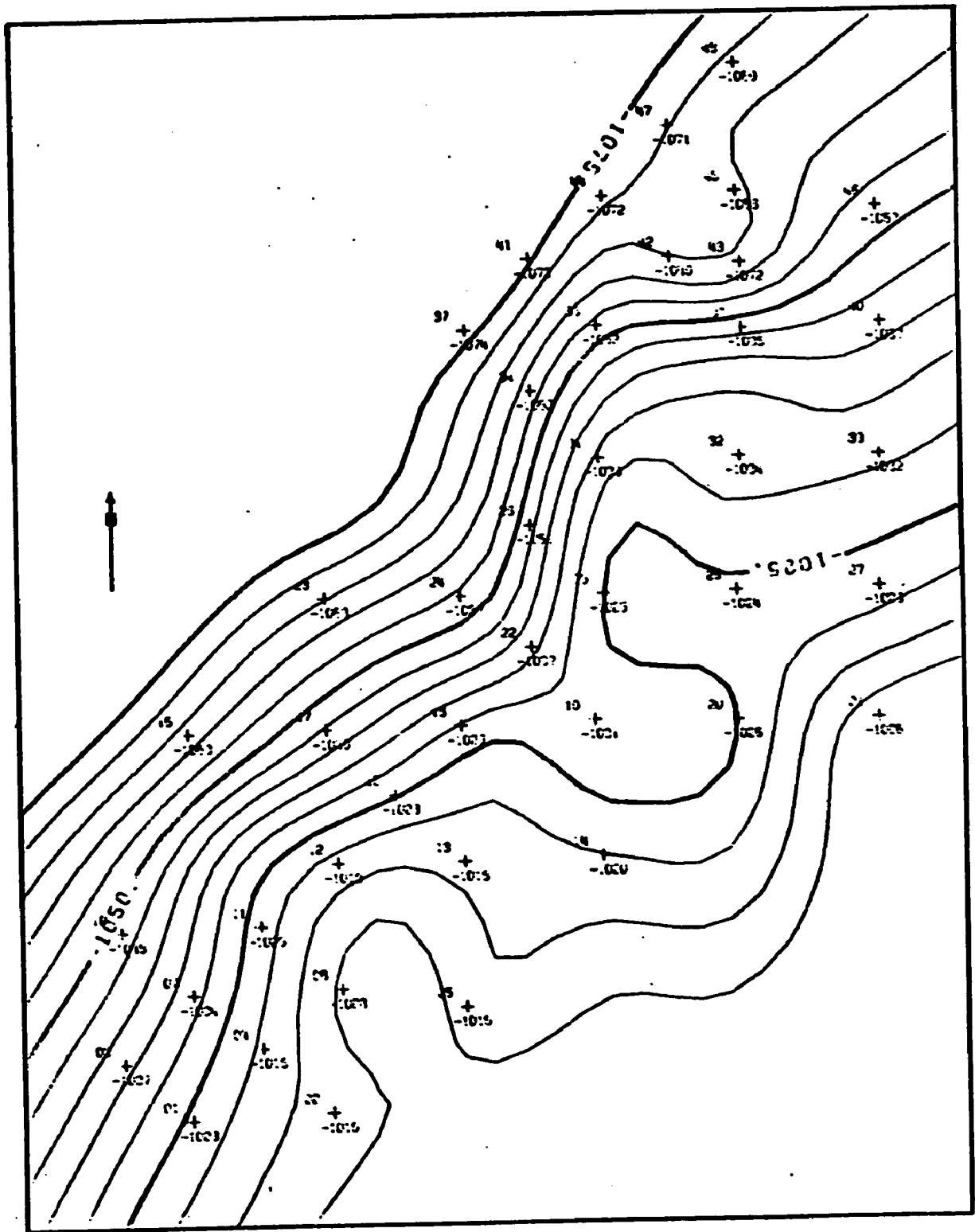


Fig. 2-2. Structure contour map, top E-Shale. Contour interval 5 feet.

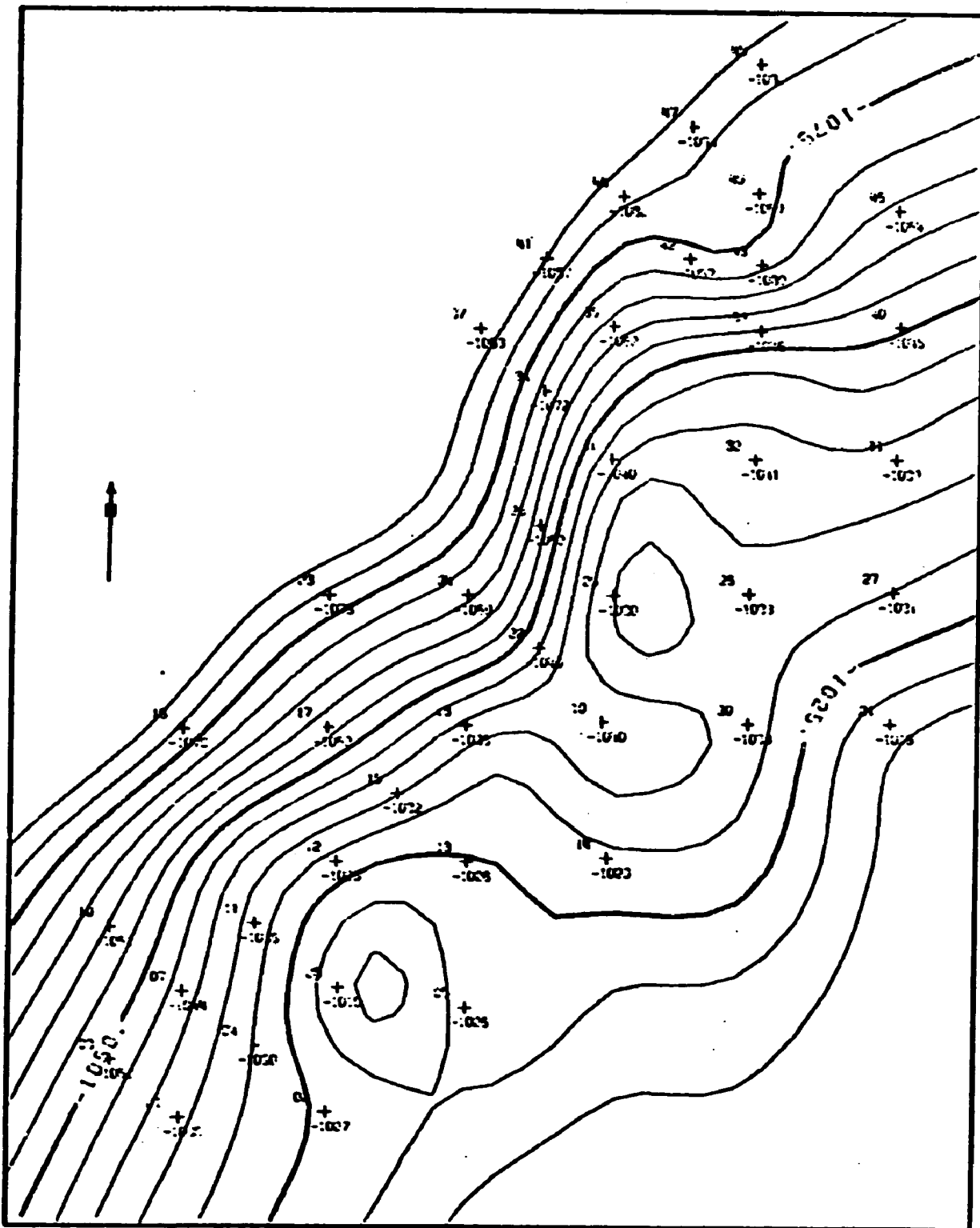


Fig. 2-3. Structure contour map, top E-Carbonate. Contour interval 5 feet.

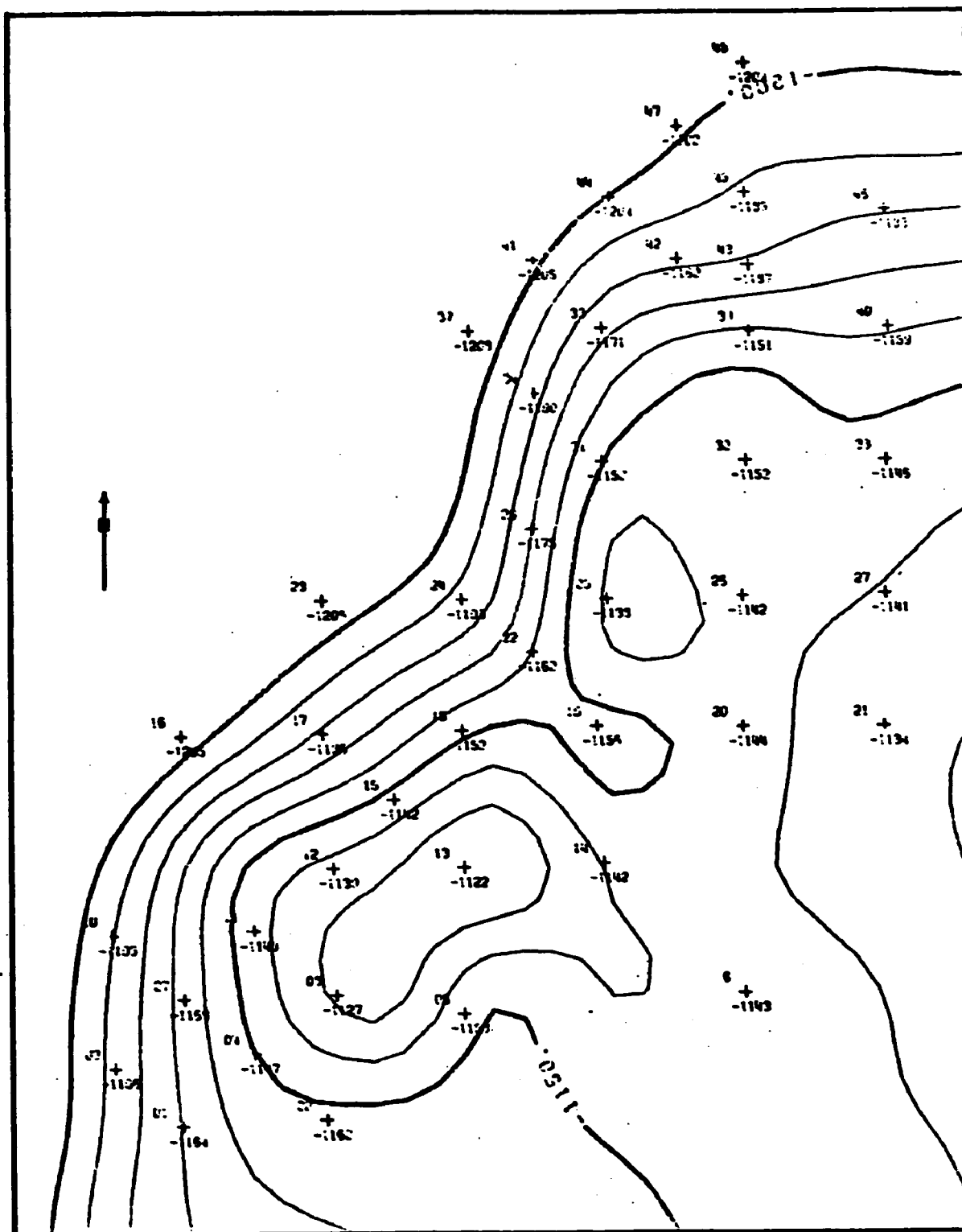


Fig. 2-4. Structure contour map, top C-Shale. Contour interval 10 feet.

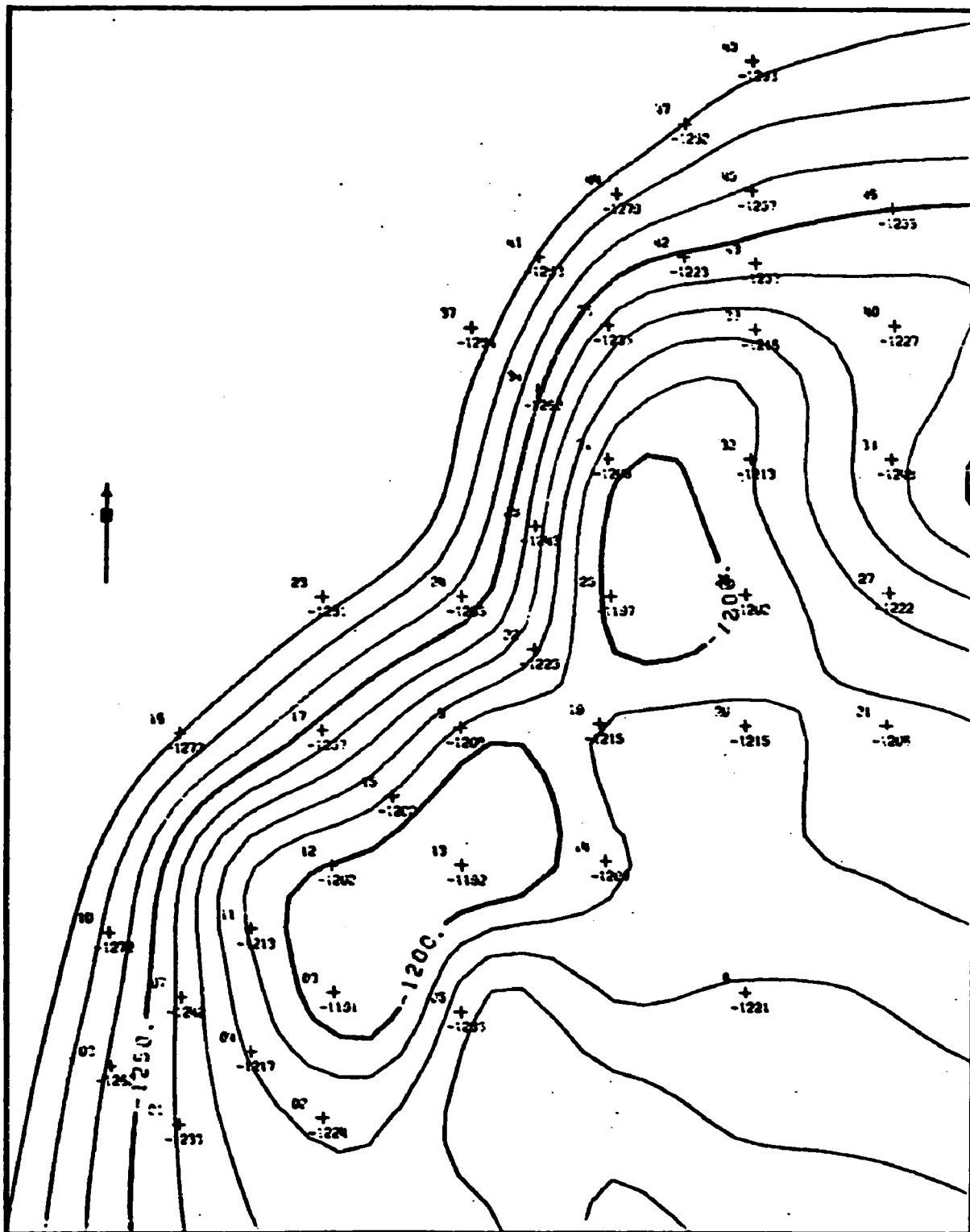


Fig. 2-5. Structure contour map, top B-Salt. Contour interval 10 feet.

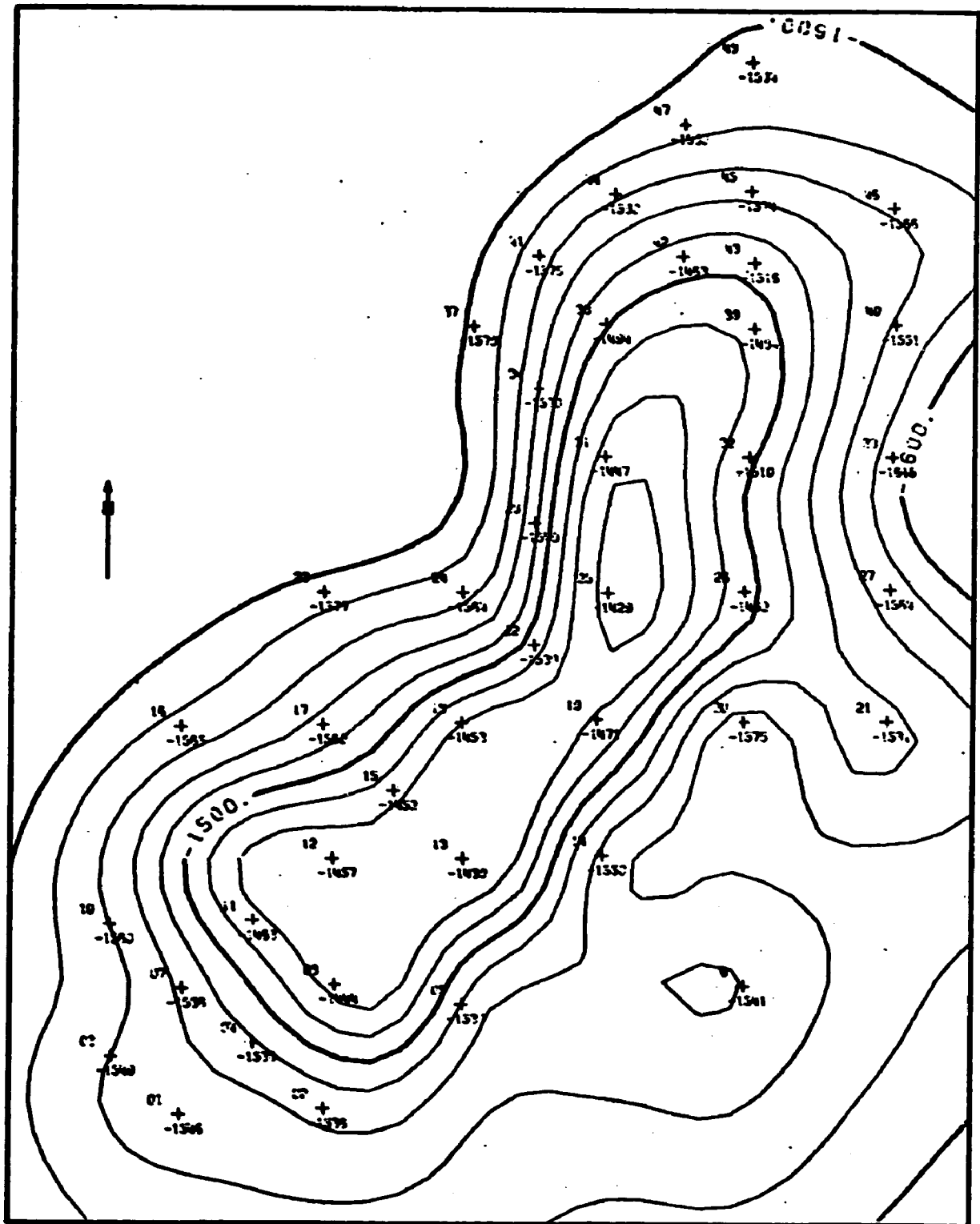


Fig. 2-6. Structure contour map, top A-2 Carbonate. Contour interval 20 feet.

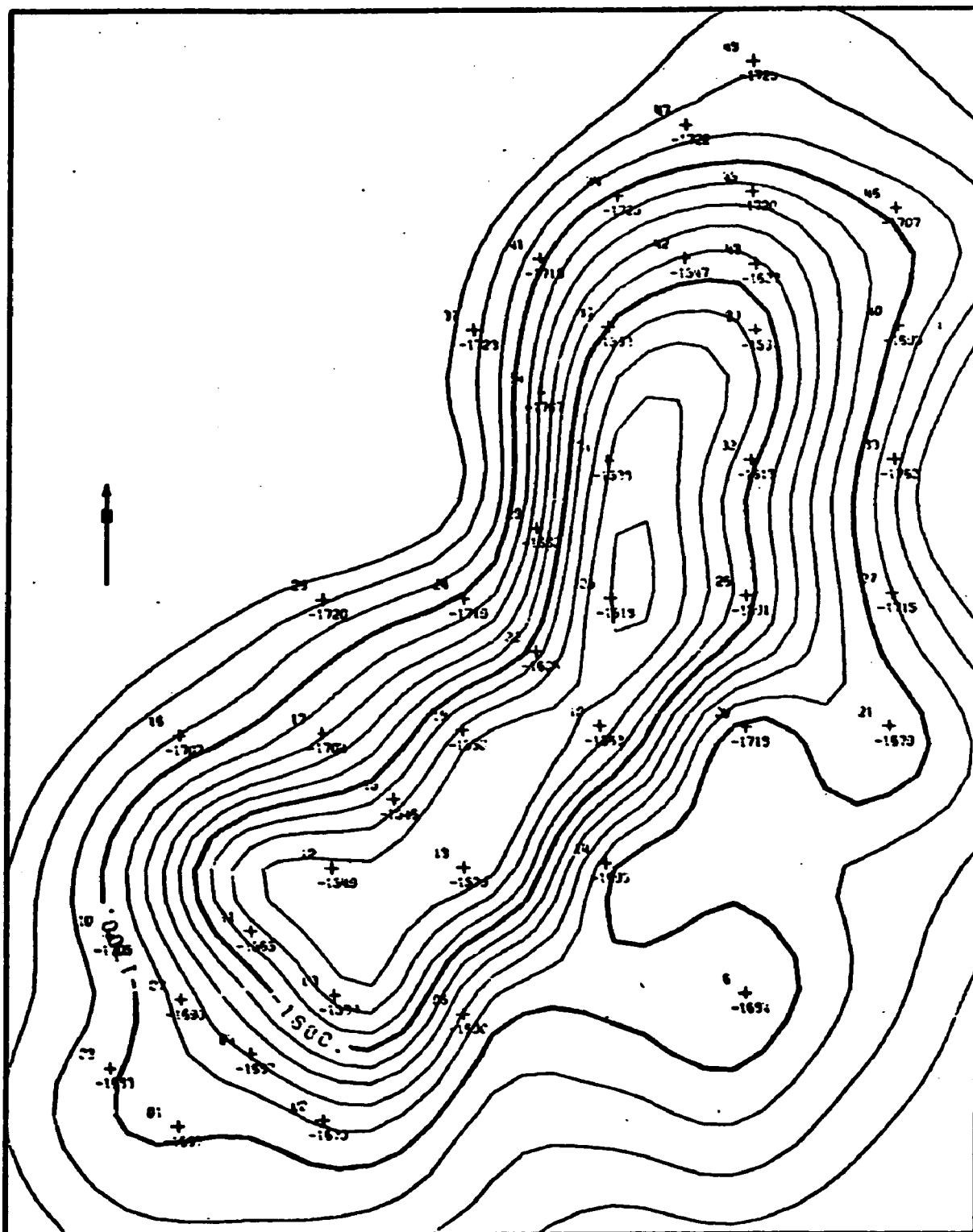


Fig. 2-7. Structure contour map, top A-2 Anhydrite. Contour interval 20 feet.

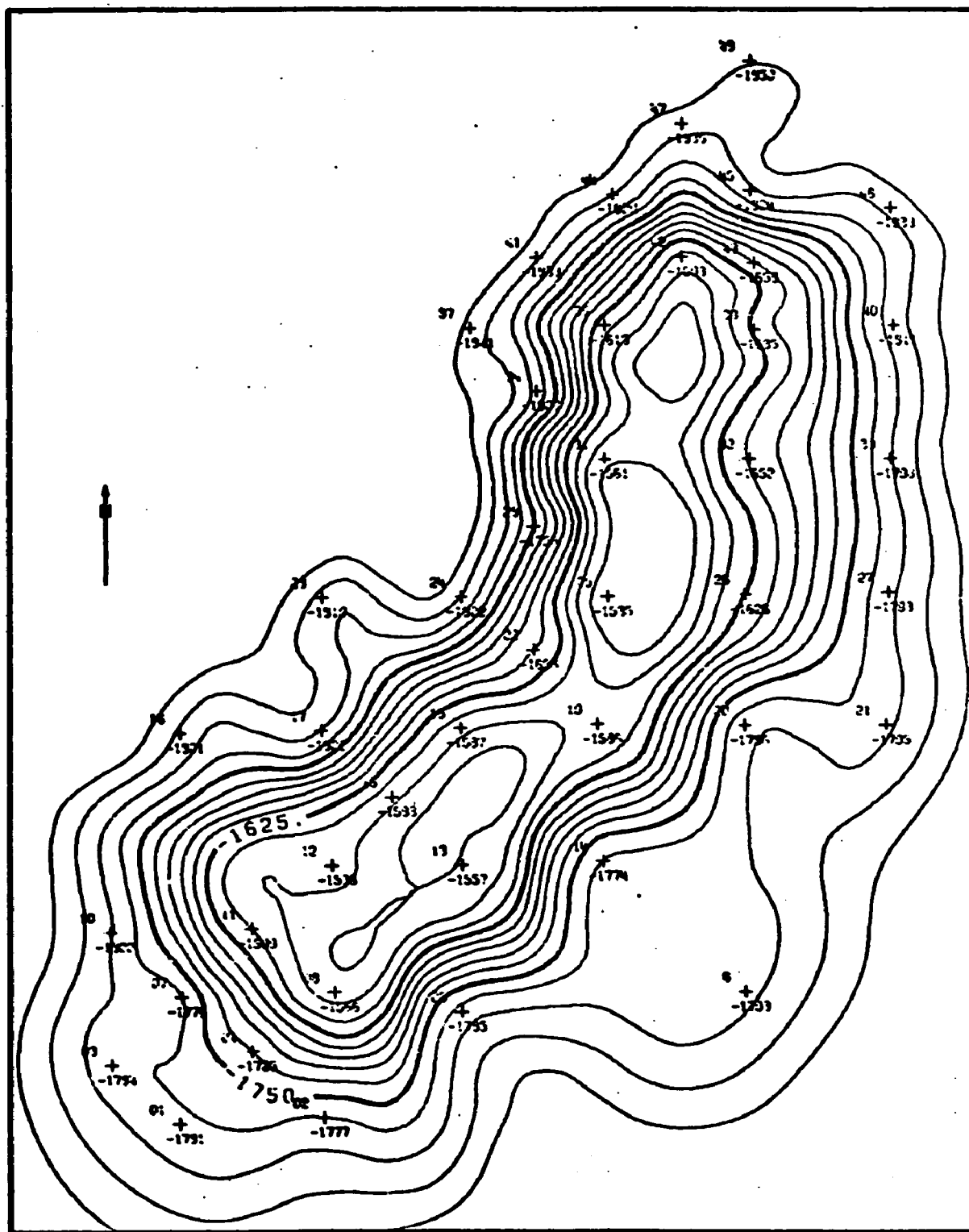


Fig. 2-8. Structure contour map, base A-2 Evaporite. Contour interval 25 feet.

map (Fig. 2-7) and finally, a map drawn on the base of the A-2 Evaporite, a diachronous horizon overlying the A-1 Carbonate in off-reef areas and the Guelph Formation over the reef (Fig. 2-8), affords a very close approximation to the actual geometry of the reef (compare Figures 2-8 and 3-14; 3-15).

A similar pattern emerges from considerations of formation thicknesses. The Salina units, up to and including the E-unit, are thinner above the reef. Thickness reduction due to differential compaction decreases consistently upwards (39% for the A-2 Carbonate, 26% for the B-salt, and 14% for the E-Carbonate). No appreciable difference in the thickness of the post E-unit sediments can be detected between reef and off-reef wells.

Pre A-2 Evaporite Stratigraphy

The subsurface stratigraphic terminology for the interval between the top of the Clinton formation and the top of the Salina A-1 Unit is shown in Fig. 2-9. The stratigraphic relationships and the subdivision of the Guelph Formation into lithostratigraphic members, as shown on the chart, embody some of the main conclusions of the present study.

The stratigraphic nomenclature in common use in Michigan was summarized by Ellis (1967) and is shown on the left hand side of the chart. This terminology developed over the years as a result of studies by Landes (1945), Cohee (1948) and modifications which were later introduced by Evans (1950), Pounder (1962) and Alguire (1962). Detailed accounts on the evolution of the Silurian stratigraphic nomenclature can be found in Martin and Straight (chart, p. 113, 1956) and in Shelden (1961).

Cohee (1948) introduced the term "Niagara" for a lithostratigraphic unit of group rank of Middle Silurian age, thus preserving the rock-stratigraphic sense of the name as it was originally defined by Hall in 1842 for Middle Silurian rocks in New York (Keroher et al., 1966).

The subsequent introduction of the name "Niagaran" as a chronostratigraphic designation (series) for the Middle Silurian time interval (Swartz et al., 1942) was unfortunate as it opened the way for potential confusion between rock and time-rock units. In accordance with the established subdivision in New York, Cohee divided the

Niagara Groups in Michigan into the Clinton Formation and the Lockport Dolomite in ascending order. More detailed stratigraphic studies, prompted by oil exploration in Ontario, resulted in further subdivision of the Lockport Dolomite into two units of unspecified rank. The term "Guelph" was used for the buff to brown porous dolomite of producing intervals, usually associated with reefs or bioherms and occurring in the upper part of the section, and the term "Lockport" for the remainder of the section (Evans, 1950). The binomial combination "Guelph-Lockport" prevails in many technical publications as a designation for the entire carbonate section between the Clinton and the Salina. Both names are in use in Northern Ohio (Ulteig, 1964; Summer-son, 1963; Kahle and Floyd, 1968). The term "Guelph" has occurred repeatedly in various stratigraphic schemes for Michigan (Martin and Straight, 1956) but its use was always informal and thus it does not appear as a recognized formal stratigraphic name in the "Lexicon of Geologic Names of the United States for 1936-1960" (Keroher et al., 1966).

An additional subdivision is based on the recognition of a three-fold vertical zonation according to predominant rock color. In ascending order it divides the Guelph-Lockport into a lower "White Niagaran", a middle "Gray Niagaran" and an upper "Brown Niagaran". This informal subdivision, inherited from driller's terminology, roughly corresponds to a noticeable three-fold subdivision of the gamma-ray log (Fig. 2-1). Its main disadvantage lies in the fact that it applies time-stratigraphic terms to rock-stratigraphic units. It has nevertheless gained wide acceptance in both Michigan and Ontario and is the prevailing terminology in the jargon of the oil industry (Pounder, 1962; Alguire, 1962; Ellis, 1967). In practical usage, "Brown Niagaran" is synonymous with "Guelph".

There are many objections to the prevailing stratigraphic nomenclature. The stratigraphic terminology employed is informal and type sections for reference and correlation have not been presented. The stratigraphic nomenclature proposed by Felber (1964) is a notable exception to the above reservations. However, his terminology has not been accepted and used, mainly because it requires the abandonment of well-established stratigraphic concepts and terminology. In addition, as will be shown below, it embodies some misconceptions in its failure to recognize the pre-Salina unconformity and the misinterpretation of the age relationships between the A-1

Unit and the reef.

The current terminology does not adequately accommodate the phenomenon of pinnacle reefs. There is a lack of uniform stratigraphic terminology. Thus the use of a different stratigraphic nomenclature in Michigan and in Ontario for the geology of contiguous subsurface Silurian strata is a source of confusion which should be corrected.

In attempting to avoid the introduction of new lithostratigraphic names, and in order to advance the standardization and uniform use of existing well established terms, I chose to use a terminology (Fig. 2-9) that represents an attempt to merge Cohee's original subdivision (1948) with that in current use in Ontario (Koepeke and Sanford, 1965). Thus, the term "Niagara" is retained for the rock-stratigraphic group containing, in ascending order, three formations: Clinton, Lockport Dolomite and Guelph. In southeast Michigan the Clinton Formation consists of about 40 feet of shale. It is probably equivalent to the Rochester Shale of Ontario. Guelph Formation is the name applied to the carbonate rocks which constitute the isolated pinnacle reefs and their thin penecontemporaneous inter-reef carbonate deposits. The Lockport Dolomite represents the regional carbonate sequence underlying the reef and interreef carbonate rock.

The Guelph Formation overlies the Lockport Dolomite conformably. The transition is gradual. The formation is presumed to be of late Middle Silurian age. This assertion is based on regional stratigraphic correlations as no direct paleontological age determinations are available. A major unconformity separates the Guelph Formation from its flanking onlapping and overlying Salina Group sediments of Upper Silurian age. The formation is fully developed only in areas of reef buildups, and in southeastern Michigan, consists entirely of dolomite.

Although dolomitization has obliterated much of the original depositional texture, there are distinct petrographic lithologic attributes by which the Formation has been divided in this study into four members. Three of the members correspond to the three distinct growth stages in the reef's evolution. They are (Fig. 2-9, 2-10)

- 1) The lowermost BRM Skeletal wackestone Member, corresponding to an initial biohermal growth stage,
- 2) The BRM Boundstone Member, corresponding to a second organic reef growth

stage and

- 3) The uppermost BRMStromatolite Member, corresponding to a terminal supratidal island growth stage.

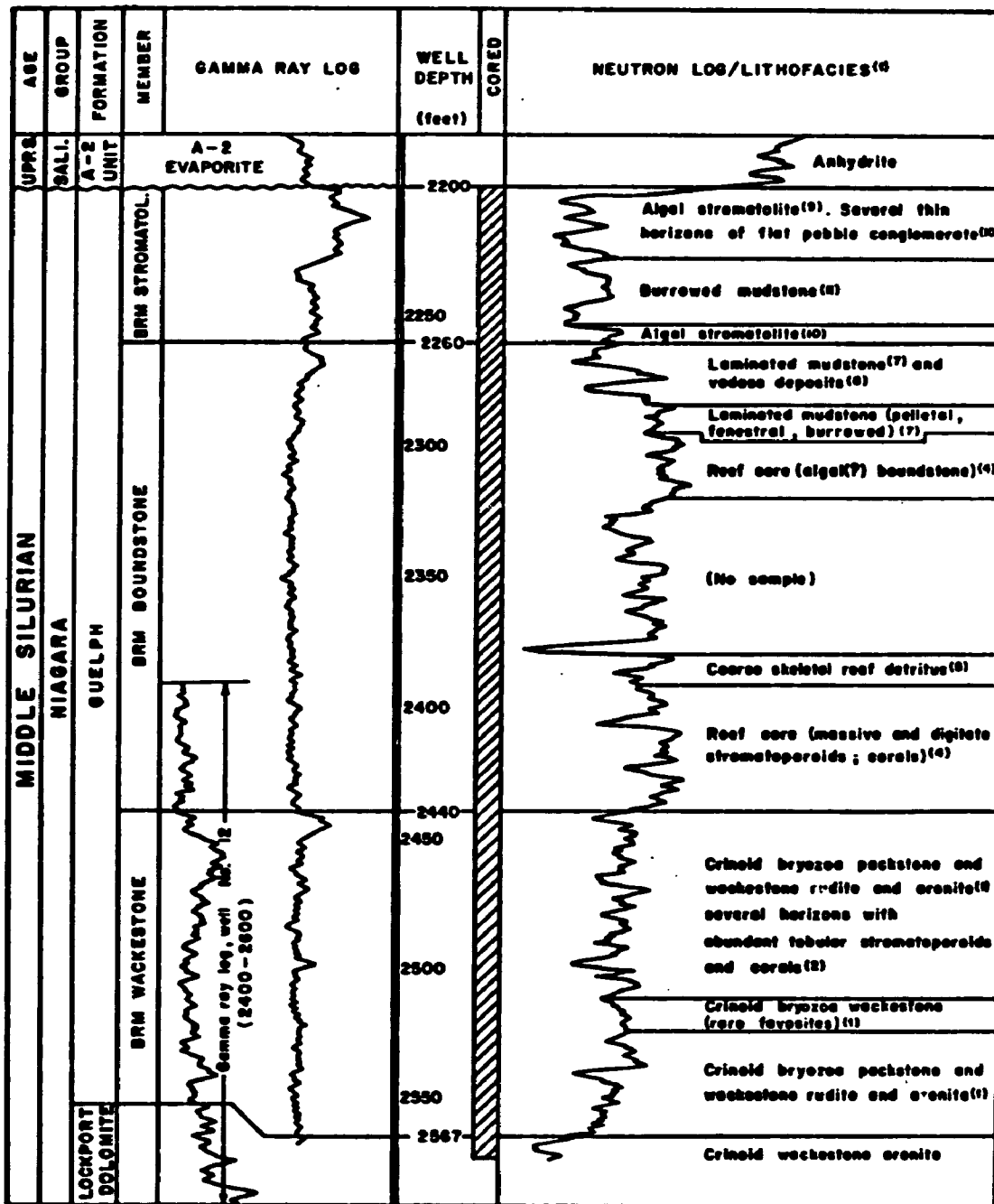
All three members are absent in off-reef areas. Their maximal thicknesses in the BRM reef are 245 feet, 202 feet and 75 feet respectively. Their maximal observed cumulative thickness is 431 feet.

The fourth member, the BRM Conglomerate, represents reef-derived rubble. A type section for this member is presented in Figure 2-11. It is confined to the lower slopes and immediate vicinity of the reef, attaining a maximal thickness in reef-flank wells where it overlies the BRM Skeletal Wackestone Member. In off-reef areas the BRM Conglomerate overlies the Lockport Dolomite (Figs. 2-1, 2-9, 2-12), and passes laterally into the regional thin interreef sediments which are time equivalent to the Guelph Formation. These sediments are commonly referred to as "Brown Niagaran".

The stratigraphic nomenclature for the Salina group was reviewed in the preceding section. In the present study, only the basal part of the section, Evans' A-1 Anhydrite and A-1 Carbonate units, was investigated in detail. A type section and a representative log for these units is shown in Figure 2-12. The nomenclature employed differs from the one in common use (Fig. 2-9) only with the addition of the "A-0 Carbonate" between the BRM Conglomerate Member of the Guelph Formation and the A-1 Anhydrite Unit of the Salina Group. This unit, only about five feet thick, was recognized earlier (R. Burgess, personal communication, 1969) but due to its limited thickness has not been identified as a separate unit and reported as such in the literature. It has been included by petroleum geologists within the upper part of the "Brown Niagara". However, it is important to recognize the A-0 Carbonate as the initial carbonate deposition in the Salina evaporite sequences.

No geologist argues that the A-2 Evaporite overlying the reef does not post-date the Guelph deposition. The main stratigraphic problem pertains to the time relationships between the lower units of the Salina Group (A-0 Carbonate; A-1 Carbonate; lower part of A-2 Evaporite; A-1 Anhydrite), which are present only in off-reef areas, and the Guelph reef structures against which these units wedge out. The juxtaposition

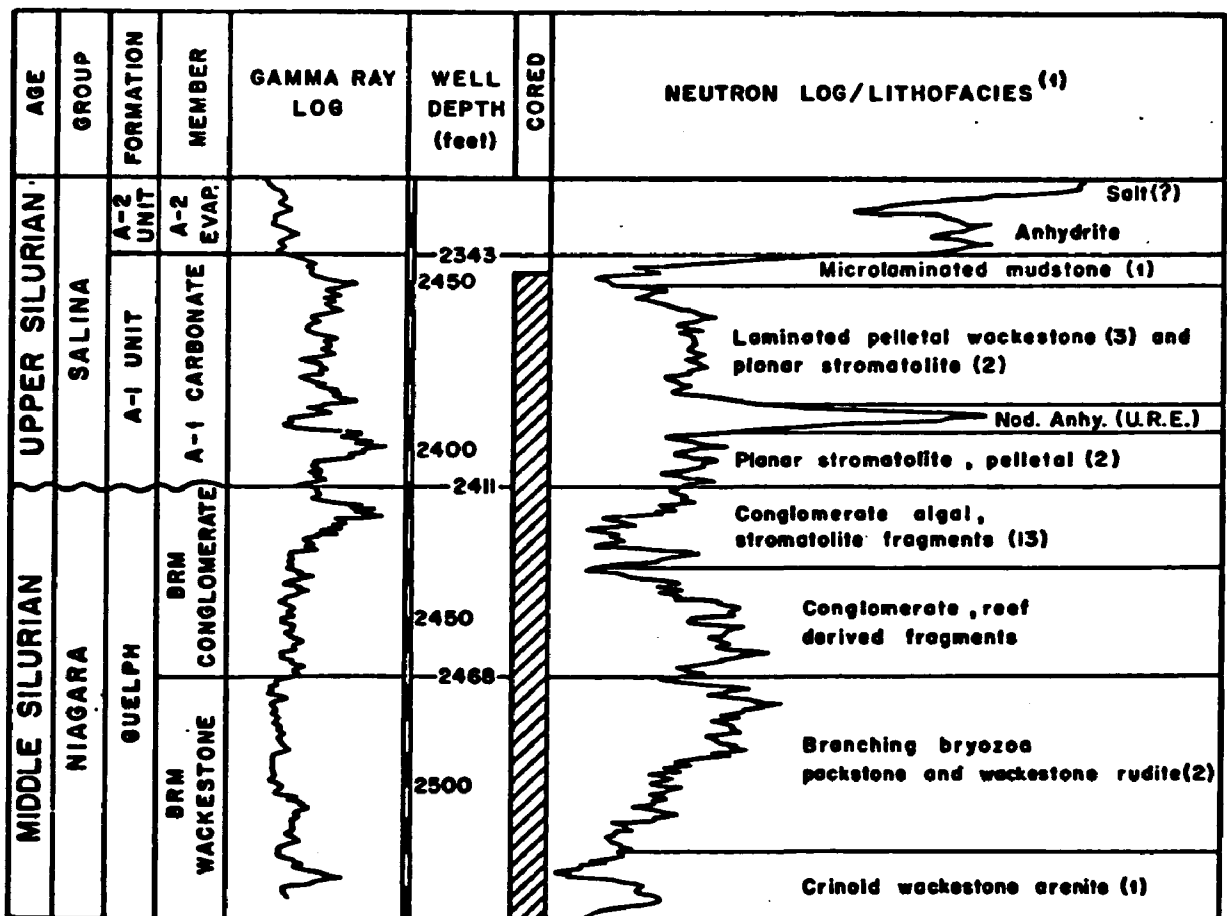
**GUELPH FORMATION
(REEF-CREST POSITION)
TYPE SECTION**
Mich. Cons. Gas Co. - R. Beier et al. no. 1
(well no. 19, interval 2200'-2567')



⁽¹⁾ Numbers in parentheses refer to lithofacies in chapter 3

Fig. 2-10. Guelph Formation (reef crest position) - type section and representative gamma ray - neutron logs.

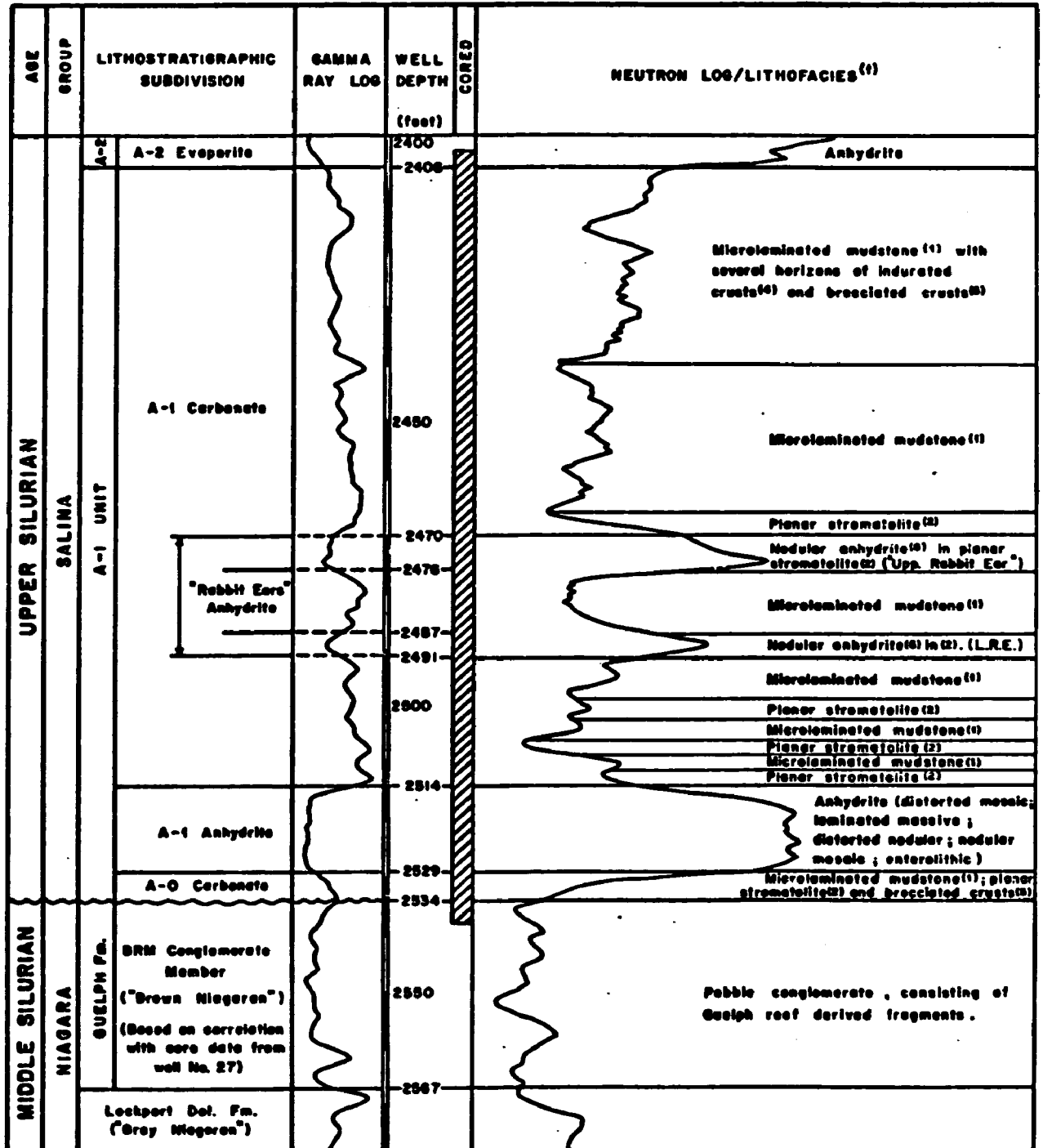
BRM CONGLOMERATE MEMBER
(GUELPH FORMATION, REEF-FLANK POSITION)
TYPE SECTION
 Mich. Cons. Gas Co. - Douglas Schunk no. 2
 (well no. 4, interval 2411'-2468')



⁽¹⁾ Numbers in parentheses refer to lithofacies in chapters 3 (Guelph) and 4 (A-1 Unit).

Fig. 2-11. BRM Conglomerate Member (Guelph Formation, reef-flank position) - type section and representative gamma ray - neutron logs.

**A-1 UNIT OF THE SALINA GROUP
TYPE SECTION**
Mich. Cons. Gas Co. - Radtke et al. no. 1
(well no. 3, interval 2406'-2534')



⁽¹⁾ Numbers in parentheses refer to lithofacies in chapter 4.

Fig. 2-12. Salina A-1 Unit - type section and representative gamma ray - neutron logs.

of reefs with an off-reef evaporitic sequence presents a perplexing stratigraphic problem which is of more than local interest. A similar situation is known to exist in other evaporite basins, notably in the Devonian and Mississippian of Alberta and Saskatchewan (Langton and Chin, 1968; McCamis and Griffith, 1968; Fuller and Porter, 1969; Shearman and Fuller, 1969) and in the Pennsylvanian of the Paradox basin (Gray, 1967). Since the Salina Group is devoid of fossils, its age relative to the reef can be derived only from lithostratigraphical relationships and from sedimentological considerations.

In most general terms, the two most likely opposing alternative interpretations can be stated as follows:

- 1) The deposition of the off-reef Salina units was contemporaneous with the growth of the reef (Felber, 1964; Sharma, 1966; Jodry, 1969; Sloss, 1969).
- 2) The Salina group post-dates the Guelph reefs.

A closely related question pertains to the existence of an erosional unconformity between the Niagara carbonates and the succeeding Salina evaporites. This question is of regional significance. If it can be proven that the Guelph reefs in the subsurface of southeastern Michigan were indeed exposed in pre-Salina times, it would necessarily follow that the same exposure prevailed also in the more elevated rims of the Michigan basin in Ontario, Ohio, Indiana, Illinois and Wisconsin. The existence of this unconformity has been the subject of much controversy and it appears that opinions are still widely divided on this issue (Ells, 1962, pp. 43-47).

Stratigraphers working in the subsurface of Ontario are the strongest proponents of an unconformity. Both Evans (1950, p. 76) and Pounder (1962, p. 9) advocate its existence on the basis of anomalous thicknesses of the Guelph-Lockport. Koepke and Sanford, although not discussing the problem explicitly, clearly indicate an unconformity in presenting cross sections for Guelph reefs in southwestern Ontario (Koepke and Sanford, 1966, Figs. 1-12, 38, 39, 42).

In Michigan opinions are still divided. Advocates of an unconformity include Alling and Briggs (1961, p. 542), Ells (1962, 1967) and Sharma (1966). On the other hand, Felber (1964, p. 19, p. 32) and more recently Jodry (1969) are opposed to it.

Investigations of surface exposures along the southern rims of the Michigan basin

have also resulted in conflicting opinions. According to Summerson (1963, p. 51) a disconformity separates the Greenfield Dolomite, the exposed equivalent of the A-1 Carbonate (Landes, 1945; Alling and Briggs, 1961; Ulteig, 1964), from the underlying Guelph. However, according to Ulteig (1964, p. 35) no unconformity seems to exist in the subsurface of northern Ohio. Shaver et al. (1961, pp. 23-25) and Pinsak and Shaver (1964, Fig. 3) review the evidence as afforded by surface exposures in northern Indiana and conclude that the existence of a pre-Salina unconformity is questionable.

These controversial questions have been hitherto unresolved since proponents of either alternative were unable to present conclusive evidence to support their interpretations. It appears that a key question which can conclusively resolve the matter pertains to the environmental conditions, particularly the water depth, which prevailed during the deposition of the A-1 Unit. This question was overlooked, avoided or otherwise not answered in all the previous studies quoted above. In Belle River Mills, the base of the Salina is some 430 feet below the reef crest. The fact that the Salina A-1, which post-dates the reef, was deposited in shallow water, necessitates that the Guelph reef was subaerially exposed previous to and during deposition of the A-1 Unit.

Any proposed unifying geological model for the Guelph reefs and their surrounding Salina sediments, if consistent, has to account for all the aspects of the stratigraphic relations. These include the geological evolution of the reef, the environmental interpretation of the A-1 Unit and the stratigraphic relationships between the above two units. In addition, stratigraphic and economic factors necessitate evaluation of the diagenetic history of the reef, which includes generation of porosity, porosity plugging by evaporite minerals, the pervasive dolomitization and the origin, migration and entrapment of petroleum.

Some of the main conclusions of the present study pertaining to the questions raised above are:

- 1) The reef developed in three growth stages, building up progressively from relatively deep water into the surf zone, eventually to the water surface.
- 2) In off-reef areas, the Salina A-1 Unit overlies the BRM Conglomerate Member of the Guelph Formation. As the conglomerate contains debris from the rocks deposited

at the crest of the reef during its terminal growth stage, the A-1 unit must be post-reef in age.

3) The Salina A-1 Unit was deposited in a supratidal sabkha environment. As such it cannot be contemporaneous with any part of the reef. During its deposition the reef was subaerially exposed.

4) The diagenetic alterations of the reef rocks originated during two periods of subaerial exposure to produce porosity and permeability through vadose leaching and dolomitization by sabkha brines.

5) The A-1 Carbonate is the source rock for the hydrocarbons contained in the reef.

Evidence to substantiate these assertions is presented in the succeeding chapters in which the petrographic and stratigraphic attributes of the Guelph Formation and the Salina A-1 Unit are discussed in detail.

GEOLOGY OF THE BELLE RIVER MILLS REEF

General

The evaluation of the geology of the reef is based on lithologic and stratigraphic data obtained from the 27 reef-wells and the ten reef-flank wells of the field (Tables 1-2, 3-1, 3-2). Cores covering the greater part of the Guelph Formation were available from twelve reef crest wells (numbers 11, 15, 18, 19, 22, 25, 26, 31, 32, 38, 39, 42). Parts of the Guelph Formation are also represented in cores from reef-flank wells (numbers 4, 28, 41) and off-reef wells (numbers 3, 5, 10, 27). The detailed Guelph stratigraphy of the remaining wells, either uncored or for which the core was not available, was established on the basis of gamma-ray log correlations. The detailed lithologic logs of the cored wells are presented in the lithofacies cross sections, Figures 3-9 through 3-13, and the pertinent stratigraphic data in Tables 3-1 through 3-4.

The entire reef lithology consists of dolomite. Although the pervasive dolomitization has destroyed much of the original limestone depositional textures, enough petrographic evidence remains to reconstruct this important parameter. The petrographic terminology used was developed for the description and classification of limestones. Dunham's (1962) classification, which emphasizes depositional textures, was found most useful. In a few cases, Folk's (1959, 1962) terminology was used. The prefix "dolo", which for the sake of completeness and accuracy should have appeared in all the petrographic designations, has not been included.

The reef consists of a multitude of rock types. Thirteen lithofacies, consisting of twenty five more or less distinct rock types, have been recognized. Within rock types wide variations in texture and constituent abundance are present. The various rock types grade into each other and interfinger spatially, and are but discrete samples of what is otherwise a continuous spectrum of variations. The grouping of lithotypes into a reduced number of broader lithofacies categories is thus instrumental in discriminating units of environmental significance whose spatial distribution can in turn be mapped and evaluated. Much of the interpretation of the mode of the reef's development and evolution is based on the lithofacies distribution shown in the cross

Well	A-1 Carb.	A-1 Anhy.	A-O Carb.	BRM Cong.	BRM Strom.	BRM Bound.	BRM Wackest.	Lock- port dolomite	White Niaga- ran	Clinton	T.D.	Cored Interval
1	2403	2514	(2529)	(2533)	-	-	-	(2562)		2525		2395-2522
2	2396	2514	(2525)	(2529)	-	-	-	(2561)		2523		-
3	2406	2514	2529	2534	-	-	-	2567	2596	2670		2406-2544
4	2343	-	-	2411	-	-	2468	(2566)				2347-2539
5	2398	2512	2526	2536	-	-	-	(2561)				2403-2546
6	2394	2508	2521	2526	-	-	-	2539				-
7	2398	-	-	2480	-	-	2509	(2574)				-
8	-	-	-	-	2184	2246	2412	2570				-
9	-	-	-	-	2193	2243	2443	(2573)				-
10	2425	2553	2566	2571	-	-	-	2588	2612	2682		2418-2513
11	-	-	-	-	2221	2265	2440	(2580)				2223-2523
12	-	-	-	-	2195	2248	2450	2562				-
13	-	-	-	-	2175	2234	2406	(2571)				-
14	2376	2483	2490	2494	-	-	(2514)	(2552)				-
15	-	-	-	-	2203	2264	2420	(2573)				2207-2521
16	2440	(2575)	(2597)	(2602)	-	-	-	(2604)				2442-2532
17	2416	2526	2541	(2550)	-	-	(2570)	(2582)				2411-2550
18	-	-	-	-	2207	2249	2418	(2578)				2210-2520
19	-	-	-	-	2200	2260	2440	2567				2200-2579
20	2390	(2495)	(2508)	(2508)	-	-	(2522)	(2557)				-
21	2400	2513	2538	2538	-	-	-	2550				-
22	-	-	-	-	2274	2312	2398	(2578)				2265-2517
23	2435	(2570)	(2597)	(2597)	-	-	-	(2601)				2436-2526
24	2441	(2556)	(2572)	(2572)	-	-	-	(2589)				2449-2521
25	-	-	-	-	2147	2214	2327	(2572)				2153-2516

Table 3-1. Stratigraphic data (well depth in feet to top of unit), Base A-2 Evaporite to well total depth.

(Parentheses denote inferred depth; dashes denote missing units).

Well	A-1 Carb.	A-1 Anhy	A-O Carb.	BRM Cong.	BRM Strom.	BRM Bound.	BRM Wackest.	Lock- port Dolomite ran	White Niaga-	Clinton	T.D.	Cored Interval
26	-	-	-	-	2231	2282	2423	(2558)			2509	2232-2505
27	2396	2493	2511	2516	-	-	-	2539	2582	2651	2671	2400-2536
28	2375	-	-	2468	-	-	2542	2584	2613	2684	2705	2377-2525
29	-	-	-	-	2145	2220	?	(2576)			2542	-
30	-	-	-	-	2241	2291	2426	(2558)			2524	-
31	-	-	-	-	2176	2232	2373	(2580)			2525	2181-2525
32	-	-	-	-	2257	2303	2419	(2560)			2507	2264-2506
33	2403	2497	2513	2518	-	-	-	2538			2554	-
34	2423	2525	(2536)	(2541)	-	-	(2561)	(2595)			2535	2424-2535
35	-	-	-	-	2176	2236	2403	(2587)			2549	-
36	-	-	-	-	2239	2285	2421	(2571)			2537	-
37	2462	(2582)	(2600)	(2605)	-	-	-	(2608)			2523	2462-2523
38	-	-	-	-	2227	2277	2437	(2592)			2512	2229-2512
39	-	-	-	-	2252	2289	2424	(2589)			2518	2256-2517
40	2418	2538	(2548)	(2553)	-	-	-	(2571)			2540	2420-2540
41	2454	2567	2579	2585	-	-	2599	2609	2646	2707	2722	2437-2601
42	-	-	-	-	2213	2279	2419	(2603)			2540	2215-2538
43	-	-	-	-	2265	2350	?	(2599)			2583	-
44	2450	2562	2582	2589	-	-	2603	2613	2644	2700	2723	2447-2553
45	2442	(2547)	(2552)	(2557)	-	-	(2577)	(2611)			2542	-
46	2438	2570	2581	2584	-	-	-	2595	2614	2673	2692	2439-2516
47	2454	2588	2610	2615	-	-	-	2627	2644	2705	2725	2455-2573
48	2468	2601	2610	2615	-	-	-	2622			2637	2476-2516
49	-	-	-	-	2168	2235	2414	(2565)			2547	-
50	-	-	-	-	2176	2234	?	(2572)			2549	-
51	-	-	-	-	2197	2261	2420	(2572)			2549	-
52	-	-	-	-	2187	2262	2404	(2559)			2528	-
53	-	-	-	-	2167	2231	2393	(2572)			2552	-
54	-	-	-	-	2171	2229	?	(2585)			2562	-

Table 3-1 (Continued)

Well	A-1 Carb.	A-1 Anhy	A-O Carb.	ERM Cong.	ERM Strom.	ERM Bound.	ERM Wackest.	Lock- port Dolomite	White Niaga- ran	Clinton	T.D.
1	1781	1892	(1907)	(1911)	-	-	-	(1940)			1903
2	1777	1895	(1906)	(1911)	-	-	-	(1942)			1904
3	1784	1892	1907	1912	-	-	-	1945	1974	1048	2065
4	1725	-	-	1793	-	-	1850	(1948)			1925
5	1785	1899	1913	1923	-	-	-	(1948)			1933
6	1793	1907	1920	1925	-	-	-	1938			1948
7	1776	-	-	1858	-	-	1887	(1952)			1948
8	-	-	-	-	1866	1628	1794	1952			1980
9	-	-	-	-	1875	1625	1825	(1955)			1948
10	1802	1930	1943	1948	-	-	-	1965	1989	2069	2071
11	-	-	-	-	1599	1643	1818	(1958)			1904
12	-	-	-	-	1585	1638	1840	(1952)			1997
13	-	-	-	-	1557	1616	1788	(1953)			1906
14	1774	1879	1886	1890	-	-	(1910)	(1948)			1906
15	-	-	-	-	1583	1644	1800	(1953)			1901
16	1821	(1956)	(1978)	(1983)	-	-	-	(1985)			1914
17	1800	1910	1925	(1934)	-	-	(1954)	(1989)			1934
18	-	-	-	-	1587	1629	1798	(1958)			1901
19	-	-	-	-	1796	1646	1826	1953			1985
20	1786	(1891)	(1899)	(1904)	-	-	(1918)	(1953)			1889
21	1801	1914	1914	1939	-	-	-	1951			1962
22	-	-	-	-	1656	1694	1770	(1960)			1899
23	1819	(1954)	(1954)	(1981)	-	-	-	(1985)			1911
24	1822	(1937)	(1937)	(1954)	-	-	-	(1970)			1902
25	-	-	-	-	1535	1602	1715	(1960)			1904
26	-	-	-	-	1626	1677	1818	(1953)			1904
27	1793	1890	1908	1913	-	-	-	1936	1979	2048	2068

Table 3-2. Structural data (feet below sea level to top of Unit), Base A-2 Evaporite to Well's total depth (parentheses denote inferred elevations; dashes denote missing units).

Well	A-1 Carb.	A-1 Anhy	A-O Carb.	BRM Cong.	BRM Strom.	BRM Bound.	BRM Wackest.	Lock- port Dolomite	White Niaga- ran	Clinton	T.D.
28	1756	-	-	1849	-	-	1923	1965	1994	2065	2036
29	-	-	-	-	1529	1604	?	(1960)	-	-	1920
30	-	-	-	-	1638	1688	1832	(1955)	-	-	1924
31	-	-	-	-	1561	1617	1758	(1965)	-	-	1910
32	-	-	-	-	1652	1698	1814	(1955)	-	-	1902
33	1798	1892	1908	1913	-	-	-	1933	-	-	1949
34	1803	1906	(1916)	(1921)	-	-	(1941)	(1975)	-	-	1915
35	-	-	-	-	1557	1617	1784	(1963)	-	-	1930
36	-	-	-	-	1630	1676	1812	(1962)	-	-	1928
37	1841	(1961)	(1979)	(1984)	-	-	-	(1987)	-	-	1902
38	-	-	-	-	1813	1863	1923	(1978)	-	-	1898
39	-	-	-	-	1635	1672	1807	(1972)	-	-	1901
40	1811	1931	(1941)	(1946)	-	-	-	(1964)	-	-	1933
41	1833	1946	1958	1964	-	-	1878	1988	2025	2086	2101
42	-	-	-	-	1593	1639	1799	(1983)	-	-	1920
43	-	-	-	-	1647	1680	?	(1981)	-	-	1965
44	1829	1941	1961	1968	-	-	1982	1992	2023	2079	2102
45	1824	(1929)	(1934)	(1939)	-	-	(1959)	(1993)	-	-	1924
46	1833	1965	1976	1979	-	-	-	1990	2009	2068	2087
47	1836	1970	1992	1997	-	-	-	2009	2026	2087	2107
48	1850	1983	1992	1997	-	-	-	2004	-	-	2019
49	-	-	-	-	1555	1622	1801	(1952)	-	-	1934
50	-	-	-	-	1586	1614	?	(1952)	-	-	1929
51	-	-	-	-	1577	1641	1800	(1952)	-	-	1929
52	-	-	-	-	1583	1658	1800	(1955)	-	-	1924
53	-	-	-	-	1550	1614	1771	(1955)	-	-	1935
54	-	-	-	-	1549	1607	?	(1963)	-	-	1940

Table 3-3 (Continued)

Well No.	A-1 Carb.	A-1 Anhy	A-O Carb.	BRM Cong.	BRM Stromat.	BRM Boundst.	BRM Wackest.	Total Guelph
1	111	11+(15)	(4)	(29)	-	-	-	(29)
2	118	9+(11)	(5)	(31)	-	-	-	(31)
3	108	15	5	33	-	-	-	33
4	68	-	-	57	-	-	75+(98)	132+(155)
5	114	14	10	10+(25)	-	-	-	10+(25)
6	114	13	5	13	-	-	-	13
7	82	-	-	29	-	-	61+(65)	90+(94)
8	-	-	-	-	62	166	158	386
9	-	-	-	-	50	200	123+(130)	373+(380)
10	128	13	5	17	-	-	-	17
11	-	-	-	-	44	175	86+(140)	305+(359)
12	-	-	-	-	53	202	112	367
13	-	-	-	-	59	172	118+(165)	349+(396)
14	105	7	4	16+(20)	-	-	(38)	16+(38)
15	-	-	-	-	61	156	101+(153)	318+(370)
16	93+(135)	(22)	(5)	(2)	-	-	-	(2)
17	110	15	9	(20)	-	-	(15)	(35)
18	-	-	-	-	42	169	103+(160)	314+(371)
19	-	-	-	-	60	180	127	367
20	103+(105)	(8)	(5)	(14)	-	-	(35)	(49)
21	113	20	5	12	-	-	-	12
22	-	-	-	-	38	76	129+(190)	243+(304)
23	92+(135)	(22)	(5)	(4)	-	-	-	(4)
24	80+(115)	(12)	(5)	(6)	-	-	-	(16)

Table 3-3. Thickness of Lithostratigraphic sub units, Guelph Formation and Salina A-1 Unit.
(parenthesized figures denote inferred thicknesses).

Well No.	A-1 Carb.	A-1 Anhy	A-O Carb.	BRM Cong.	BRM Stromat.	BRM Boundst.	BRM Wackest.	Total Guelph
25	-	-	-	-	67	113	189+(245)	369+(425)
26	-	-	-	-	51	141	861+(135)	278+(327)
27	97	18	5	23	-	-	-	23
28	93	-	-	74	-	-	42	116
29	-	-	-	-	75	?	?	397+(431)
30	-	-	-	-	50	135	98+(132)	283+(317)
31	-	-	-	-	56	141	152+(207)	349+(404)
32	-	-	-	-	46	116	88+(141)	250+(303)
33	94	16	5	20	-	-	-	20
34	102	10+(11)	(5)	(20)	-	-	(34)	(54)
35	-	-	-	-	60	167	146+(184)	373+(411)
36	-	-	-	-	46	136	116+(150)	298+(332)
37	61+(120)	(18)	(5)	(3)	-	-	-	(3)
38	-	-	-	-	50	160	75+(155)	285+(365)
39	-	-	-	-	37	135	94+(165)	266+(337)
40	120	2+(10)	(5)	(18)	-	-	-	(18)
41	113	12	6	14	-	-	10	24
42	-	-	-	-	64	140	121+(184)	327+(390)
43	-	-	-	-	33	?	?	318+(344)
44	112	20	7	14	-	-	10	24
45	100+(103)	(5)	(5)	(20)	-	-	(34)	(54)
46	132	11	3	11	-	-	-	11
47	134	22	5	12	-	-	-	12
48	133	9	5	7	-	-	-	7
49	-	-	-	-	67	179	133+(151)	379+(397)
50	-	-	-	-	58	?	?	373+(396)
51	-	-	-	-	64	159	129+(152)	352+(375)
52	-	-	-	-	75	142	124+(155)	341+(372)
53	-	-	-	-	64	157	164+(184)	385+(405)
54	-	-	-	-	58	?	?	391+(414)

Table 3-3 (Continued)

SubUnit Well	A-1 Unit			Guelph Formation				Lockport
	A-1 Carb.	A-1 Anhy.	A-O Carb.	BRM Cong.	BRM Stromat.	BRM Boundst.	BRM Wackest.	Dolomite
1	+	+						
3	+	+	+	+				
4	+			+			+	
5	+	+	+	+				
10	+	+	+	+				
11					+	+	+	
15					+	+	+	
16	+							
17	+	+	+					
18					+	+	+	
19					+	+	+	
20	+							+
22					+	+	+	
23	+							
25					+	+	+	
26					+	+	+	
27	+	+	+	+				
28	+			+				
31					+	+	+	
32					+	+	+	
34	+	+						
37	+							
38					+	+	+	
39					+	+	+	
40	+	+						
41	+	+	+	+			+	
42					+	+	+	
44	+							
46	+							
47	+							
48	+							

Table 3-4. Representation of Guelph Formation and Salina A-1 Unit in cores.

sections (Figs. 3-9 to 3-13). These facies diagrams attempt to project a limited number of discrete raw data into a continuous spatial picture. The wide separation of the control points does not enable an objective and unambiguous between-wells interpretation. The saw tooth between-well interpolation lines are by default questionable; therefore, the interpolation process is by necessity subjective. As such, it is partly based on some preconceived notions as to how the various facies might be interrelated, thereby introducing an element of conceptual bias into the interpretation. Consequently, the facies distribution charts cannot be regarded as independent proof of the validity of the conceptual model which was employed in their construction.

Much has been written on the subject of "reef-terminology". Comprehensive discussions on this subject can be found in Cumings (1932), Lowenstam (1950), Newell *et al.* (1953), Pray (1958), Nelson *et al.* (1962), Klován (1964) and Klement (1967). Most authors accept the genetic connotations and environmental implications of the term "reef" but propose to restrict the usage of the term "bioherm" to a descriptive morphological designation for a mound-shaped skeletal accumulation. In the present study, both terms are used in a genetic as well as morphologic sense. The term "reef" or "organic reef" is employed in accordance with Lowenstam's (1950) often-quoted definition. To qualify as a reef, structures must show evidence that they were erected and strengthened by organisms capable of building and raising a skeletal framework above the sea bottom and potentially capable of growth into turbulent surface waters, to which they would be wave resistant (Lowenstam, 1950, p. 435). "Thus a reef, in terms of ecologic principles, is the product of the actively building and sediment-binding biotic constituents, which, because of their potential wave resistance, have the ability to erect rigid, wave resistant topographic structures" (*ibid.*, p. 433). On the other hand the term "bioherm", as used here, connotes mound-shaped bodies which form sea floor prominences consisting of skeletal material embedded in a predominantly mud matrix, which are believed to have developed in relatively deep and quiet water, below wave base. "Bioherm" in this sense of the definition is also used by Cloud (1952, p. 2127) and Sangree (1960, p. 94).

The analysis of the geology of the Belle River Mills reef is presented from an evolutionary standpoint. As stated earlier, the Guelph Formation is divided into four lithostratigraphic members, corresponding to distinct growth phases in the reef's

history. Each of the sections in this chapter treats a separate member (growth stage), in terms of its boundaries, thickness and distribution, gamma-ray log characterization, the various lithofacies present and their distribution and environmental interpretation.

Reef Substrate - The Lockport Dolomite

The Lockport Dolomite overlies the Rochester Shale Member of the Clinton Formation. Depending on its position relative to a reef mass, the Lockport Dolomite is overlaid by the different lithofacies of the Guelph Formation, the BRM Skeletal wackestone Member in the reefs, and in off-reef areas, the BRM Conglomerate or its penecontemporaneous basinal equivalent, the "Brown Niagaran" (see Fig. 2-9). Only 15 of the 54 wells studied have encountered this formation (see Table 3-1). Of those, the seven off-reef wells and one reef-flank well (28) which bottomed in the Clinton Formation penetrated the entire Lockport Dolomite, whereas the remaining seven wells, three of which are reef-wells, penetrated only the uppermost part of this formation.

Only eight feet of core was available for study of reef substrate (interval 2567-2575 in reef-well no. 19). Disjointed crinoid stem debris, up to 0.5 cm in diameter, constitute about 10% of the rock and are scattered in a dense argillaceous carbonate mud matrix. This lithology is also present in the lowermost portion of parts of the overlying BRM Skeletal Wackestone Member (wells 4, 11, 15, and 32), in places grading into dense mudstone with abundant stylolites (Pl. 1/1). Pronounced compactional features are developed in rocks of stylolitic dense mudstone in well no. 4, a reef-flank well in which the Salina Group directly overlies the BRM Skeletal Wackestone Member. The rock has a nodular fabric. The nodules are elliptical in shape, elongated parallel to the bedding and are surrounded by dark argillaceous material which appears to be squeezed around the nodules (Pl. 1/2). A similar fabric, termed "sedimentary boudinage" has been described in the Devonian Ireton Formation of Alberta (McCrossan, 1952). Its origin was attributed to the effects of compactional forces, acting differentially on components of different plasticity in an inhomogeneous sediment. The boudinage fabric in argillaceous mudstone occurs also in core samples

from the Lockport Dolomite in the northern part of the Lower Peninsula of Michigan: McClure Griner no. 1 (16-24N-13W; 5583'-5605') and Northern Mich. Expl. Dreeves no. 1 (5-26N-10W; 5810'-5830'). A compactional origin is also advocated for the nodular fabric observed in this study. Lacking the "protective" cover of the more rigid rocks of the BRM Boundstone Member, the Lockport Dolomite in off-reef and reef-flank areas was thus more exposed and susceptible to compaction.

The lithologic transition from the reef substrate to biohermal rocks is gradual. This is further manifested by the indistinctness of this boundary on the gamma-ray log. In well no. 19 in which the transition zone was cored, no boundary is apparent on the log. The boundary can be discerned only in the marked decrease in argillaceous content in the basal part of the bioherm, apparent also in wells 8 and 12, the only other reef-wells which bottomed within the Lockport Dolomite. See reef type section (Fig. 2-10). The contrast in content of clayey material between the off-reef Guelph and the underlying Lockport is more pronounced and hence, in off-reef wells the boundary is readily recognized on gamma ray-logs (Fig. 2-12).

These criteria for recognition of the Lockport-Guelph contact were used in constructing the Lockport structure contour map (Fig. 3-1). Since the present regional dip is only about 40 feet to the mile (less than 0.5 degrees to the northwest) this map also represents a reconstruction of the topography of the reef substrate or pre-Guelph surface. Shown on the map are the approximate boundaries of the biohermal buildup and the reef's crest. It is apparent that the localization of the reef bears little relationship to any pronounced bottom topographic features. The topography is one of a broad, gently sloping and rather flat and regular shelf surface, probably below the influence of wave agitation. Inhabitation by the pioneering population of bryozoans and crinoids, initiating biohermal development, probably relates to some random localization of favorable ecological conditions, such as the distribution pattern and intensity of bottom currents, availability of nutrients and the like.

The reef substrate, derived from the Lockport structure contour map, constitutes an important reference horizon to which all subsequent isopach computations are related. The map was instrumental also in estimating elevations of the top of the Lockport in 39 wells which bottomed above this marker (Table 3-2). This inherent

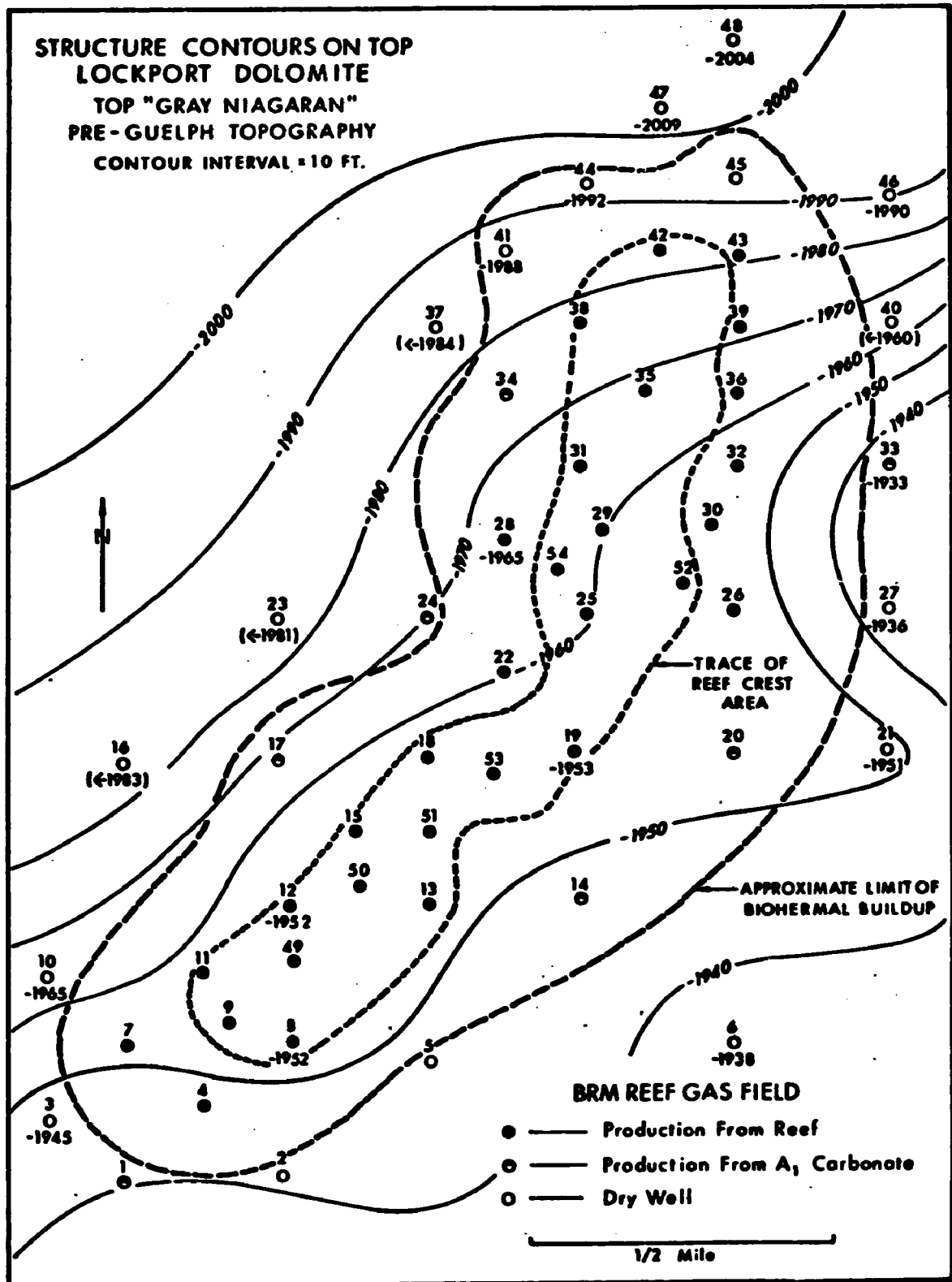


Fig. 3-1. Structure contour map on top Lockport Dolomite Formation portraying topography of reef's substrate.

limitation should not be regarded too critically, however. In the first place, the Lockport structure map is based on 15 broadly distributed wells which is adequate for the size of area in question. Furthermore, through the construction of isopach and structure maps of the various stratigraphic units overlying the Lockport Dolomite, reasonable thicknesses can be projected to forecast the downhole stratigraphy of undrilled intervals in each well. These independently obtained estimations are compatible with the depth figures obtained through interpolation.

Biohermal Stage -- The BRM Skeletal Wackestone Member

Boundaries, Thickness and Distribution

Stratigraphically the BRM Skeletal Wackestone is the lowermost member of the Guelph Formation. The unit is present only in areas of Guelph-reef development. It overlies the Lockport Dolomite and is overlaid by the BRM Boundstone Member of the Guelph Formation (Fig. 2-9). The unit can be recognized on gamma ray logs, although the log features which characterize it are not everywhere as well developed as in the type log (Fig. 2-10). Typically, the gamma ray intensities are intermediate, slightly lower than in the underlying argillaceous substrate and higher than in the clay-free organic reef rocks. The curve is rather wiggly and "noisy", most probably due to the rapid vertical variations in clay concentration, as observed in lithotype 1 of the biohermal rocks (see below). On the basis of these attributes it was possible to differentiate the member in 11 of the 15 reef wells which were not cored. Exceptions to the general pattern occur whenever lithotypes 5 and 6 (see below) are present at the top of the unit. In these cases the top of the member can not be reliably read from the log. This is apparent in wells no. 11, 15, 16, 22, 31, 32, 38, 39, 42 in which the top could nevertheless be determined from core samples. In wells no. 29, 43, 50, and 54 on the other hand, cores were not available and the top of the member could not be determined. A similar correlation problem exists in reef-flank wells. The log attributes are again not distinct enough to separate the BRM Skeletal Member from the overlying BRM Conglomerate Member with confidence (see reef-flank type section, Fig. 2-11). Both members are present in cores from wells no. 4 and 41. In wells no. 7, 28 and 44 their recognition is based on tentative correlation.

The thickness and distribution of the BRM Skeletal Wackestone Member is summarized in Table 3-3 and presented graphically in the isopach and structure maps, Figures 3-2, 3-3 and the topographic cross sections, Figures 3-17, 3-18.

The isopach map (Fig. 3-2) provides a reconstruction of the configuration of the buildup at the termination of the biohermal stage. The bioherm forms an elliptical mound, elongated in a northeasterly direction. It is about two miles long and 0.75 miles wide. At its base it covers an area of about 700 acres. It attains a maximum thickness of 245 feet (well no. 25) in the central part of the mound. The mound is slightly asymmetrical. Slopes on the south and the eastern side are gentle, between 5 and 9 degrees. On the western and northern flanks the overall slope varies between 8 and 13 degrees. In the upper part of these flanks, slopes might reach 33 degrees (Fig. 3-2 between wells no. 28 to 42, see also topographic profile B, Fig. 3-17). The outline of the base of the structure was arrived at by extrapolating the slopes outward until they merge with the level at which the Lockport Dolomite is encountered (see structure map, Fig. 3-1). In doing so, it became evident that the BRM Skeletal Wackestone Member should be present in some additional wells in which drilling bottomed in the Salina Group above it. Therefore, wells no. 14, 17, 20, 34, and 45 are considered as flank wells for which an estimated biohermal thickness is indicated on the map (parenthesized figures in Fig. 3-2 and Table 3-3). A further justification for employing this procedure can be derived from the stratigraphy of well no. 41. The well is located on the periphery of the structure and the presence of biohermal rocks in it is confirmed by core samples (see facies cross section H, Fig. 3-12).

Lithofacies Classification

The three lithofacies which comprise the biohermal stage are the Skeletal Biomicrite ("biohermal") Facies, the Bioherm-core ("Knoll") Facies, and the Skeletal-lithoclast Facies. A detailed description of each lithofacies and its constituent lithotypes follows.

Lithofacies 1: Skeletal biomicrite ("Biohermal") Facies (Plates 1, 2). A wide range of rock types, with a complete gradation from one type to the other, is present. On the basis of skeletal constituents, these can be divided conveniently into three types:

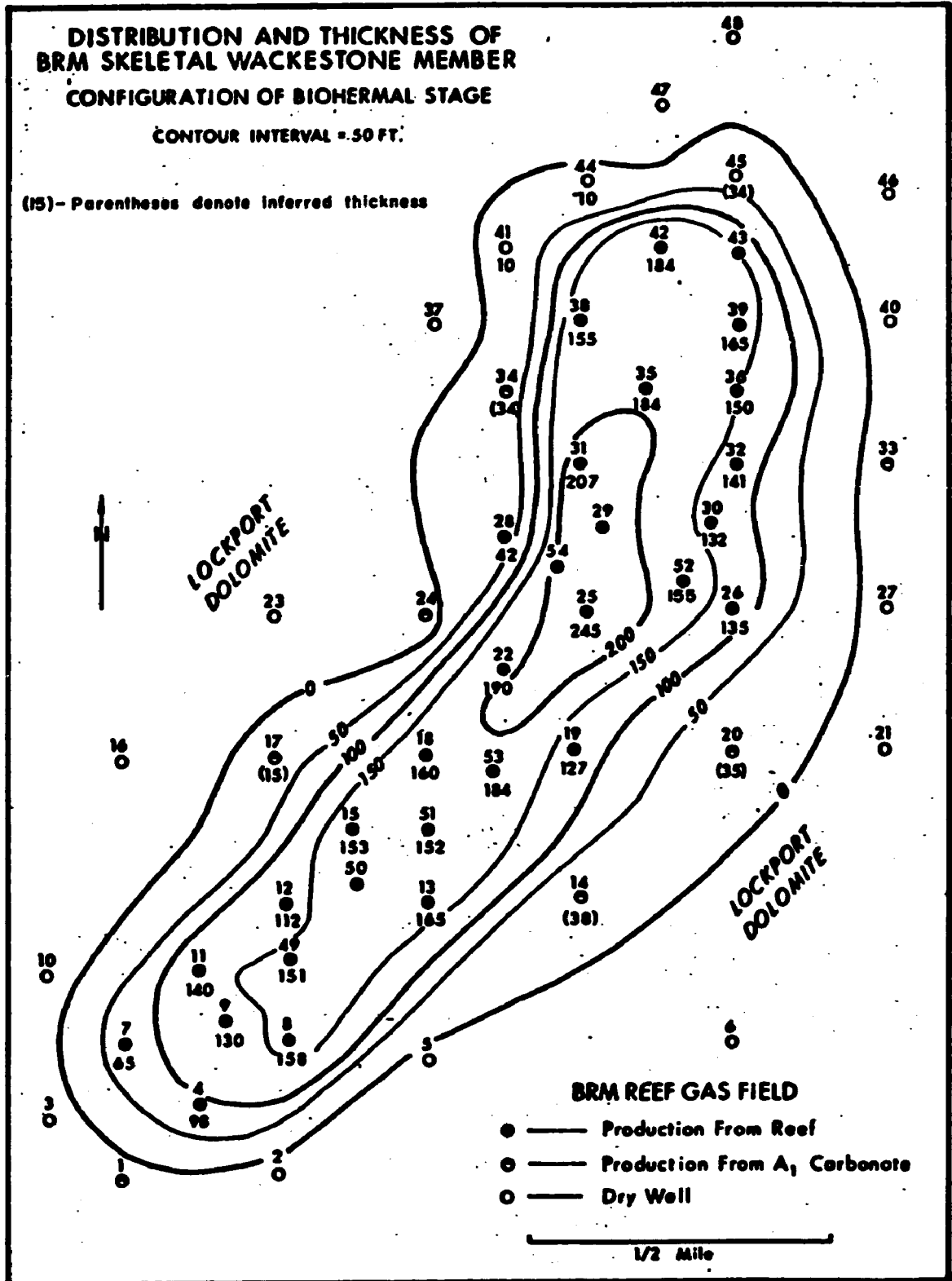


Fig. 3-2. Isopach map, BRM Skeletal Wackestone Member.

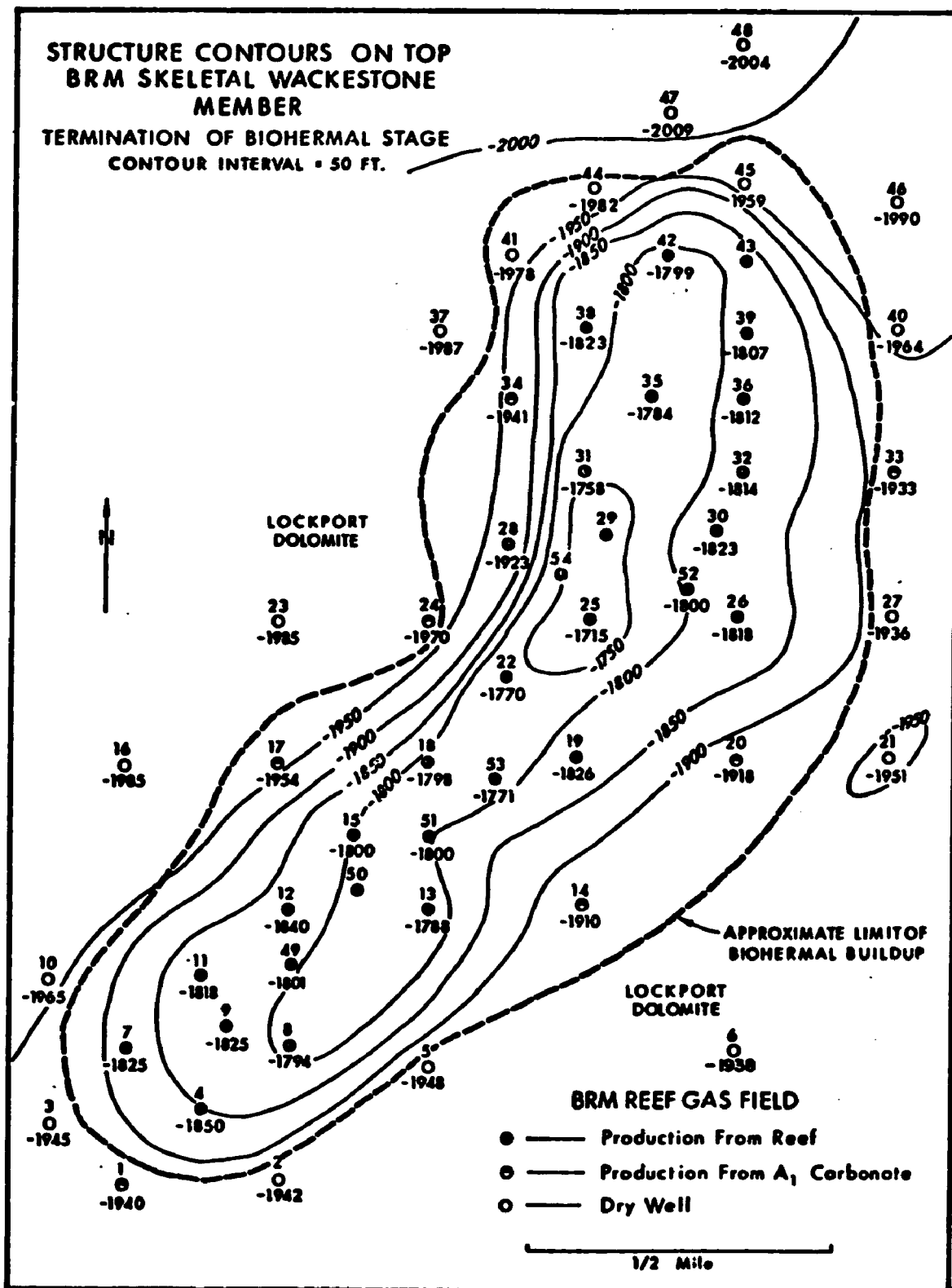


Fig. 3-3. Structure contour map on top BRM Skeletal wackestone Member.

crinoidal biomicrite, crinoid-bryozoa biomicrite and skeletal biomicrite with frame builders.

Lithotype 1: The main textural components of the crinoidal biomicrites are crinoid fragments and a micritic mud matrix. Depending on the relative abundance of skeletal grains and carbonate mud, on the skeletal grain size range and in particular on the grain vs. mud support attributes, more detailed rock types can be recognized (Plate 1, Figs. 3, 4, 6) including crinoid wackestone arenites and rudites, and crinoid packstone arenites and rudites. Quite commonly the lithotypes are intimately mixed. In presenting the raw lithologic data on the various facies cross sections, I have attempted to portray and represent these small scale variations by using designations like "crinoid wackestone, locally packstone, rudite" (CW(P)R, well no. 25, Fig. 3-10) or "crinoid wackestone arenite and rudite" (CWA,R, well no. 42, Fig. 3-13. See also legend to facies cross sections, Table 3-5).

The crinoid biomicrites are light to dark gray in color. Bedding is massive. Only in a few places are rudimentary bedding features present. These can be recognized by slight variations in color along short, discontinuous undulating lines and when present are probably associated with local concentrations of argillaceous material (Pl. 1/6). Sorting of skeletal grains varies considerably within very short distances and might frequently change within the dimensions of individual slabbed surfaces. The skeletal fragments do not show any preferred stratigraphic orientation and are scattered randomly throughout.

The nature of the original matrix of the crinoid biomicrites can be evaluated from thin section observations. Presently, intraskeletal material consists of a densely interlocked xenotopic mosaic of anhedral dolomite crystals, 20 to 40 microns in size. Relicts of the original carbonate mud matrix can, however, be traced to the occasional occurrence of dolomitized but unrecrystallized dark brown patches of micritic material. Similar material is often present as infillings of central canals of crinoid stems (Pl. 1/4) or as a flat-topped internal sediment in brachiopod shells (Pl. 1/9) which represents entrapment of original carbonate mud present at the site and time of deposition.

Lithotype 2: The crinoid-bryozoa biomicrite is essentially similar to the crinoidal

biomicrite with the conspicuous addition of very delicate, feather-like forms of bryozoans. Mud supported wackestone rudite, in which grain abundance ranges from 10 to 30 percent and grain size ranges from a few millimeters up to 4 centimeters, is the most abundant rock type (wells 11, 15, 42, 38, 22; see facies cross sections and Pl. 1/5 and Pl. 1/7). As in the case of the crinoidal biomicrites, a multitude of more specific rock types which grade into each other can be separated on the basis of grain abundance and size, thus, combinations like "crinoid bryozoa packstone, locally wackestone, rudite and arenite" (CBP(W)R, A; well no. 19, Fig. 3-9), which represents mixtures of the more specific petrographic end numbers, are not uncommon.

Lithotype 3: Skeletal biomicrites with frame builders are characterized by corals and tabular stromatoporoids in subordinate amounts embedded in the above two lithotypes. In some rocks, only an individual organism (or colony) is present. Their occurrence is sporadic and individuals do not interlock to form a rigid frame. Some are in growth position but many are not. These might nevertheless be in place or derived from the neighboring and interfingering knoll areas. Favosites (Pl. 1/8) and Halysites species are the most common tabulate corals present. Other tentatively identified species include Heliolites Sp (?) (Pl. 2/2), Arachnophyllum Sp (?) (Pl. 2/1), Alveolites Sp (?) and Syringopora Sp (?). Also present are solitary and colonial rugose corals (Pl. 1/8), some of which have been tentatively identified as Tryplasma Sp (?).

Their occurrence is represented on the facies distribution charts by parenthesized designations (see legend to cross sections, Table 3-5).

In all of the rock types which comprise the biohermal stages, assessment of the nature of the original matrix in the grain supported rock types is somewhat more dubious. The problem is compounded due to dolomitization. It can be resolved by applying petrographic criteria (Bathurst, 1958; Orme and Brown, 1963; Folk, 1965; Chilingar *et al.*, 1967) to distinguish between "grain growth" or "neomorphism" and "open-space filling" recrystallization mosaics. The present dolo-sparry cement is very fine grained, has implicate curved and irregular crystal boundaries and lacks the systematic crystal size enlargement away from grains which is considered typical of void filling cements. An additional grain growth feature is the presence of replacement syntaxial rims around crinoid ossicles. They are in optical continuity with the

single-crystal crinoid fragment and show highly irregular crystal boundaries. It is noteworthy that the optical continuity was preserved despite the subsequent dolomitization process.

Lithofacies 2: Bioherm Core ("Knoll") Facies. The bioherm core facies consists of a tabular stromatoporoid subfacies, and a branching bryozoa subfacies.

Lithotype 4: In the tabular stromatoporoid subfacies, platy tabular stromatoporoids, embedded in skeletal biomicrite, constitute in places up to about 30 per cent of the rock. Individual colonies are usually very thin, less than 0.5 cm in thickness. In the majority of cases no internal structure is preserved and colonies appear as thin planar, sometimes undulating white streaks (Pl. 2/4) which might occasionally show internal laminations due to differential leaching (Pl. 2/5). Only rarely do colonies reach a thickness of 2 to 3 cm. It is in these rocks that one can vaguely discern some indication of an internal stromatoporoidal organization of fine laminae with vertical short pillars between them (Pl. 2/3). Large tabulate and small rugose corals occur in subordinate amounts (Pl. 2/6) in some rocks.

This lithology persists through some vertical sections ranging in thickness from 10 to 60 feet (in well 42, Fig. 3-13). Often the continuity of the facies is interrupted by interbedded skeletal biomicrites lacking stromatoporoids similar to Lithofacies 1 (sections E and I, Figs. 3-9, 3-13).

Lithotype 5: Petrographically the branching bryozoa subfacies consists of tan skeletal packstone and wackestone rudites with a micritic mud matrix. Branching bryozoans occur in great abundance, typically constituting up to 40 per cent of the rock (Pl. 2/7, 2/8) and commonly to the exclusion of other organisms. Rugose corals, and to a lesser extent, crinoid ossicles, occur in subordinate amounts. In comparison with the delicate plumose bryozoans encountered in other parts of the bioherm (Lithofacies 1), the present species is typically a more robust form characterized by a thicker wall structure and a relatively large size. Fragments and well preserved whole individuals reaching 4 cm in length are not uncommon. The branching bryozoan lithology forms biostromal units 10 to 20 feet in thickness which interfinger with other rock types of the biohermal stage (see in particular wells 11 and 39, Sections E and H, Figs. 3-9, 3-12). Small buildups reach a thickness of 40 feet (well 38, section I,

Fig. 3-13).

Lithofacies 3: Skeletal-lithoclast Facies. Skeletal fragments and lithoclasts constitute from 30 to 60 percent of the lithology. The skeletal fragments represent the entire suite of organisms mentioned so far with the conspicuous addition of whole and broken brachiopod shells (Pl. 2/9). Entire and broken crinoid and bryozoan fragments are abundant; coral and tabular stromatoporoid fragments are less common.

The lithoclasts fragments consist of very fine grained, dense, brown-gray micritic dolomite; most are subrounded to angular, with a highly irregular outline and with a size range of 1 to 20 mm. Sorting of both the skeletal and the rock particles is poor. Many grains are coated by a thin dark-brown micritic envelope (Pl. 2/10). The matrix consists of a xenotopic mosaic of very fine anhedral dolomite crystals with occasional irregular minute patches of dolomitized but otherwise unaltered carbonate mud. Fabric includes both grain and mud support, the former being more abundant. In a few places bedding planes are inclined up to 20 degrees. The skeletal lithoclast forms massive beds mostly from 10 to 25 feet thick, and more rarely continuous vertically for 60 feet (wells 22, section F, Fig. 3-10 and Fig. 3-31, sections G and I, Figs. 3-11, 3-13).

Facies Distribution and Environmental Interpretation

The lithofacies comprising the biohermal stage, as portrayed in the facies cross sections, Figs. 3-9 through 3-13, grade into each other and interfinger spatially. Although each individual cross section seems to show a somewhat different pattern, reflecting local facies variations, all cross sections share some aspects in common, thus permitting the construction of a generalized facies distribution model. This is best illustrated in the longitudinal north-south section (Fig. 3-13) which, due to its larger areal coverage, is also more representative of the structure as a whole.

Volumetrically, the crinoid-bryozoan biomicrite is the most abundant lithofacies, being the most widespread and constituting the bulk of the "knoll" areas as well. This lithofacies is estimated to constitute about 70 percent of the total biohermal lithotype.

Several textural, fabric, paleoecologic and stratigraphic properties attest to a low-energy origin for this facies. The presence of argillaceous material, and the abundance of mud, indicate that water movement was too low to winnow out clay size

material. Both crinoids and bryozoans are mud dwelling organisms with a structure too delicate to sustain wave pounding (Kissling, 1969; Duncan, 1957). The accumulation of crinoid stem plates and bryozoan debris, even in places where it forms a rather coarse packstone calcirudite, represents disintegration in situ rather than an active current accumulation. This is further confirmed by the lack of any definite bedding features, the diverse orientation of the skeletal grains and the intricate temporal small scale transitions from a grain supported to a mud supported bioaccumulation. Furthermore, except for cross section G (Fig. 3-11) in which this facies is present throughout, it appears that the facies is better developed in the inner, more protected parts of the mound, and less widespread in its exposed outer flanks.

Biohermal construction continued due to the sediment trapping capacity of the intricate crinoid root system, the dense population of bryozoans, and the sporadic presence of frame building organisms like corals and tabular stromatoporoids.

Additional constructional support was afforded by the growth of the more rigid bioherm-cores (Lithofacies 2) formed either by concentrations of platy tabular stromatoporoids, with or without corals (lithotype 4), or by the great abundance of more robust forms of branching bryozoans (lithotype 5). The tabular stromatoporoids form small knolls which are locally continuous vertically for several tens of feet and in other places spread laterally in a biostromal fashion. They occupy the flanks as well as the central parts of the mound and played a significant part in shaping and maintaining the rigidity of the structure. Their presence, however, does not mark any significant environmental change as the bulk of the sedimentary material is still the skeletal biomicrites of lithofacies 1. The branching bryozoan facies, on the other hand, might indicate a small change in environmental conditions. It is more prevalent in the upper parts of the mound and where better developed is devoid of crinoids and delicate forms of bryozoans. These features, along with the more robust nature of the bryozoans constituting this lithotype, probably indicate a gradual increase in water turbulence as the bioherm mound approached wave base due to its growth above the surrounding sea floor. Greater water turbulence is strongly indicated also by the nature and distribution of the skeletal lithoclast facies.

Lithofacies 3 caps and flanks the biohermal buildup. Its lithoclast constituents are

most probably rock fragments derived from the surrounding and underlying already consolidated biohermal rocks as might be the greater part of its skeletal constituents, many of which show a fine micritic envelope which might indicate coating formed during transport or relicts of a previous consolidating agent. The scarcity of mud and argillaceous matter indicated by the light tan color and the existence of bedding planes inclined at 20 degrees, further attest to the relatively high energy origin of this facies.

The most significant expression of the environmental changes which resulted from the biohermal growth, however, are the drastic changes in the faunal assemblages and the lithofacies which mark the termination of the biohermal stage and the transition to a new stage in the evolutionary history of the structure. The main biohermal dwellers and builders, crinoids and bryozoans, were not adapted and could no longer survive the new turbulent conditions. They were replaced by a new community of organisms which built the succeeding organic-reef stage.

Thus, in summary, initiation and continued biohermal development can be attributed to the mud trapping capacity of crinoids and bryozoans, with the additional constructional support afforded by framebuilding organisms forming knolls and and biostromal horizons. The bioherm developed in relatively quiet water below wave base. Biohermal accumulation exceeded rate of subsidence. The mound, rising to a height of 200 feet above its surrounding sea floor, built itself up into shallow water thereby creating a new environmental and ecological regime more suitable for the development of an organic reef.

Similar crinoid-bryozoa bioherms which occur either as separate mounds or as an initial growth stage of a more complex reef structure are well known from the Niagaran of the Great Lakes area and the adjacent states of Iowa and Ontario Canada (Lowenstam, 1950; Textoris and Carozzi, 1964; Felber, 1964; Philcox, 1970; Kissling, 1969; Hill, 1968. For additional references, see footnote on page 3). Analogous crinoid biomicrites and dendritic coral beds very similar to the branching bryozoa facies of lithotype 5 form the deep shoal which also serves as the foundation for the Middle Devonian Keg River Formation reefs of Alberta (Langton and Chin, 1968). Crinoid-bryozoa bioherms have been extensively documented from the Mississippian in various parts of the

United States (Pray, 1958; Harbough, 1957; Troell, 1962; Anglin, 1966; Stockdale, 1931; Cotter, 1965, 1966), and from the Silurian of Gotland (Hadding, 1950; Manten, 1962). Most of these bioherms also have been interpreted as carbonate buildups which developed in quiet waters below wave base. This is also the paleoecological setting advocated for Paleozoic bryozoa in general (Duncan, 1957). Tabular stromatoporoids, which are abundant in parts of the BRM Skeletal wackestone Member in other instances also have been assigned to essentially relatively deep, low energy shoal environments, as in the examples of the Devonian reef complexes of Alberta (Klovan, 1964; Murray, 1966; Leavitt, 1968; Fischbush, 1968), and the Devonian Reefs of the Ardanes (Lecompte, 1956).

It is of interest to note that many of the studies cited above, in particular those pertaining to the Niagaran and Mississippian bioherms and the one by Lecompte (1956), make extensive mention of "stromatactis". "Stromatactis" has been regarded as of organic origin by some of the investigators who attribute it to the altered remains of the framebuilding organism primarily responsible for the construction of the mounds. Although "stromatactis" and related features are significant components of the biohermal stage of the BRM reef, I believe them to be of strictly diagenetic origin. This subject is treated in greater detail in a later section (p. 117).

Organic-Reef Stage -- The BRM Boundstone Member

Boundaries, Thickness and Distribution

The BRM Boundstone Member of the Guelph Formation constitutes that part of the reef lithosome which represents true organic-reef growth in the wave resistance sense of Lowenstam (1950). It overlies the BRM Skeletal Wackestone Member and is overlaid by the BRM Stromatolite Member. With the few exceptions resulting from difficulties in recognizing the bottom of the unit (as discussed earlier) the member can be reliably recognized on the gamma ray log (Fig. 2-10). Throughout most of the log interval corresponding to the BRM Boundstone Member, very low intensities are recorded. The log appears as an almost straight line, with only small scale irregularities superimposed on it. This pattern changes towards the top of the unit. Relatively high readings are recorded in the uppermost 10 - 20 feet of the log in

response to the lagoonal lithofacies of this interval or to features due to vadose diagenesis. The top of the unit on the log occurs where gamma ray intensities decrease, coincident with the base of the overlying BRM Stromatolite Member.

The member has an average thickness of 150 feet. Thicknesses range from 76 feet in Well 22 to a maximum of 202 feet in Well 12 (see isopach map, Fig. 3-4). The distribution of this member was determined to a large extent by the configuration of its "substrate" - the biohermal mound. Recall that reef development commenced when the bioherm constructed itself into shallow water. The organic reef lithosome is centered with respect to the underlying mound. As can be further determined from the isopach map (Fig. 3-4) reef growth was principally vertical rather than lateral, resulting in a structure having an increased height of about 150 feet and steeply inclined slopes (Figs. 3-17, 3-18).

Lithofacies Classification

The main facies which comprise the organic reef stage are the Reef Core Facies, the Reef Detritus Facies - coarse skeletal wackestone, the Reef Dwellers' Facies - fine skeletal wackestone, the Lagoonal Facies, and the Subaerial and Vadose Deposits. A detailed description of each lithofacies follows.

Lithofacies 4: Reef Core Facies (Plates 3, 4). Reef building organisms, which provide the wave resistance framework of the pinnacle reef, are the essential fabric component of the Reef Core Facies. There are three groups of framebuilding organisms: stromatoporoids, tabulate corals, and algae.

a. Stromatoporoids: Although stromatoporoids are the main and most important frame builders, their recognition is difficult in as much as the internal organic structure characterizing this group was completely obliterated by diagenesis. Thin sections provide little help in this regard as invariably the stromatoporoid structures are completely recrystallized into an equigranular xenotopic mosaic of densely interlocked anhedral dolomite crystals, typically without the slightest trace of porosity (Pl. 3/1). Thus, specimens which can be identified with certainty as stromatoporoids are indeed very rare. Some of the better preserved specimens, which admittedly leave much to be desired, are shown in Plate 3, Figures 2, 3, and 6. In these samples the characteristic stromatoporoidal internal organization of laminae separated by minute pillars is

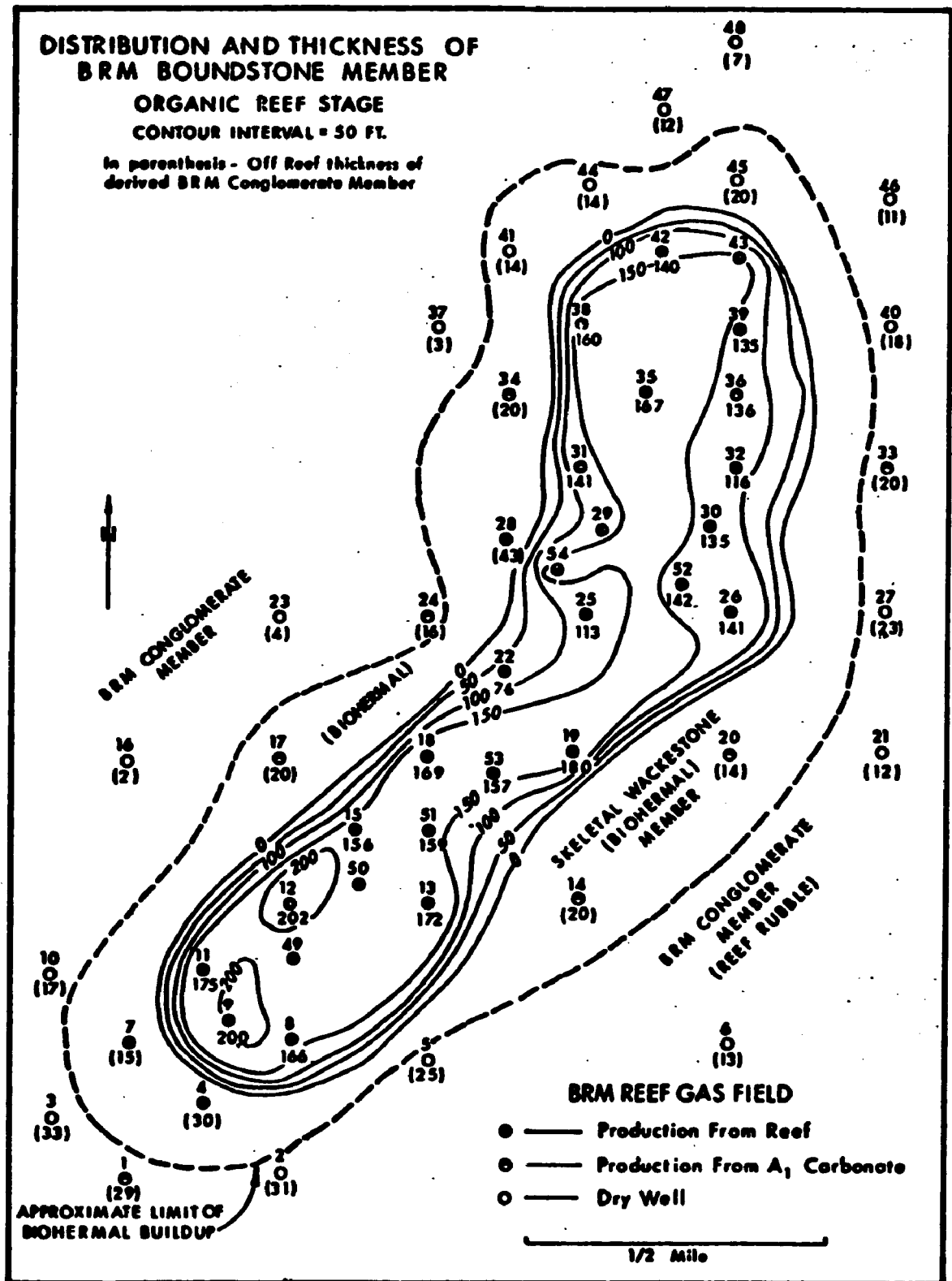


Fig. 3-4. Isopach map, BRM Boundstone Member.

still partially preserved. Selective leaching of chambers along organic laminae enhances the cellular appearance of the reticulated organic framework. For the most part, however, these identifying elements are no longer preserved or, at best, are vaguely discernable. Commonly, stromatoporoids appear as brown homogeneous masses showing only occasionally traces of internal lamination (Pl. 3/4). However, similar features resulting from diagenetic alterations of cavity infillings which are not necessarily related to the presence of stromatoporoids are also present (Pl. 10). Thus, macroscopically, these similar but unrelated features cannot always be distinguished. Identification is particularly difficult when fragmented stromatoporoidal debris is concerned. Often, thin sections might be needed to provide the answer. The diagenetic features which might be confused with stromatoporoidal debris are characterized by a distinctly non-granular fibrous texture (Pl. 10/11) and hence, in thin sections, they can be readily distinguished from the granular mosaic typical of recrystallized stromatoporoids (P. 3/1).

In accordance with the practice employed by Canadian students of Devonian stromatoporoids (Klovan, 1964; Murray, 1966; Laevitt, 1968; Fischbush, 1968) the group can be divided on the basis of gross morphological features into the following main types:

Massive stromatoporoids - relatively large colonies (usually larger than 5 cm in height) which have a relatively smooth and regular peripheral outline and show horizontal, inclined, undulating or hemispherical lamination (Plate 3, Figures 2, 3, 5, 6). When in growth position, some colonies are continuous vertically for up to 2 feet (Pl. 3/5).

Digitate stromatoporoids - these forms are characterized by an irregular outline, showing finger-like outgrowths (Pl. 3/7, 3/8) or the development of other irregular extensions (Pl. 4/1). Well developed digits in growth position are rare. In the few well preserved specimens the digits are tabular, with a roughly circular base 2 cm in diameter (Pl. 3/8) and a height up to 7 cm (Pl. 3/7). Compared to the massive forms, digitate stromatoporoids are more fragile. Specimens having poorly developed digits cannot be distinguished from broken abraded massive stromatoporoids. Also included in this group are the more delicate branching dendroid stromatoporoids of the Canadian

authors mentioned previously. Mr. Chin of the Banff Oil Company, Calgary, was able to identify the dendroid genus Stachyodes in a sample from Well 31, depth 2289 feet (Chin, written communication, March 24, 1970). Much of the stromatoporoidal debris constituting the coarse skeletal facies (see below) is derived from the fragile dendroid stromatoporoids.

Encrusting stromatoporoids - this group is characterized by its unique mode of encrustation. The ultimate form an encrusting colony assumes is a function of the surface morphology it encrusts. Many different forms are encountered. Colonies might develop into a highly intricate spatial network, engulfing and binding skeletal material in the process (Pl. 3/9) or appear as relatively horizontal flat or undulating encrustations (Pl. 3/10). Some occurrences of irregular forms which appear more massive than the digitate forms and are continuous vertically for several centimeters might be interpreted as encrustations of almost vertical surfaces.

b. Tabulate corals: Although tabulate corals are conspicuous and eye-catching because of color differences and easy identification, they are subordinate in abundance and only locally significant contributors to the reef core facies. In fact, only in two rather limited intervals (Well 31, 2324-2342 and Well 42, 2301-2310) do they display framebuilding capacity. In most other occurrences only broken material is present (see Coarse Skeletal Facies, below). Two main types of corals occur, Favosites Sp (Pl. 4/1, 4/2) - in situ colonies which reach a height of 10-15 cm., and encrusting colonies (Pl. 4/3, 4/4), a more effective frame builder due to a low profile and sediment binding capability. In comparison, the Favosites are elevated above their substrate and are more exposed to abrasion in a turbulent environment.

c. Algae: Direct and conclusive evidence for algal frame builders in the organic reef is scarce. Encrusting forms occur which resemble laterally linked hemispheroid stromatolites (Logan et al., 1964). More simple undulating or flat clusters of algal laminae are present in limited amounts in Well 39 (depth 2353'-2354', Pl. 4/7). Minute threadlike aggregates of cells, 60 x 150 microns in dimensions, forming a "spaghettilike" network of microfilaments in a core sample from Well 39 (2368 feet depth) have been interpreted as an algal structure and tentatively identified as cf. Coactilum Sp Maslov (Dr. R. Rezak and B. Buchbinder, written communication,

June 28, 1970). Additional rare occurrences of similar structures, presumed to be related to the remains of noncalcareous (?) blue-green algae, have been noted in Wells 39 and 38. The occurrences are sporadic and volumetrically insignificant. By themselves they do not substantiate a major framebuilding role for the algae. However, on the basis of indirect and circumstantial evidence derived from stratigraphic, sedimentologic and petrographic considerations, there is reason to believe that algae were important, and probably the only reef-builders in certain parts of the organic reef-mass. Pertinent evidence and arguments for the above will be presented and discussed in the section dealing with the various rock types constituting the organic reef stage.

Rock types

By volume, framebuilders in growth position comprise only about 30% of the reef core facies. Their abundance is estimated to range between 10 and 50 percent. In places massive stromatoporoids are persistent vertically for several feet. A conspicuous example is Well 25 in which the basal part of the BRM Boundstone Member consists of a 15 foot interval (2312-2327) of solid massive stromatoporoids. Encrusting stromatoporoids and algae (?) are the only other organisms which might form a framework continuous vertically for more than one foot. For the most part intervals in which framebuilding organisms construct the entire section are rare. Their spatial continuity is interrupted by skeletal wackestones of the reef-detritus facies, which often constitute more than 50 percent of the organic sublithosome.

A number of more specific rock types can be recognized on the basis of the dominant framebuilder present. Skeletal material of roughly similar composition forms a substantial part of all lithotypes.

Massive stromatoporoid boundstone (Plate 3, Figures 2-6). This is the most abundant rock type in lithofacies 4. Colonies in growth position which range in height from 3 to 8 inches are fairly common. Larger ones, reaching a height of two feet or more, are also present.

Encrusting stromatoporoid boundstone (Pls. 3/9, 3/10, 4/4). Encrusting stromatoporoids are the dominant framebuilding organism in the reef-core sections of Wells 19, 32 and 31, occasionally forming a network continuous vertically for several feet

(well 31, 2324 feet-2342 feet). Encrusting stromatoporoids are commonly associated with massive stromatoporoids and, in places, with encrusting tabulate corals (Pl. 4/4).

Digitate stromatoporoid and coral boundstone (Pls 3/7, 4/1, 4/2). This less common lithology commonly occupies short intervals within the stromatoporoid boundstone. Fragments of digitate stromatoporoids and more rarely favositid corals are the major constituents of the coarse skeletal facies, indicating that these organisms inhabited the reef in great abundance. Their original habitat was probably one of the more protected intrareef zones, sheltered by small scale prominences formed by the other, more robust framebuilding organisms. Evidence for this econiche is substantiated by their frequent association with the more delicate reef dwellers like bryozoans (Pls. 3/7, 4/2).

Sections which are composed exclusively of a single rock type are rare. The three lithotypes and the ubiquitous coarse and fine skeletal wackestones are closely associated and intertongue on all scales. For all practical purposes they constitute a single reef-core lithofacies which cannot be meaningfully resolved into mappable subunits. An additional algal boundstone is a distinct rock type which is widespread in certain parts of the organic reef lithotype as part of the reef-core.

Algal boundstone (?), macroscopically best described as a brown to tan, massive, mottled ("clotted") mudstone. Clots are finer grained, denser and darker than the surrounding matrix. They are highly irregular in shape, commonly displaying a dendritic pattern with ill-defined diffuse boundaries (Pl. 4/8). More regular, somewhat rounded and even pelletoidal patterns are also present (Pl. 4/9). On occasions, clots interlock spatially to form what appears to be a continuous network (Pl. 4/8). Small amounts of fine shell fragments are sometimes present (Pl. 4/9), but for the most part the rock is devoid of any skeletal or other grains. Highly irregular vugs, up to 2 cm long, infilled with several generations of concentrically arranged coarse fibrous vuglining layers are very common (Pl. 4/5).

In thin sections, the darker mottled parts or clots typically consist of very dense micrite which exhibits evidence of grain growth recrystallization resulting in a xenotopic mosaic of anhedral, very fine, less than 10 micron, dolomite crystals. In some samples the clots are riddled with aggregates of micritic grains which form a

bifurcated dendritic structure. Individual dendrites are commonly about 0.5 mm long; larger ones reach 1.3 mm in length and are segmented into rods and grains which are about 0.05 mm wide and up to 0.1 mm long. This microstructure is somewhat reminiscent of some minute bush-like Cambrian Red algae described by Johnson (1966; compare with his description of Epiphyton, p. 15 and plate 2/1; Chabakovia and Sajania, p. 22 and plate 5). Although not meant to imply generic identification, the similarity is striking and suggestive of an organic, algal origin for these structures. According to Riding and Wray (1972) Epiphyton probably belongs to the blue-green algae. Both Epiphyton and Chabakovia are apparently also known in the Devonian (ibid.) and thus, their occurrence in the Silurian should not be surprising.

The mottled appearance is a manifestation of the distribution pattern of dolomite crystals having two distinct size classes. The finer grained darker micritic clots form a framework around interstices filled with coarser grained, lighter colored sparry cement. The cement consists of a drusy mosaic of fine (120 micron) to coarse (600 micron) subhedral to euhedral dolomite crystals with well-defined plain boundaries, often displaying a systematic increase in crystal size away from the micritic void boundary. Such drusy textures are considered typical of void filling cements (Bathurst, 1958). If the clotted areas were indeed formed by an algal framework, the drusy areas might represent early diagenetic infilling and cementation of primary constructional framework interstices. Further support for a primary origin is afforded by several other observations. Secondary solution cavities are almost invariably characterized by multigeneration concentric vug linings of coarse fibrous cement in which the fibers are perpendicular to the cavity wall (Pl. 4/5, Pl. 10). This cementation pattern is distinctly different from the drusy pattern described above. Furthermore, the highly irregular shape, diffused and blurred boundaries, intricate distribution and great abundance suggest a primary origin.

Scattered sporadically within the algal boundstone (?) are features perhaps attributable to diagenetically altered algae. Minute filamentous threads are interlaced within aggregates to form continuous undulating laminae (Pl. 4/6). In addition minute, pillar-like elongated grains (3 mm long) when interwoven with the horizontal filaments appear to form a continuous framework (Pl. 4/10). Additional fabrics which might be related to the sediment binding by algae are sporadic, finely laminated

encrustations (Pl. 5/1). Their occasional association with stromatoporoids, in the form of hemispherical layers within colonies, or as external coating of colonies, is similar in some respects to the "stromatoporoid-algal-consortium" described from Devonian reefs in Alberta (Klovan, 1964; Fischbush, 1968).

The massive mottled or clotted algal boundstone (?) are widespread in the northern half of the reef structure. In certain wells algal boundstone (?) comprises the bulk of the organic-reef stage sediments (wells 22, 38, 39). In the northern edge, between wells 38 and 39, the entire BRM boundstone member consists almost exclusively of this lithology, which appears to be continuous laterally across the structure (section H, Fig. 3-12). In three additional wells this lithotype builds shorter intervals at the upper part of the member (well 19, 2294'-2320'; well 31, 2265'-2277'; well 42, 2290'-2301'). Thus, interpretation of the mottled mudstone as algal boundstone within the reef-core facies is based on its stratigraphic and sedimentologic distribution as well as on its internal fabric.

This interpretation for the algal boundstone (?) is strongly supported by the available literature on what might be termed "the problem of micritic reefs". In general terms, it pertains to the common prevalence, often dominance, of carbonate mud or recrystallized microcrystalline aphanitic material in bioherms, banks and reefs of various kinds, which is difficult to account for in view of the lack of a mud trapping agent or under the turbulent or semi-turbulent environments usually inferred for these structures. Of the numerous authors who have addressed themselves to this question, many have concluded or otherwise speculated that this phenomenon is related to the presence, action, decay or alteration of algal material.

To further substantiate this interpretation, some of the pertinent literature on the subject is reviewed in the following paragraphs. The structures to which the discussion is pertinent can be divided into the categories of bioherms, mud mounds, organic reefs, and other occurrences.

Bioherms (in the sense defined previously, mounds formed in a low energy environment, below wave base). Some occurrences of crinoid-bryozoa bioherms analogous to the BRM Biohermal Stage, have been reviewed elsewhere in this study (pp.69-70). Mud accumulation is attributed to the baffling and mud trapping capacity of the organisms present and its retention to the low energy nature of the environ-

ment. Therefore the abundance of mud in bioherms is readily accounted for and indeed can be regarded as their principal inherent attribute.

Pray (1958), in his analysis of the Mississippian bioherms of the southwestern United States, states that despite the lack of algal framebuilders "much of the lime mud was of algal origin, either as carbonate needles secreted in an organic framework (Lowenstam, 1955) or as an algal slime formed on or near algal plants and precipitated as the plants extracted carbon dioxide from the immediate adjacent sea water" (Pray, 1958, p. 265).

Mud mounds. There has been considerable controversy concerning the origin of mound structures consisting of an unbedded massive mudstone core with apparently little or no faunal remains, reaching a depositional relief of several hundred feet and displaying steep flanks. The Lower Carboniferous (Waulsortian) "Reef knolls" of the British Isles are a well known and frequently cited example of such structures (Black, 1954; Bathurst, 1959; Parkinson, 1957; George, 1954; Schwarzacher, 1961; Lees, 1961, 1964; Nichols, 1965). Similar structures have been reported from the Upper Pennsylvanian and Lower Permian of New Mexico (Otte and Parks, 1963). The main difference between the mud mounds and the bioherms discussed earlier is the scarcity of faunal remains in the mounds which could serve as an effective mud trapping agent. Bryozoans and crinoids, although present, are not abundant enough to effectively fulfill this function. Consequently, researchers have had to resort to some speculative explanations:

Stromatactis, the fossil remains of a high speculative and hypothetical organism of unknown affinity, was the framebuilder responsible for the crection of the mounds and the trapping and retention of their mud component (Bathurst, 1959; Otte and Parks, 1963). This explanation is untenable since the sedimentary fabric is clearly diagenetic in origin.

Soft-bodied unpreserved organisms baffle the mud. Lees (1961, p. 108; 1964, p. 521) draws attention to the analogous present-day mud banks of the Florida Bay in which Thalassia grass traps carbonate mud (Ginsburg and Lowenstam, 1958) and concludes that similar soft-bodied baffles, which did not leave any fossil remains, furnish the only satisfactory answer. As the mud baffling agent could be non-calcareous

algae, this explanation does not differ significantly from the one favored by the majority of investigators, namely, that the predominance of mud represents both trapping and indigenous mud and disintegration products of algae as the prime mound-forming organism (Black, 1954; George, 1954; Parkinson, 1957; Nichols, 1965). This mechanism was also contemplated and not categorically rejected by proponents of the alternative explanations discussed above (Bathurst, 1959, p. 518; Schwarzacher, 1961).

Organic reefs A third group, in some respects more directly relevant to the present study, includes structures which are known to be true reefs. Predominance of mud and clotted calcilutite in the reef-core facies of Devonian reefs in Australia are attributed to algae and algal action by Wolf (1965a) and Playford (1967, p. 360). Since calcareous algae are the dominant framebuilding organism in these structures (see also Wray, 1967, 1970) and as all gradations from well-preserved algal remains to unrecognizable cryptocrystalline disintegration products have been documented (Wolf, 1965, a, b, c), the algal origin of the mud in question is convincingly established.

Other occurrences. Additional occurrences of micritic and clotted mudstones associated with carbonate construction of diverse origin related to algae have been reported from the Permian Capitan carbonate bank complex (Newell, et al., 1953, p. 108, 176); Silurian of Gotland (Hadding, 1950, 1958, 1959); Cambrian and Ordovician of Southwestern Alberta (Aitken, 1967); Ordovician mounds in West Texas (Klement and Toomey, 1967) and from the Pennsylvanian phylloid algal mounds of the U. S. Mid Continent (Heckel and Cocke, 1969; Crowley, 1966).

From the foregoing discussion it appears that most authors advocate one or a combination of the following processes as their explanation to the enigmatic problem of "micritic reefs".

Indigenous micrite. The micrite is indigenous to the depositional environment in which it presently occurs. It consists of carbonate needles which in part are disintegration products of calcareous algae, and in part chemical precipitate formed by algae extracting carbon dioxide from the immediately adjacent seawater. Identical processes are presently taking place in Southern Florida and the Bahamas (Lowenstam, 1955; Lowenstam and Epstein, 1957; Stockmann et al., 1967).

"Cryptalgal" origin. Non-calcareous algae, through their capacity to baffle and stabilize mud particles, are responsible for the growth of the mound structures. Subsequent decay of the organic tissues accounts for the absence of any recognizable fossil remains. Aitken (1967) developed an entire classification of algal limestones which is based on this premise. According to this classification, the algal boundstone (?) of the BRM reef would be termed "cryptalgal biolithite" or with reference to the rocks with the clotted texture - "thrombolite". This, again, is supported at least in part by observations from the Recent (Ginsburg and Lowenstam, 1958).

"Grain diminution". The micrite is at least in part a result of a micritization or grain diminution process, whereby algal colonies or other carbonate grains are corroded, bored or otherwise weathered by algal action to form a fine-grained sediment (Wood, 1941; Wolf, 1965c, Klement and Toomey, 1967, to mention but a few of the proponents of this idea). The formation of micritic envelopes as observed in Recent sediments (Bathurst, 1966) represents an early grain diminution stage and provides insight into the mechanism of the process.

Additional explanations. The clotted fabric represents an altered algal framework (Hadding, 1959; Aitken, 1967) or a denser carbonate slime-coagulation related to algal activity (Hadding, 1958, as quoted in Carozzi, 1960, p. 210). In contrast, the clots may be the unaffected remnants of a once homogeneous algal grain-diminished sediment which underwent partial grain-growth recrystallization (Wood, 1941; Hadding, 1958). The clotted texture could also result from the dissolution of unstable aragonitic algae, with a subsequent infilling of the voids thus formed by denser mud (Heckel and Cocke, 1969).

Lithofacies 5: Reef Detritus Facies (Pl. 5). Coarse fragments of stromatoporoids are the main skeletal constituent of this coarse skeletal wackestone (Plate 5, Figs. 2, 3, 4, 7). Fragments vary in size considerably, ranging from a few millimeters up to about 10 cm (Pl. 5/7). Most are very angular. Sorting is poor. Stromatoporoid fragments which have been preferentially leached and subsequently infilled with a fibrous cement are quite common. In fact, it is not always possible to distinguish between the former and diagenetic patches which are unrelated to the presence of stromatoporoid fragments. Large fragments of tabulate corals, reaching a few centimeters in size,

are fairly common (Pl. 5/5, 5/6). Other grains present include smaller fragments of rugose corals and bryozoans, and lithoclasts up to 5 cm in diameter.

The rock is mud-supported. Skeletal grains commonly constitute about 30 percent of the rock. The remainder of the rock consists of sand to silt size skeletal debris embedded in a carbonate mud matrix. In thin sections the matrix appears as an equigranular, dense, xenotopic grain-growth mosaic of anhedral to subhedral fine dolomite crystals, 40-80 microns in size. Unrecrystallized small patches of original micrite can still be detected in places.

As mentioned earlier, the reef detritus comprises a substantial part of what has been mapped as the reef core facies. In this association fragments of bryozoa and rugose corals are fairly abundant (Pls. 3/5, 4/2). In addition, the reef detritus forms mappable rock units within the overall reef configuration, either as intra-reef deposits, which occur as small patches of limited vertical and lateral extent in between reef-core zones, or as fore-reef deposits, which form an apron around the reef-core facies.

Lithofacies 6: Reef Dwellers' Facies (Plate 5). Reef Dwellers' Facies is a fine skeletal wackestone that consists of skeletal fragments of organisms which apparently formed an intra-reef community of crinoids, bryozoans, solitary rugose corals, small colonial tabulate corals and brachiopods. Fragments of the reef building organisms, stromatoporoids and favositid corals, are conspicuously absent. Very fine grained lithoclasts locally are abundant.

The several more specific rock types within the Reef Dwellers' Facies differ in the type and proportion of their skeletal constituents. In order of decreasing abundance, these include:

Bryozoa-coral wackestone fine rudite (Pl. 5/8, 5/9), consisting of skeletal fragments of branching and encrusting bryozoans and of small tabulate and rugose cup corals, together comprising between 20 to 40 percent of the rock. Whole fossils are locally abundant (Pl. 5/8). Grain size varies considerably, ranging between 2 to 20 mm. Larger bryozoans or corals are occasionally up to 3 and 4 cm in size. Sorting is poor.

Skeletal lithoclast wackestone arenite, locally grain supported (Pl. 5/10). Arenite-

sized crinoid and bryozoa fragments, and sparse larger brachiopod shell fragments, are the main skeletal constituents. In great abundance are sand-sized angular to sub-rounded micritic lithoclasts. Sorting is good. Grain abundance varies from about 30 percent in mud-supported rocks to about 60 percent in grain-supported ones. The two types grade into each other, wackestone predominating.

Brachiopod packstone and wackestone (Pl. 5/11), in which whole and broken brachiopods are the main, often the only skeletal grains present. They are mostly about 1 cm in diameter and constitute up to about 50 percent of some rocks. Crinoids, lithoclasts and in places unbroken solitary corals and bryozoans occur in minor amounts. The matrix is a micritic carbonate mud. Packstones grade into and are interbedded with wackestones in which skeletal grains constitute only about 20 percent of the rock.

The above rock-types are frequently interbedded. They are confined to intra-reef areas, except for the bryozoa-coral wackestone, which occurs also in the fore-reef lithotype as interbedded thin tongues within the reef detritus coarse skeletal facies (particularly in wells 18 and 26).

Abundant remains of the reef dwelling organisms occur locally within parts of the reef-core facies, as small patches of limited (less than 2 feet) vertical extent. In some, the bryozoa, coral and brachiopods are encrusted by stromatoporoids (Pl. 3/9, 3/10).

Lithofacies 7: Lagoonal Facies (Plate 6). Two main rock types comprise the Lagoonal Facies:

1. Laminated pelletal mudstone (Plate 6, Figures 1-5), composed of even, parallel bedded horizontal, very thin laminae, ranging in thickness between a fraction of a millimeter to 3 mm. Laminae comprise carbonate mud and recrystallized micrite in an xenotopic mosaic of anhedral dolomite crystals, mostly 10 to 40 microns in size. Well rounded and elliptical pellets, elongated parallel to the bedding, constitute in places up to about 20 percent of the rock. Most pellets are less than a millimeter in diameter and can be seen only in thin sections. Larger, 2 to 3 mm pellets, are locally very abundant, comprising the bulk of certain grain supported laminae (Pl. 6/1). The rock is devoid of skeletal material. The only fossils are sparse, unbroken, small,

elliptical, undetached, bivalved shells, 1 to 10 mm in size (Pl. 6/1, 6/2), most probably relatively large, thick-shelled ostracods. Preservation is too poor to enable a definite identification, but unusually large ostracods have been reported from the Niagaran of the Northern peninsula of Michigan (Copeland, 1970).

Of environmental significance in the Lagoonal Facies is the sporadic occurrence of the following additional features:

a. Burrows, well defined, mud-filled irregular patches, several centimeters in size, which cut across and disrupt laminae (Pl. 6/2). Zones completely reworked by closely spaced burrows are occasionally present.

b. Fenestral (birdseye) fabric. In parts of the section, certain zones are riddled with small pores concentrated along laminae planes (Pl. 6/3, 6/4). The voids are spherical or lenticular, elongated parallel to stratification, most about 1 mm or less in size. In places pores coalesce to form much larger voids (Pl. 6/3). Some voids are filled with a sparry mosaic of dolomite or coarse anhydrite crystals. The fabric closely resembles the "fenestral" or the "laminoid fenestral" fabric described by Tebbutt *et al.* (1964) or the "birdseye" fabric of many authors (Choquette and Pray, 1970, p. 246). Within the lagoonal facies, it is commonly associated with algal features.

c. Algal lamination. Very thin (less than 1.0 mm), undulating, dark brown seams, probably represent residues of algal mats (Pl. 6/3). In places they form short, planar to undulating stromatolite-like suits of laminae. Algal coated structures are also present, although rare (Pl. 6/4). Typically, the algal coating is restricted to the upper, exposed parts of pebbles or other small scale surface irregularities and does not extend to the bottom part of the coated element.

2. Massive, mottled (burrowed) pelletal mudstone (Pl. 6/5), a rock consisting of 10 to 20 percent very small (less than 1.0 mm), well-rounded, elliptical pellets embedded in a micritic matrix. No bedding is apparent. Irregular dark brown patches of micrite with indistinct boundaries scattered throughout the light grey to tan mudstone give the mottled appearance to the rock. The mottled fabric is most probably a manifestation of intensive burrowing (Winder, 1968). No fossils are present, except for very restricted, local concentrations of unoriented skeletal fragments of crinoids,

bryozoans, solitary corals and brachiopods. Birdseye texture occurs sporadically.

The laminated and the massive pelletal mudstones are interbedded. Laminated mudstone is volumetrically more abundant, comprising about 70 percent of the lagoonal facies. Sharp, well defined conformable contacts mark the transition from one lithology to the other (Pl. 6/5).

Lithofacies 8: Subaerial and vadose deposits (Plates 6, 7). The chemical precipitates (caliche) formed during the first of the two periods of subaerial exposure of the BRM structure are confined to the uppermost part of the organic reef section. They replace the pre-existing lithofacies to form a very complex lithology, consisting of the following associated sedimentary features:

Laminated caliche (Pl. 6/6, 6/8), consisting of extremely finely laminated deposits, individual lamina being in places only about 50 microns thick. The laminae are conformable. The mode of lamination varies within short vertical intervals among planar, undulating and highly irregular "enterolithic" patterns. The vertical continuity of orderly laminated caliche sections rarely exceeds several centimeters in thickness. The caliche is usually horizontal. In places it is draped over highly inclined surfaces. Cross cutting veins and intervening horizons on non-laminated material are common.

Vadose pisoliths (Pl. 6/7, 6/9, 6/10). Most pisoliths are between 1mm (oolite size) to 5 mm in size. Exceptionally large ones, with diameters up to 10 cm, are rare, but when present always occur as individual spheroids and not as aggregates (Pl. 6/10). Pisoliths vary considerably in shape. Roughly spherical and elongated forms are common, most commonly somewhat deformed. Highly irregular pisoliths are also present. Composite pisoliths, in which aggregates of pisoliths are clustered by an envelope of concentric coating layers, are rare. Individual pisoliths do not show any preferred orientation. Elongated grains, with their long axis inclined or perpendicular to the horizontal bedding surface, are common. Pisoliths' cores or nuclei commonly consist of micrite or of aggregates of silt-sized angular particles. Some pisoliths develop around fragments of older pisoliths. Well developed pisoliths, showing several concentric layers, are associated with poorly developed ones, in which only one layer is present, and with angular micritic grains having no coating at all.

The concentric layering forming pisoliths consists of successive very thin envelopes of micrite, 0.1 mm or less in thickness, or of alternations of micritic envelopes separated by single-crystal-wide sparitic layers, composed of anhedral dolomite crystals, 0.04 to 0.10 mm in size. Pisoliths are, for the most part, in contact with each other, or with the associated non-coated particulate grains, to comprise a grain-supported fabric. Intergranular space is infilled with a coarse crystalline sparry cement. Larger interstices are infilled with coarse fibrous mosaics which grow perpendicular to void boundaries, display wavy extinctions and a sharp central suture, marking the juncture of crystals growing from opposite walls. Except for rare ostracods, the remnants of the original lagoonal rocks which were replaced, pisoliths are devoid of skeletal material.

Pisolitic caliche. The association of laminated caliche and pisoliths results in quite spectacular and exceedingly complicated enterolithic fabric patterns, representative examples of which are shown in plate 7. The pattern commonly resembles a highly complicated structural map, or a contour map of rugged topography, with numerous compound local closures, asymmetric structures, monoclines, saddles, faults, narrow valleys and the like. The "contour lines" consist of micritic layers, 0.1 mm or less in thickness, inscribed in a sparitic groundmass of equigranular anhedral to subhedral dolomite crystals, 0.04 mm in size. Intervening within the laminated fabric are irregular patches of particulate material, consisting of poorly sorted, grain supported angular lithoclasts, fragments of pisoliths and laminated caliche embedded in a granular silt sized matrix. In places, hematite is present in the form of very thin, brown "rusty" threads.

Macroscopically, pisolitic caliche occurs as horizontal layers (Pl. 7/1), as inclined or vertical layers forming thick coatings on walls or open cracks (Pl. 7/2) and as coarse pebble-sized debris infilling open cracks (Pl. 7/2, 7/6).

Infilled cracks and carbonate veins. Joints and cracks range in thickness from about 1 cm to greater than 10 cm, the width of the core. The limits of the core dimensions prevent an appraisal of the full extent of the relatively large features. Most are straight but some are sinuous (Pl. 7/3).

As mentioned earlier, the walls of some cracks are paved with pisolitic caliche

layers. The space formed by their opening is infilled with brecciated debris of unsorted lithoclasts and broken pisoliths and caliche crusts (Pl. 7/2, 7/3, 7/6). Commonly, the entire crack is infilled with dark brown homogeneous multi-layered fine and coarse fibrous dolomite crystals, forming a "carbonate vein" (Pl. 7/4). The dark brown coloration might be due to staining by oxidized iron minerals.

Facies Distribution and Environmental Interpretation

On the basis of the preceding lithologic description and the facies distribution diagrams (Figs. 3-9 through 3-13) the following generalizations appear justified:

The reef core facies is the most widespread lithofacies. It occupies the bulk of the central part of the build-up. Massive and encrusting stromatoporoids are the most important framebuilding organisms present. Although stromatoporoids in growth position comprise only about one third of the reef-core material, they are the essential fabric component of the reef-core facies as they provide the wave resistance potential of the resultant reef structure. The bulk of the reef-core, however, consists of fragmented stromatoporoid debris, further attesting to the high energy conditions in which active reef growth took place. These observations are in close agreement with what other students of Paleozoic reefs inferred to be the paleoecological niche occupied by massive stromatoporoids (Lecompte, 1959; Klovan, 1964; Murray, 1966; Fischbuch, 1968; Leavitt, 1968). Their reef building role appears to be analogous to that of the robust corals Acropora palmata (Fischbuch, 1968, p. 502) or Montastrea annularis of modern coral reefs. Unlike many modern and ancient reefs, which often display a systematic lateral arrangement of biozones, the distribution of reef building organisms within the core of the BRM reef is rather homogeneous, the only marked lateral variations being the algal reef-core facies.

Algae, probably calcareous, are important framebuilding organisms in the reef. Algal boundstone comprises most of the organic reef rocks of wells 22, 38 and 39, and is present in the upper part of the BRM Boundary Member in three additional wells (19, 31 and 42). Stromatoporoid-constructed and algal-constructed reef-core lithology interfinger in the northern part of the structure (section I, Fig. 3-13) in which algal boundstone prevails. Particularly between wells 38 and 39, the entire organic reef section consists almost exclusively of algal boundstone, which appears

to be continuous laterally across the structure (section H, Fig. 3-12). The other two framebuilding organisms, digitate stromatoporoids and tabulate corals, played only a subordinate reef-building role. They are less abundant, rarely observed in growth positions, and are mostly fragmented.

The reef-core is surrounded on all sides by the coarse skeletal reef detritus facies (Lithofacies 5) which occupies a fore-reef niche. No fore-reef facies seems to exist whenever algal boundstone constitutes the reef-core (Figs. 3-10, 3-12). Tongues of the coarse skeletal facies emanate from the reef-core area at various levels and coalesce to form the fore-reef environmental facies. Lithofacies 5 also occurs as lenses within the reef-core area, implying that the site of active reef proliferation shifted with time. The reef builds itself up over its own debris. This concept is substantiated by the fact that the reef-core lithology comprises about 50 percent of reef-detritus material.

The fine skeletal wackestone (Lithofacies 6), interpreted to be a "reef dwellers" facies, occurs as lenses of limited vertical and lateral extent. Most probably, it represents in situ accumulation of fossil debris from an assemblage of organisms which inhabited protected pools formed within and in between more rigid reef-core prominences. In comparison with the robust reef-building fauna, the fine skeletal facies consists of rather delicate forms of crinoids, bryozoans, brachiopods and small rugose corals which sought physical shelter from the turbulent waters that characterized the reef.

The laminated and massive pelletal mudstone of Lithofacies 7 are interpreted to represent a lagoonal environment. This lithofacies is confined to the uppermost 20 or 30 feet of the organic reef section (Figs. 3-9 to 3-13). It probably represents the development of protected shallow lagoonal pools throughout the crestal area of the reef. At this stage in its evolution the reef formed an elevated flat plateau, very close to sea level. The fine laminations and the predominance of mud indicate low-energy, quiet water conditions. Shallow water conditions are indicated by burrow marks, fenestral fabric and algal laminations. The latter probably indicate the intermittent existence of supratidal conditions. The absence of a fauna other than scarce ostracods might indicate the prevalence of higher than normal water salinities in

which only algae and soft-bodied burrowing organisms could survive. These burrowers are responsible for the abundance of faecal pellets in this lithofacies.

Lithofacies 8 represents an association of sedimentary features which are products of vadose and subaerial diagenetic alterations. The infilled cracks and joints probably represent solution-enlarged, subaerially-formed desiccation cracks. The pisolitic caliche formed both subaerially and in the subsurface within the vadose zone. The pisoliths are practically identical to similar features described from the Permian Capitan Reef of Texas and New Mexico (Newell *et al.*, 1953; Dunham, 1969; Kendall, 1969). Several of the attributes advocated by Dunham (1969) as evidence for the concretionary-vadose, rather than algal-oncolitic, origin of the pisoliths, have been observed in the BRM pisoliths as well. These include the fitted polygonal fabric; the downward elongation and vertical asymmetry of individual pisoliths; the interruption of concentric growth by fracturing and its association with cementation and internal sedimentation; the fact that pisolith nuclei invariably are either broken pisoliths or non-skeletal grains and finally, the lack of any filamentous or cellular algal structure. Furthermore, they are practically identical to present-day cave deposits (Pl. 7/12).

The distribution of the subaerial and vadose deposits of lithofacies 8 is restricted to the topmost part of the BRM boundstone member. It is thickest (35 feet) and most intensively developed in wells 25 and 31 (Figs. 3-10, 3-11) which are located on the crest of the structure (Fig. 3-14). Lithofacies 8 develops mostly at the expense of rocks of the lagoonal facies. In the facies diagrams, its distribution has been shown to be bound by two unconformity surfaces. The lower one marks the lowest level at which the diagenetic features of this lithofacies are present. The upper one marks the termination of the organic-reef growth stage which, stratigraphically, was chosen to coincide with the top of the BRM Boundstone Member.

The configuration of the BRM structure at the termination of the organic reef growth stage is provided by an isopach map of the cumulative thicknesses of the BRM Skeletal Wackestone Member and the BRM Boundstone Member (Fig. 3-5). The structural map, drawn on top of the BRM Boundstone Member, essentially provides a similar picture (Fig. 3-6): The build-up formed a mound with steep slopes and a rather flat crestal plateau, about 300 feet above the penecontemporaneous sea floor.

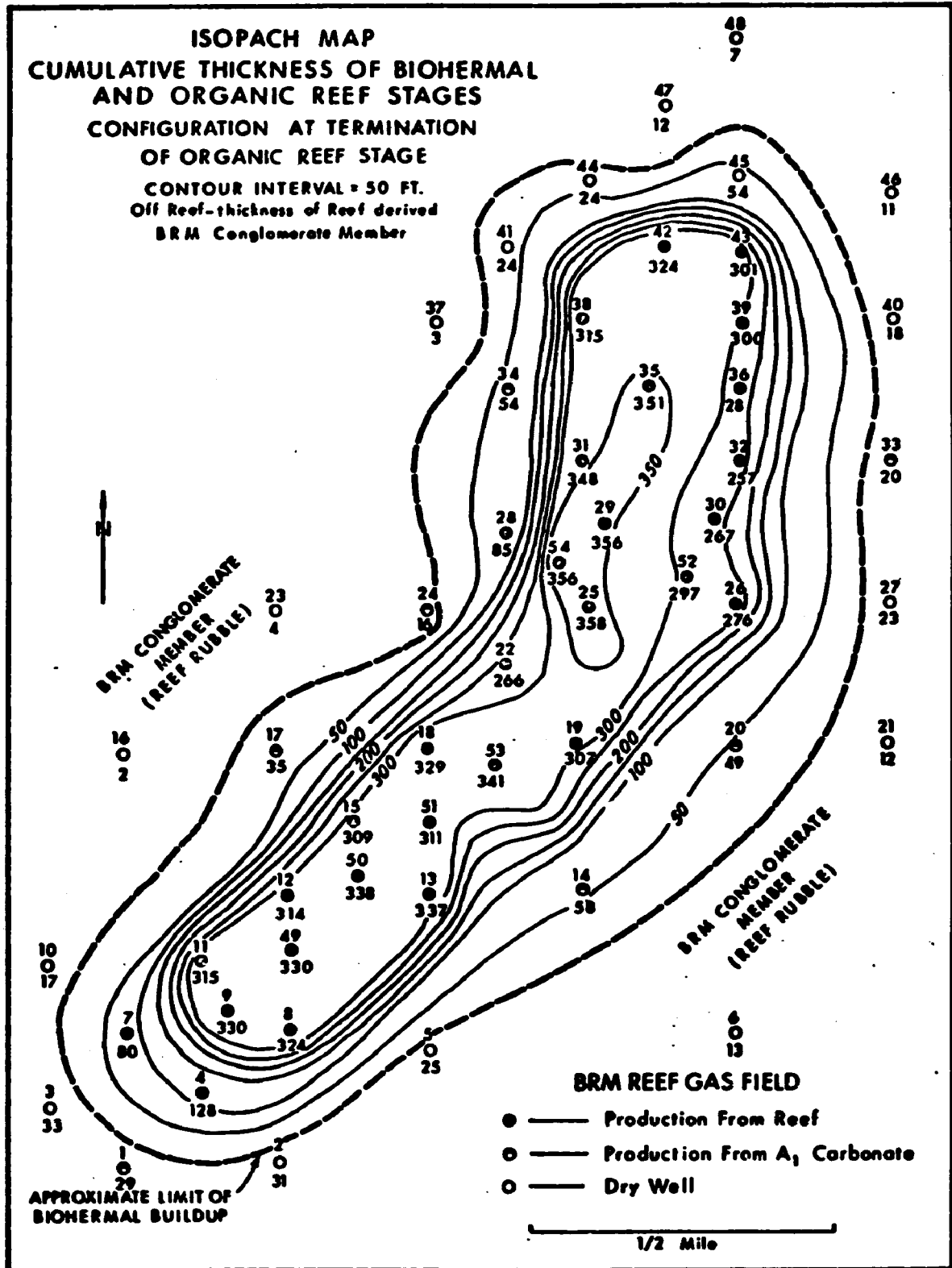


Fig. 3-5. Isopach map, BRM Skeletal Wackestone and BRM Boundstone Member.

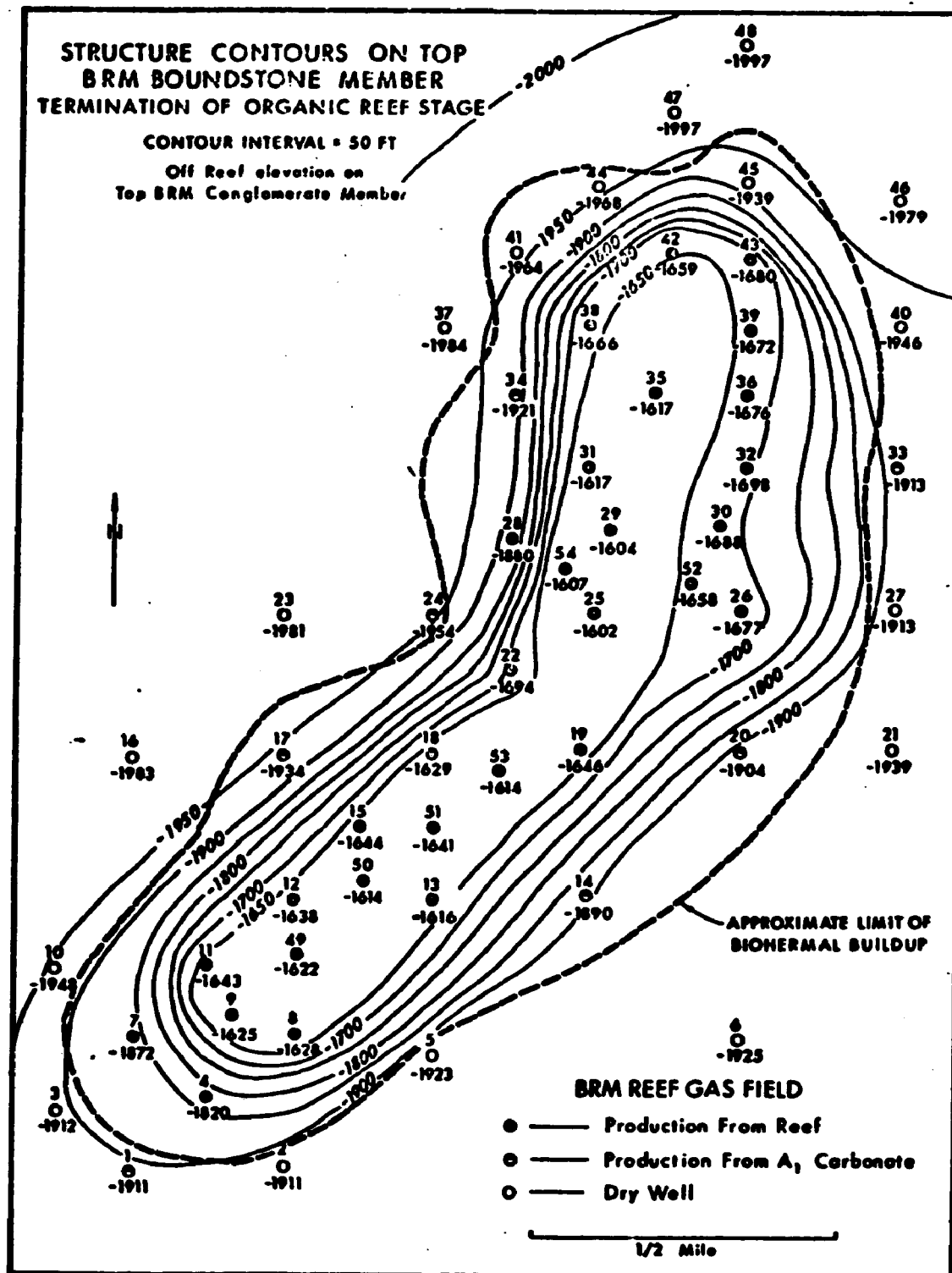


Fig. 3-6. Structure contour map on top BRM Boundstone Member.

A local high, marked by a closure of the + 350 contour line, occurs between wells 25 and 35, and expands northward the outline of the crestal high observed in the preceding biohermal stage (Fig. 3-3). The reef is steeper on the west and north sides, possibly indicating that these were the sites of more active growth and therefore, that prevailing winds and waves might have been from the northwest.

The degree of wave turbulence which existed during the growth of the organic reef stage can be estimated from wind fetch and strength. The reef structure lies at the southeastern edge of the Michigan basin. If prevailing northwest winds had a fetch of at least 200 miles (Figs. 1-1, 1-2), a moderate "fresh breeze" of 20 knots would produce waves having a wave length of 180 feet (Scripps Institute of Oceanography, 1944). This implies a wave base at about 90 feet (half the wave length). When the reef grew into shallower waters and eventually reached the water surface, at least the upper two-thirds of the reef structure was exposed to wave-induced turbulence. The mere fact that the structure attained its prominence above the surrounding sea floor in itself attests to the fact that it must have been wave resistant. Direct evidence for the prevalence of high energy conditions is further afforded by the coarse skeletal detritus of lithofacies 5 which flanks the reef and dominates the reef-core facies as well, and by the accumulation of fans of reef-derived rubble further down the slopes of the structure (the BRM Conglomerate Member). In view of these arguments, it is exceedingly difficult to account for the abundance of mud which forms the matrix of all the reef lithofacies. One can envision entrapment of mud within the reef-core, but by what mechanism was mud retained along the fore-reef fronts? Sediment binding by non-calcareous algae is a convenient (and by now "traditional") answer, but in view of the lack of direct evidence this must be regarded as a tentative, speculative solution to a problem which is still unresolved.

In summary, during the time interval represented by the BRM Boundstone Member, the areal distribution of the organic reef stage was constrained by the configuration of the preceding biohermal mound which serves as its substrate (Figs. 3-2, 3-4). Reef development was confined to vertical growth. The structure emerged as a pinnacle. It was too narrow for the development of a back-reef facies or a central atoll-like lagoon. The basic mode of reef growth and the resultant facies distribution pattern is a rather simple central reef-core surrounded by an apron of a fore-reef detritus.

As in the case of the preceding biohermal growth stage, reefal construction exceeded the rate of the regional subsidence. The structure gradually elevated itself into shallower water, and shallow lagoons formed along the entire crestal area of the reef. The reefal build-up eventually reached the water surface at which point active reef growth was terminated. The crestal area, rising some 300 to 350 feet above the surrounding sea bottom, was actually emergent above water and subjected to diagenetic alterations and to the weathering effects of vadose waters and subaerial conditions. Cessation of reef growth, the short episode of subaerial exposure and the ensuing supratidal conditions marked by the succeeding BRM Stromatolite Member are all in response to a marked change in the regional paleogeographic setting of the Michigan basin which took place toward the end of the Niagaran series. The commencement of the silling of the basin, manifested by the thick evaporite deposits of the Upper Silurian Salina Group, can be traced to these events.

Supratidal Island Stage - the BRM Stromatolite Member

Boundaries, Thickness and Distribution

The BRM Stromatolite Member overlies the BRM Boundstone Member. An erosional unconformity separates it from the overlying anhydrite beds of the Upper Silurian Salina A-2 Evaporite Unit (Fig. 2-9). The Stromatolite Unit can be reliably recognized on gamma ray logs (Fig. 2-10) by relatively high gamma ray intensities in comparison with the underlying BRM Boundstone Member. Particularly high gamma ray intensities are consistently recorded from the upper half of the Stromatolite Unit, and the top is readily identified on both gamma ray and neutron curves as the transition from carbonate to anhydrite lithologies. The log attributes of the BRM Stromatolite Member are very similar to those of the off-reef Salina A-1 Carbonate Unit. The superficial similarity misled many investigators to conclude that the A-1 Carbonate Unit covers the reef crest (Alguire, 1962, Fig. 3; Ellis, 1967, Figs. 5, 8, 9; Jodry, 1969, Fig. 10; Beards, 1967, Fig. 8). The erroneous correlations led to wrong concepts relative to the stratigraphic framework of the reef and off-reef relationships, resulting in misinterpretations of the evolutionary history of the reef and of the early Cayugan paleogeography of the Michigan basin.

The thickness and distribution of the BRM Stromatolite Member is shown in the isopach map of Fig. 3-7: The areal distribution of this member is confined to the crestal area of the preceding organic reef stage. Its zero thickness contour line roughly coincides with the + 300 isopach contour (Fig. 3-5). The exact original thickness of this member can not be determined since, subsequent to its depositional construction, the reef structure became subaerially exposed and eroded. Presently the BRM Stromatolite Member has an average thickness of 60 feet. It thickens gradually towards the crestal area of the reef structure, attaining a maximum thickness of 75 feet in wells 29 and 52 (Fig. 3-7).

Lithofacies Classification

The four lithofacies which comprise the BRM Stromatolite Member are the Algal Stromatolite Facies, the Flat Pebble Conglomerate Facies, the Burrowed Mudstone Facies, and the Pelletal Wackestone Facies.

Lithofacies 9: Algal Stromatolite (Plate 8). This lithofacies consists of an algal stromatolite, which in terms of its growth form, can be best described as composed of closely spaced, laterally linked hemispheroids of low amplitude (LLH-C type of Logan et al., 1964). In a vertical section, the general appearance is that of a compact succession of extremely fine undulating even laminae, displaying a high degree of congruence (Pl. 8/1, 8/2). The basic growth pattern of "laterally linked hemispheroids" is more evident when viewed from the top, in sections cut parallel to the bedding (Pl. 8/5). Additional well developed domal "heads" are shown in Plate 8, Figs. 3, 4. For the most part, the basal diameter of individual hemispheroids does not exceed 2-3 cm. Most are less than 1 cm in height. As hemispheroids diminish in size, the lamination becomes less undulatory. Zones of almost flat lying stromatolites are quite common. It should be noted, however, that the limitation of core samples does not allow a correct appraisal of the full dimensions of individual hemispheroids or "heads". It is quite possible that some of the broadly arched and flat laminated crestal samples represent portions of much larger heads. From several samples in which the core happened to penetrate steeply inclined hemispheroids' flanks (Pl. 8/7), one can deduce that structures as large as 1 or 2 feet in height

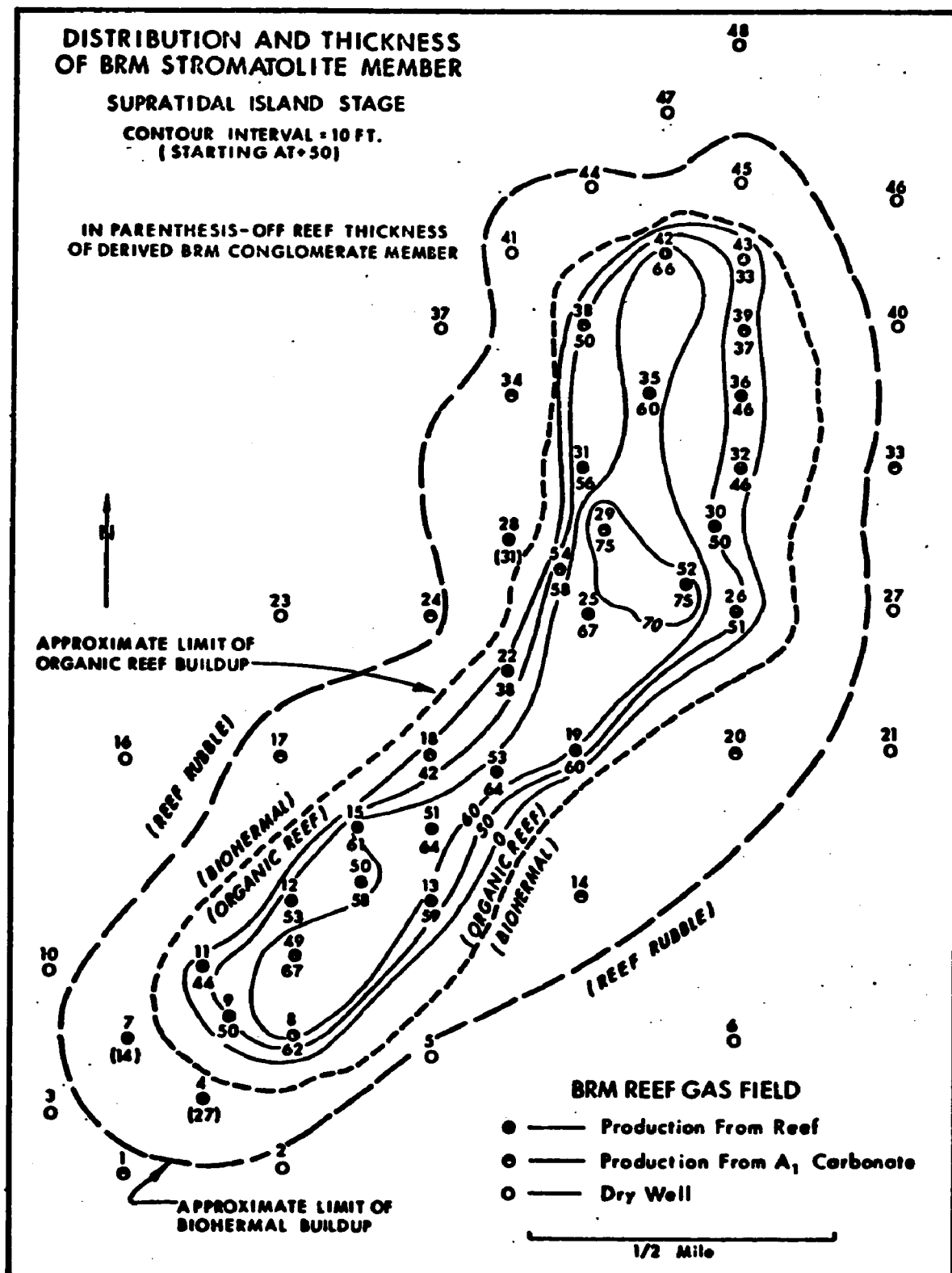


Fig. 3-7. Isopach map, BRM Stromatolite Member.

occur.

In thin sections, the stromatolite appears as a succession of couplets of micritic laminae, about 0.05 mm thick, separated by somewhat thicker, 0.1 to 1 mm thick dolo-sparitic laminae (Pl. 8/8). The sparitic laminae consist of dolomite crystals with a considerable size range within the same slide. Some laminae are composed of a dense microsparitic (0.01 mm) xenotopic mosaic of anhedral crystals. Commonly, laminae consist of a hypidiotopic mosaic of subhedral to anhedral crystals, 0.05 to 0.10 mm in size. Laminae composed of well developed euhedral dolomite rhombs up to 0.2 mm in size are also present. The sparitic laminae commonly have a fenestral fabric largely infilled by coarse anhydrite crystals. In some samples anhydrite crystals are very abundant, constituting about 20 percent of the sparitic layers.

Lithofacies 9 occurs as two distinct horizons which are referred to as the "lower" and the "upper" algal stromatolite. The foregoing description more typically applies to the lower algal stromatolite. In contrast the upper stromatolite exhibits a similar but less well developed LLH growth-form. Laminations are less finely defined and commonly discontinuous, being interrupted and in places partly reworked by burrows. The vertical stacking is not as conformable; hemispheroids are smaller. Flat to only slightly undulating lamination is common and the entire succession of laminae appear not as well organized as in the lower stromatolite.

Anhydrite crystals are present in both the lower and the upper stromatolite. The abundance of anhydrite increases towards the upper part of the member. Two morphologies of anhydrite have been noted, lath and block.

Anhydrite laths. Laths are rectangular. Their width is fairly constant at about 0.25 - 0.5 mm and they vary in length between 1 and 5 mm. Laths do not show any preferred orientation. They occur either as randomly scattered individual crystals or in clusters which show cross cutting relationships (Pl. 8/6) or rosette arrangement. The laths are cleavage flakes, split parallel to the crystal's 100 plane (Shearman and Fuller, 1969, Fig. 2). Most show a perfect rectangular cleavage.

"Blocky" anhydrite. Crystals are equidimensional, mostly irregular in shape, and range in size from 0.1 mm to 1 mm. They appear to be tightly intergrown with the surrounding dolomosaic. Blocky anhydrite is particularly abundant in the uppermost few feet of the BRM Stromatolite Member in zones of anhydritic dolomite.

Coarse anhydrite crystals constitute about 30 percent of the rock (Pl. 8/9). This lithology typically consists of very coarse rectangular and square anhydrite crystals, some up to 5 mm in size, showing a perfect rectangular cleavage. The anhydrite crystals occur either as aggregates of interlocking crystals which form an almost continuous layer or as small clusters of individual porphyrotopes embedded in an equigranular mosaic of anhedral to subhedral, much smaller (0.05 mm) dolomite crystals.

Lithofacies 10: Flat Pebble Conglomerate (Pl. 9, Figs. 1-4). Pebbles consist almost exclusively of broken fragments of the algal stromatolite of Lithofacies 9. Most pebbles are pronouncedly elongated. The conglomerate is composed of particles which cover the entire size range from silt to small cobbles. Some of the larger pebbles are up to 8 cm long and 3 cm wide. No sorting is evident. Most pebbles are very angular. Pebbles having a rectangular shape, with fairly straight edges and sharp corners, are very common. Except for the larger pebbles, which tend to lie with their long axis parallel to the bedding, most pebbles do not show any consistent orientation. They are scattered randomly, in places with their long axis at high angles or normal to bedding planes. Pebbles are in mutual contact, many displaying a "pile of bricks" fabric. For the most part, pebbles are loosely packed. The groundmass between pebbles consists of sand- and silt-sized lithoclasts, the provenance of which is not always clear. Most consist of micrite and are angular and structureless. Some display microlaminae and are probably very fine stromatolite debris.

Lithofacies 11: Burrowed Mudstone (Plate 9, Figs. 5, 6). The burrowed mudstone lithofacies is very uniform in appearance (Pl. 9/5). Petrographically, it consists of massive mottled mudstone (or dolomicrite). The brown to dark brown micrite underwent only slight crystal enlargement during dolomitization. Mottles have a lighter, tan color. They consist of a homogeneous xenotopic to hypidiotopic mosaic of equigranular dolomite crystals, about 0.05 mm in size. Mottles are of two distinct size groups. Patches of recrystallized micrite, a few millimeters across, with highly irregular diffused boundaries, form the small mottles observed within the brown sediment. Larger mottles, most exceeding 5 cm in size, comprise in places up to 50 percent of the rock. They show an abrupt and well-defined contact with the adjacent

sediment. The larger mottles most probably represent infilled burrows (Pl. 9/6). Some burrows have a distinct vertical orientation. Others tend to be horizontally elongated. For the most part however, burrows have a highly irregular shape and no consistent orientation. They commonly swell and thin to form a rather intricate maze. Some burrow infillings have a pronounced fenestral fabric. In places, burrow infillings contain abundant anhydrite laths forming aggregates in which laths penetrate and criss-cross each other.

The burrowed mudstone is devoid of skeletal material. Scarce pellets are scattered sporadically and are the only grains present.

Lithofacies 12: Pelletal Wackestone (Pl. 9/7). Pellets comprise between 10 and 30 percent of the pelletal wackestone, most pellets being 2 mm or less in size, and spherical or elliptical in shape. The matrix consists of a grain-growth mosaic comprised of enlarged recrystallized micrite. Patches of unrecrystallized mud are also present. Commonly the rock has a massive appearance, showing only rudimental bedding features marked by local concentrations of pellets along horizontal planes or by thin, undulating dark gray seams. Features that occur sporadically include grain-supported fabric, in which in some horizons pellets are in contact with each other; fenestral fabric and mottling, due to reworking by burrowing organisms. In places, lamination is well developed.

Facies Distribution and Environmental Interpretation

The BRM Stromatolite Member is the only member of the Guelph Formation that shows "normal", laterally persistent stratification. This is in marked contrast with the situation in the two preceding growth stages which are characterized by rather complex facies interfingerings and which, except for their gross stratigraphic superposition, do not show any stratification.

From bottom to top, the member can be divided into three subunits: a lower algal stromatolite complex, a middle burrowed mudstone unit and an upper algal stromatolite complex. This subdivision is in most wells also recognizable on the gamma-ray log: the burrowed mudstone is marked by readings which are slightly higher than the responses in the two stromatolite beds (Fig. 2-10). All three units

appear to be persistent all over the reef's crest. Only in a small area in the north-eastern corner, around well no. 39, is the middle unit absent (Fig. 3-12).

The two algal stromatolite complexes consist primarily of frequent interbeddings of lithofacies 9 and 10. The flat pebble conglomerate rarely forms beds which are more than one foot thick. As the vertical transitions are too frequent and thicknesses too small to be properly represented, the relationships as shown in the cross sections are to a large extent an oversimplification. In places, sharp unconformable contacts of cut and fill relationships can be observed. The pelletal mudstone of lithofacies 12 is also found interbedded within the stromatolite complexes. However, it has a very limited distribution and is only present in wells no. 22 and 31 (Figs. 3-10, 3-11).

The environmental interpretation which follows is based on the analogy of the various lithofacies to numerous other occurrences, both Recent and ancient, which have been extensively reported on in the literature in recent years. The lithofacies in the BRM Stromatolite Member are very similar to some of the lithofacies present in the A-1 Carbonate Unit. These are evaluated in detail in succeeding sections (Chapter IV). Therefore, the conclusions arrived at there will be drawn upon freely here without further elaborations.

The algal stromatolite is comparable to the planar stromatolite (lithofacies 2) of the A-1 Carbonate. It is indicative of intertidal conditions. It probably designates also an elevation in the salinity of the water which prohibited other marine invertebrates from inhabiting the site of deposition. The presence of hemispheroid forms indicates high energy conditions, analogous to the ones present in intertidal headlands in Shark Bay, Western Australia (Logan, 1961; Logan *et al.*, 1964; Davies, 1970). The fenestral fabrics and particularly the anhydrite laths denote periodic exposure and subjection to supratidal, sabkha-type diagenetic processes.

The flat pebble conglomerates (lithofacies 10) are identical in genesis to the intra-formational breccia and flat pebbles (lithofacies 5) of the A-1 Carbonate. This lithofacies indicates early induration, desiccation and storm-induced turbulence in a supratidal environment. As the pebbles are essentially still in place, their repetitious interbedding with the algal stromatolite designates frequent exposure to subaerial conditions. The storms, which relocated pebbles on the reef's crest, transported substantial amounts of stromatolite debris to the off-reef periphery. This rubble consti-

tutes the upper part of the BRM Conglomerate Member (following section).

Lithofacies 11 and 12 (in analogy to lithofacies 1 and 3 of the A-1 Carbonate) were deposited in shallow subtidal conditions. The burrowed mudstone bed thus marks a renewed, short-lived inundation in the middle part of the member.

In summary, the BRM Stromatolite Member marks the onset of significant changes in the geological framework of the Michigan basin at the later part of the Niagaran. Following the emergence of the reef to the water surface at the end of the organic reef stage, its crestal area constituted an island which was repeatedly flooded. There are indications that the salinity of the water was higher than normal. Although the member as a whole still indicates a continuous rise in sea level, this trend was soon to be reversed. The deposition of the member stopped as a result of intensive evaporation which, at the beginning of the Cayugan, had lowered the water level drastically and exposed the entire reef structure to the air.

Reef Rubble - the BRM Conglomerate Member

Boundaries, Thickness and Distribution

The stratigraphic position occupied by the BRM Conglomerate Member is shown in Fig. 2-9. In off-reef wells it overlies the Lockport Dolomite and is overlaid unconformably by the A-0 Carbonate, the basal unit of the Upper Silurian Salina Group. Around the lower biohermal flanks of the reef, the conglomerate overlies the BRM Skeletal Wackestone Member and is unconformably overlaid by the onlapping Salina A-1 Anhydrite and A-1 Carbonate Units. The lower part of the conglomerate accumulated during the organic reef growth stage (Fig. 3-4) whereas the provenance for the upper part is the BRM Stromatolite Member (Fig. 3-7).

The isopachous pattern is highly irregular, but suggests that the conglomerate accumulated in submarine fans. Two such fans are indicated by the abnormally high thickness in well 28 (74 feet) and well 4 (57 feet). See also cross sections, Figs. 3-9 and 3-10. As far as can be determined from the available data, the BRM Conglomerate Member is restricted to the immediate vicinity of the reef. It is thickest on the reef-flank. Within one half mile from the reef the conglomerate member wedges out (2, 4 and 3 feet respectively in wells 16, 23 and 37, east of the reef, Fig. 3-4). Away

from the reef it passes laterally into the "Brown Niagaran" (Fig. 2-9), which was not investigated in the present study. Most probably the "Brown Niagaran" represents the regionally thin inter-reef sediments which are time equivalent to the Guelph Formation of the pinnacle reefs.

It is of interest to note that, although not recognized as a separate unit, the presence of apparently similar conglomerates around other reefs in southeastern Michigan has been mentioned by Kiddoo (1962, p. 11) and by Felber (1964, p. 23). Therefore, in all probability, the BRM Conglomerate Member is not confined to the BRM reef alone.

Recognition of the BRM Conglomerate on gamma-ray logs is possible only in off-reef areas. In most wells its lower boundary (corresponding to the "Brown Niagaran" - "Gray Niagaran" contact) is marked by a drop in log readings (see off-reef type section, Fig. 2-12). Log intensities are low throughout the section and increase again in the A-0 Carbonate Unit, marking the top of the member. In reef-flank wells the member cannot be separated from the underlying BRM Wackestone and only the upper contact with the A-1 Carbonate is distinct (Fig. 2-11).

Lithofacies 13: Conglomerate (Plate 9, Figs. 8-10). The stratigraphic distribution of the lithoclast composition of the BRM Conglomerate allows a stratigraphic division into a "lower" and "upper" to be made. The lower part consists of dark brown rock fragments, composed of a homogeneous mass of recrystallized micrite. The rock fragments do not show any internal structure or fabric. The fragments vary in size from sand-sized particles to elongated cobbles, up to 8 cm in length. Pebbles, 1 to 3 cm in diameter, are the most abundant size class present. The lithoclasts are angular. Sorting is very poor. Conglomerate or breccia layers, one to three feet in thickness, are interbedded with zones in which pebbles are present only in subordinate amounts. The intervening beds consist of mottled mudstone, in places with scattered crinoid fragments.

The upper part of the BRM Conglomerate is present in only three wells (Fig. 3-7). It is represented in core samples in well 28 (2468'-2499') and well 4 (2411'-2438'), and on the basis of similarities in the gamma-ray log attributes it is recognized in the interval 2480'-2494' in well 7. This part of the conglomerate consists of debris composed exclusively of algal stromatolite (Pl. 9, Figs. 8-10). All the larger particles

clearly show the delicate internal organization of stromatolites, displaying a growth mode of either small LLHs or flat to slightly undulating very fine conformable laminations. Sorting is poor. Particle size ranges from sand to large cobbles, large pebbles and cobbles predominating. Most are elongated or highly irregular in shape, with angular edges. Pebbles do not show any systematic orientation, although some of the larger cobbles lie with their long axis at high angles to the horizontal (Pl. 9/10).

Interpretation and Stratigraphic Significance

The source of the conglomerate constituents can be traced to the upper two growth stages of the adjacent reef mass. The structureless and homogeneous appearance of the pebbles in the lower part of the conglomerate resemble the algal boundstone and recrystallized massive stromatoporoids, both present in the reef-core facies (Lithofacies 4) of the Boundstone Member. Therefore, the lower part of the conglomerate is thought to represent reef-derived-rubble which accumulated along the lower adjacent slopes of the structure during the organic reef growth stage. It is further manifestation of the turbulent water conditions which prevailed during this growth stage. The intervening thin beds of mottled mudstone with which the conglomerate is interbedded represent extensively burrowed and reworked sediments which were deposited around the reef in relatively deep water during the time span represented by the Guelph Dolomite. The conglomerate sediments are equivalent, both in time and in stratigraphic position, to the lower part of the regional inter-reef "Brown Niagaran" Unit of some authors (Alguire, 1962; Ellis, 1967).

The algal stromatolite represented in pebbles in the upper part of the conglomerate is essentially identical to the algal stromatolite which builds the BRM Stromatolite Member (Lithofacies 9), the only stromatolite in the Guelph Formation. The stromatolite in the pebbles doubtlessly originated in the BRM Stromatolite Member, during late Guelph time. Their origin is in the Flat Pebble Conglomerate (Lithofacies 10), being formed from the reef crest during storms and dislodged into the sea to accumulate along the lower slopes of the reef structure. One cannot exclude the possibility that the uppermost part of the conglomerate might have been

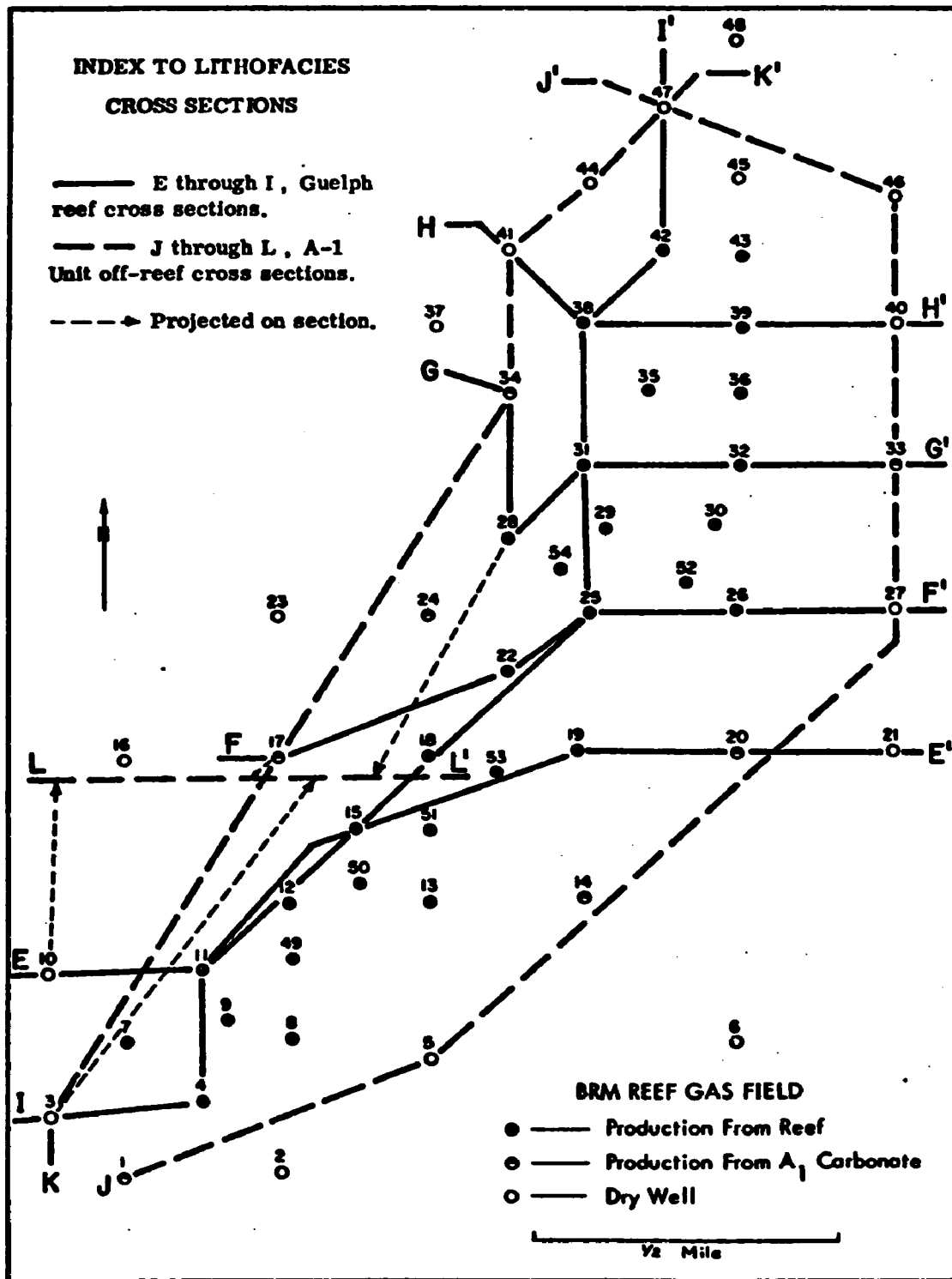


Fig. 3-8. Index to lithofacies cross sections.

III BRM Stromatolite Member.**S - Stromatolite****F.P.C. - Flat Pebble Conglomerate****L.P.M. - Laminated Pelletal Mudstone****B.M. - Burrowed Mudstone****II BRM Boundstone Member.****RC - Reef Core****CS - Coarse Skeletal****FS - Fine Skeletal****A - Algal Boundstone****L - Lagoonal****V - Vadose deposits****C, CL - Caliche****I BRM Skeletal Wackestone Member.****Organic Constituents****C, CR - Crinoids****B, BRY - Bryozoans****BB - Branching Bryozoans****Cl.- Corals****Ts - Tabular Stromatoporoids****F - Favosites****H - Halysites****Constituents and rocktypes****S - Skeletal****Lt - Lithoclasts****W - Wackestone****P - Packstone****A - Arenite****R - Rudite****() - designates subordinate
type or amount.**

associations of different rocktypes are abbreviated as follows:

CWR, A - "Crinoid Wackestone rudite and arenite"

CW(P)R - "Crinoid Wackestone, locally Packstone, Rudite."

**Table 3-5. Legend to Guelph Formation Lithofacies cross sections
(figures 3-9 through 3-13).**



FIG. 3-10. EAST WEST STRATIGRAPHIC CROSS SECTION 7-F AND DEEP FACIES DISTRIBUTION CHART

FIGS. 9-11. EAST WEST STRATIGRAPHIC CROSS SECTION G-G' AND REEF FACIES DISTRIBUTION CHART.

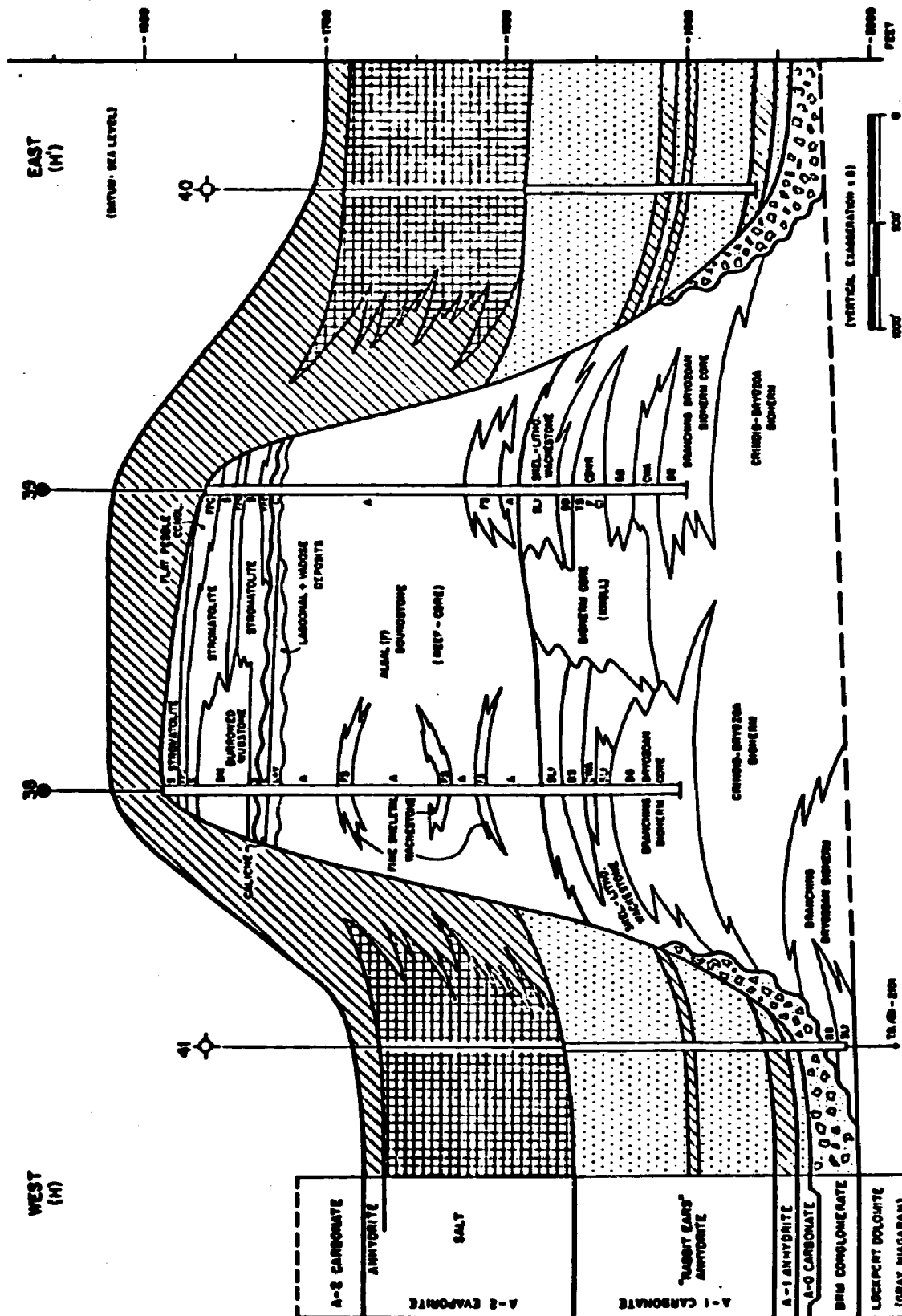


FIG. 3-12. EAST WEST STRATIGRAPHIC CROSS SECTION N-N' AND REEF FACIES DISTRIBUTION CHART.



accumulated during early Salina (Upper Silurian) times when the entire reef structure was exposed to subaerial weathering and erosion. However, no reef debris has been found within the reef-flanking Salina units, and I doubt that any significant reef erosion took place in lower Salina time.

As stated in Chapter I, one of the main stratigraphic problems presented by reef studies in general, and by the Niagaran reefs of Michigan in particular, is the resolution of the time relationships between the reef construction and its surrounding and flanking off-reef sediments. The BRM Conglomerate Member provides an invaluable stratigraphic clue which resolves much of this controversy. The final events in building the reef are recorded in the algal stromatolite pebbles of the conglomerate. The conglomerate underlies the overlapping A-0 Carbonate, A-1 Anhydrite and A-1 Carbonate Units of the Salina Group in the off-reef and reef-flank areas. It thus provides indisputable evidence for dating the entire off-reef sequence as post-reef in age. As will be emphasized in the following discussion, there appears to be ample independent evidence from other sources to support the same interpretation.

Reef Geometry

The present subsurface configuration of the BRM reef reflects its complex evolutionary history. Each growth stage contributed to the final shape of the structure. Indeed, the morphological evolution of each stage of reef construction controls the environment of succeeding growth phases. The organic reef proper could not develop as long as the biohermal mound remained below wave base level. Supratidal conditions originated in response to the reef emerging from the sea.

The morphological evolution of the reef structure, from a featureless flat sea bottom to its present mound or pinnacle shape, has been portrayed by means of isopach maps (Figs. 3-2, 3-4, 3-5, 3-7) and structure maps (Figs. 3-1, 3-3, 3-6) in the foregoing sections. A reconstruction of the final geometry is presented in Fig. 3-14, an isopach map of the Guelph Formation. The topographic cross sections (Figs. 3-17 and 3-18) are based on this map. The four lithostratigraphic members

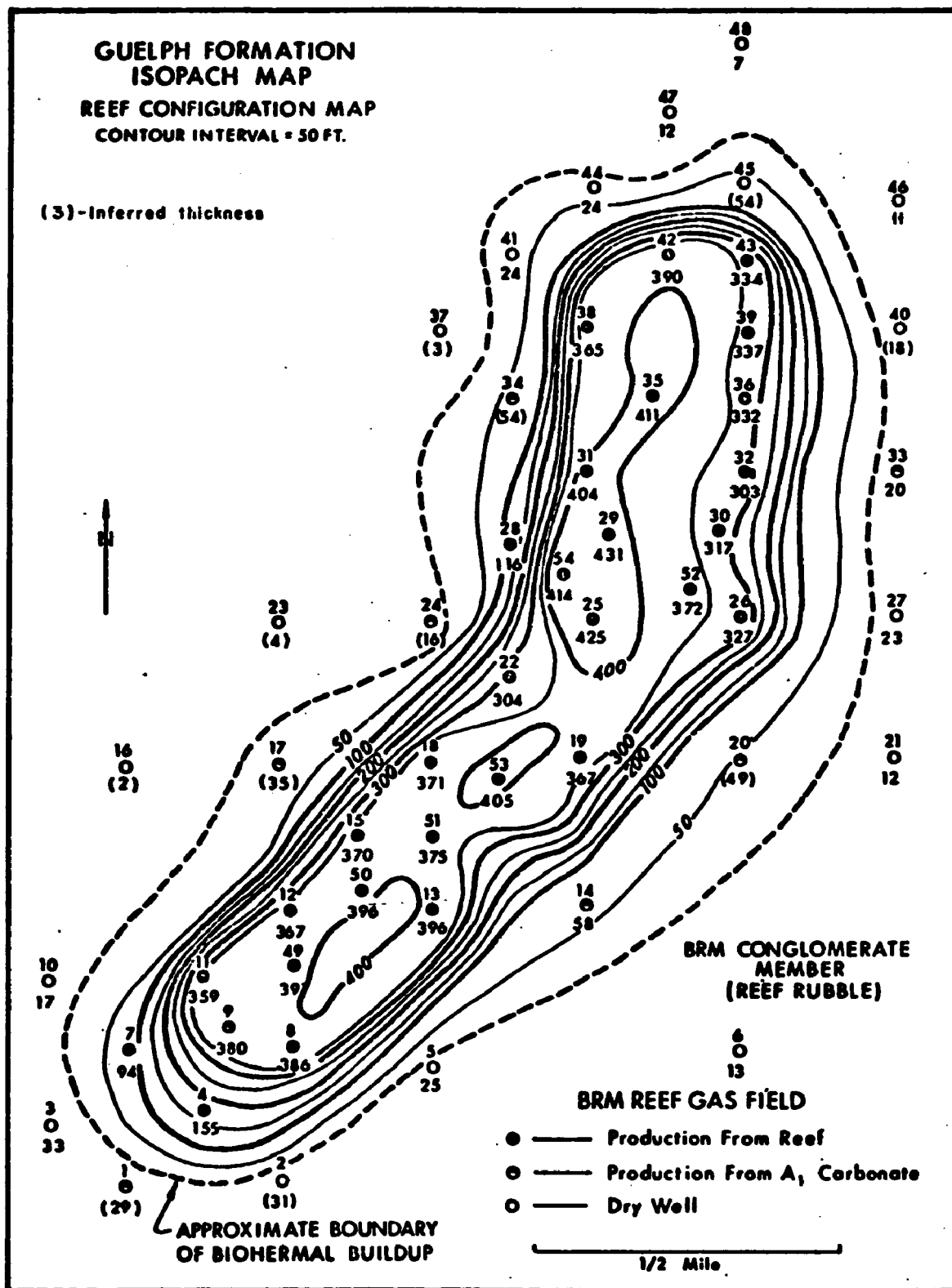


Fig. 3-14. Guelph Formation isopach map.

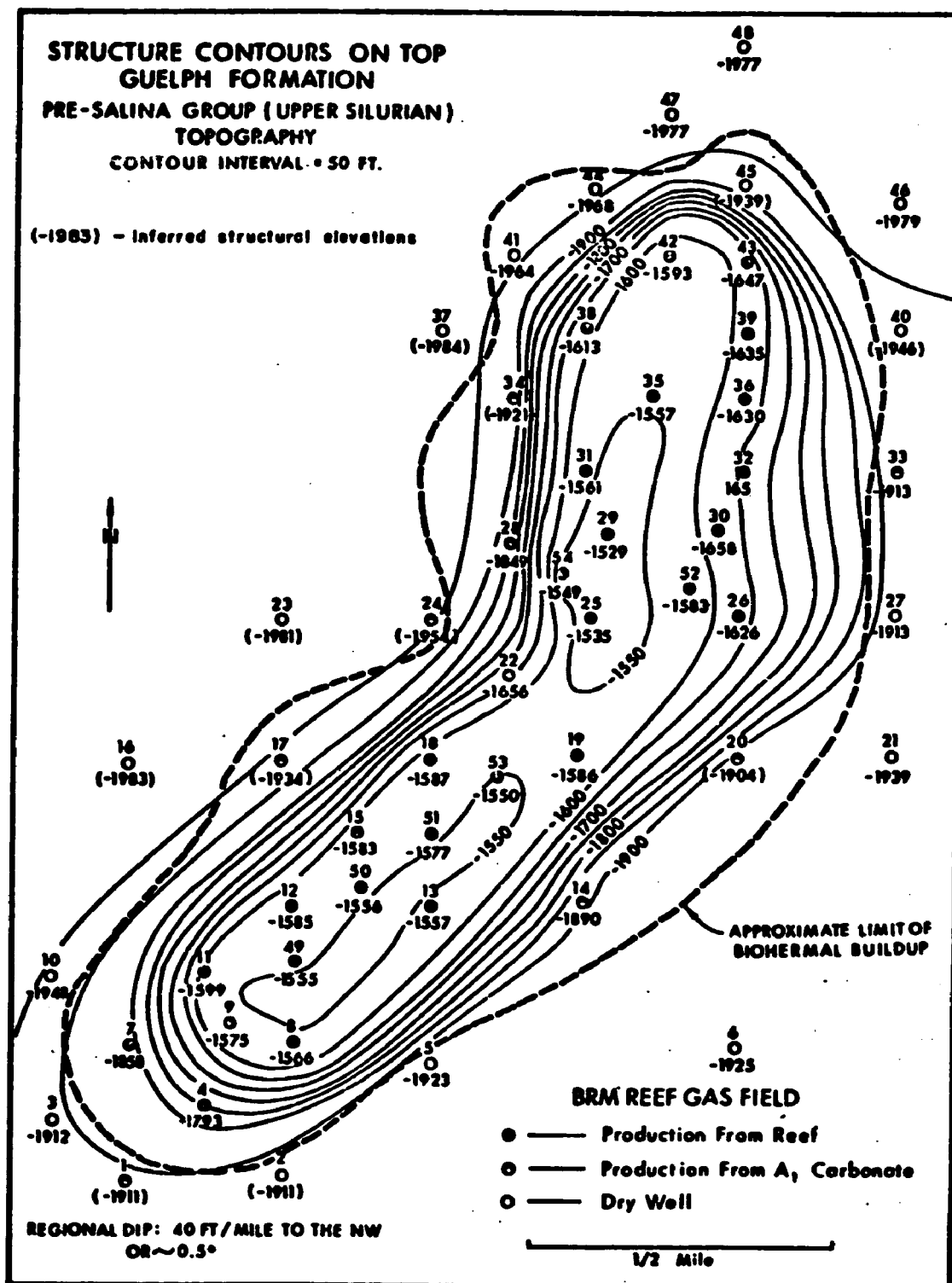


Fig. 3-15. Structure contour map on top Guelph Formation.

comprising the Guelph Formation, shown on the profiles, illustrate the contribution of the various growth stages to the total reef. An additional representation of the paleotopography of the structure is afforded by the structure map on top of the Guelph Formation (Fig. 3-15). This map also represents a reconstruction of the Upper-Salina unconformity surface. Owing to the unconformity and the resulting onlapping relationships between the off-reef Salina units and the Guelph Formation (Fig. 2-4), the map is contoured on elevations which mark different stratigraphic contacts in different parts of the map. In reef wells it is drawn on the contact between the Niagaran BRM Stromatolite Member and the Salina A-2 Evaporite. In flank wells, elevations mark the boundary between the Niagaran BRM Conglomerate Member and Salina A-1 units, whereas in off-reef wells it is drawn on the contact between the Niagaran BRM Conglomerate Member and the Salina A-0 Carbonate. Since the present regional dip is only about one-half degree to the NW (Adams, 1965, Fig. 2), the structure contour map (Fig. 3-15) provides an undistorted reconstruction of the configuration of the reef (cf. Figs. 3-14 and 3-15).

In plan view, the reef structure is elliptical in shape, elongated in a northeasterly direction. Its geographical orientation thus conforms to the trend of the majority of reefs in southeastern Michigan (Fig. 1-4). North of the juncture, between wells 22 and 19, the longitudinal axis of the structure bends more northerly, thereby dividing it into a southern and a northern half. The base of the reef is about 2 miles long. It covers an area of about 700 acres. The structure has a maximal width of 4000 feet at its center. It narrows to an average width of 3500 feet in the northern half and 3000 feet in the southern half.

In profiles drawn perpendicular to the reef's long axis (Fig. 3-17) three topographic zones can be recognized:

- 1) Crestal area - As defined by the + 350 contour line, the reef's crest encloses an area of about 250 acres. It is centered with respect to the outline of the base of the structure. It is somewhat domal in cross section, sloping gently (at about 6 degrees) towards both flanks. Relief differences within the crestal area average about 50 feet, with a maximum of 81 feet (20 percent of the total relief).

Local closures of the +400 foot isopachous contour define two small knobs in the

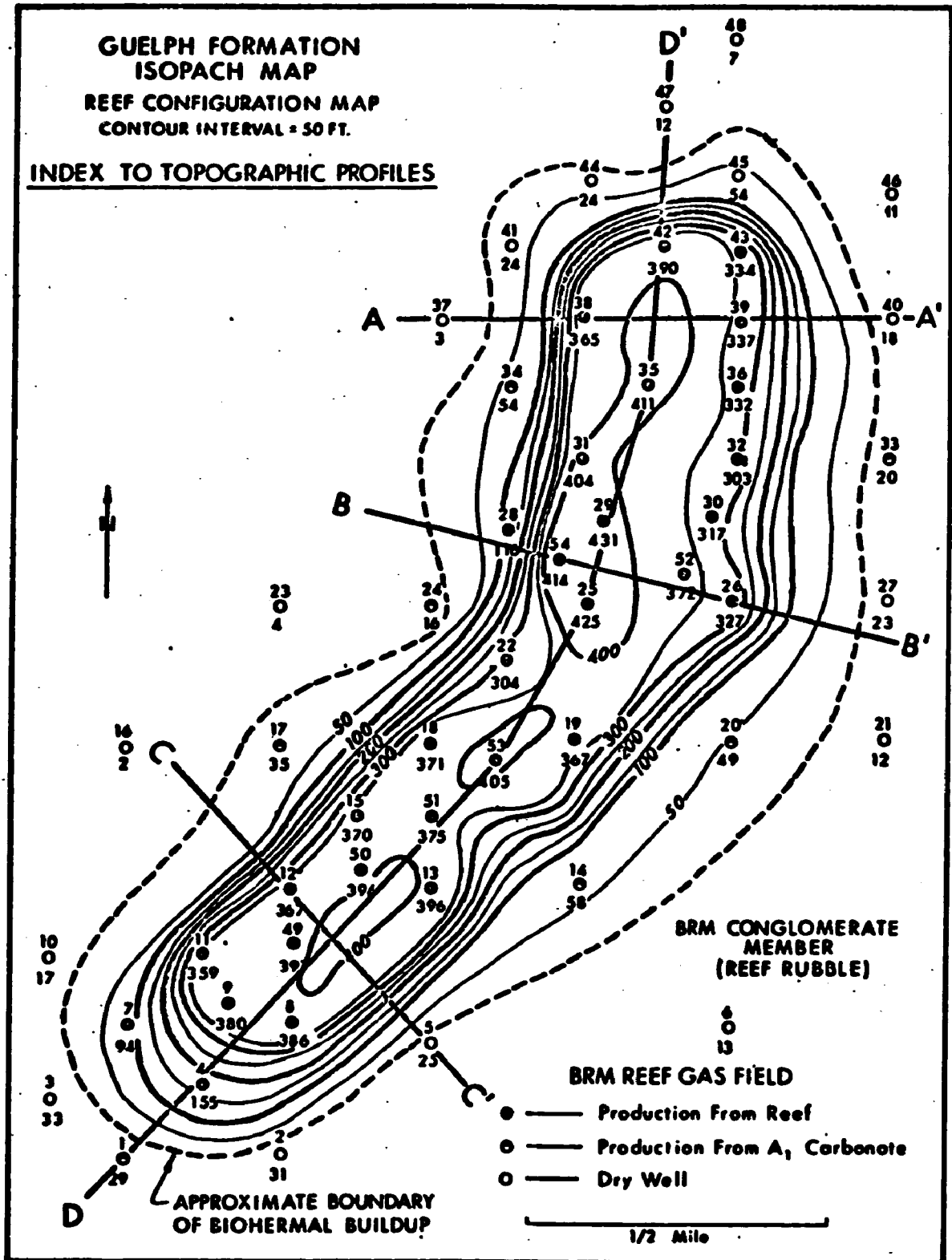
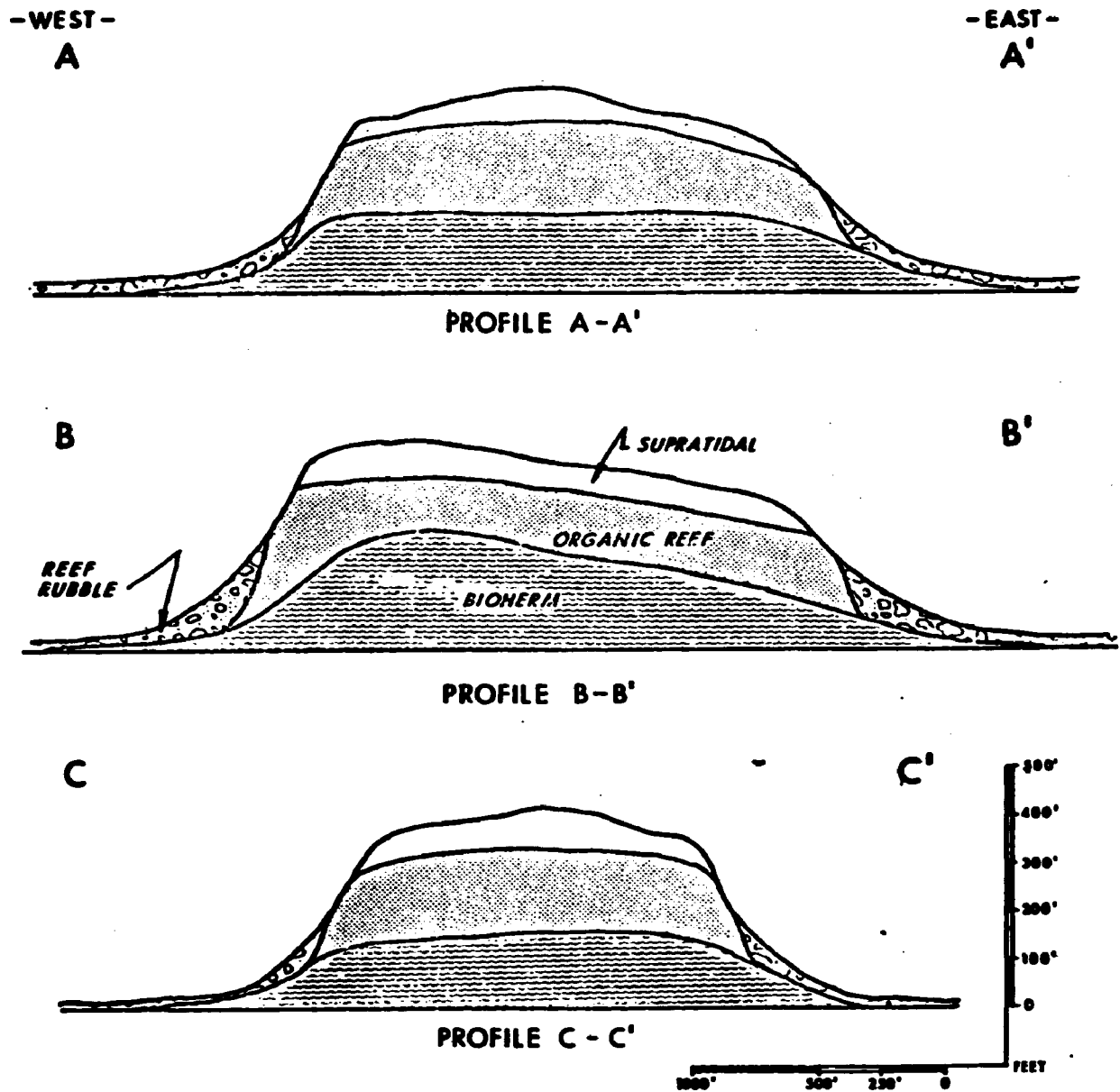


Fig. 3-16. Index to topographic profiles.



BRM REEF
EAST-WEST TOPOGRAPHIC
AND STRATIGRAPHIC PROFILES
(PERPENDICULAR TO REEF'S LONG AXIS)
VERTICAL EXAGGERATION X2

Fig. 3-17. East-west topographic profiles.

BRAM REEF
NORTH-SOUTH LONGITUDINAL
TOPOGRAPHIC AND STRATIGRAPHIC
PROFILE
 VERTICAL EXAGGERATION X 2

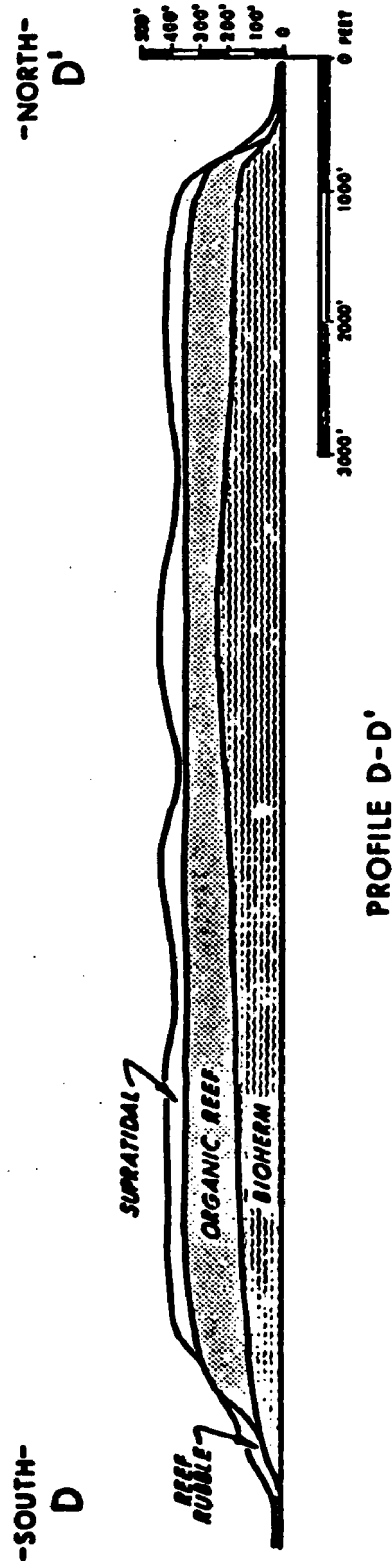


Fig. 3-18. North-south topographic profile.

central part of the southern half and an elongated ridge paralleling the long axis along the northern half. The reef attains its maximum relief of 431 feet at the center of this ridge (well 29). The margin of the crestal area appears relatively smooth. Only at two areas along its circumference (wells 22 and 51) is the crestal margin indented by broad depressions transecting the slope.

2. Reef escarpment - Between the + 350 and the + 100 contour lines, the reef edge drops very steeply to form an escarpment, 250 feet high. This escarpment is a manifestation of the organic reef stage. It coincides with the reef walls which were formed during this growth phase. Slopes on the west flank range from 30 degrees in the south to 40 degrees in the north. On the eastern flank, slopes are more moderate, but still rather steep, varying between 20 and 30 degrees. The northern plunge is very steep (40 degrees) whereas the southern one is the most gentle one (14 degrees). This can be attributed to the accumulation of reef debris of the BRM Conglomerate Member along this edge, thereby moderating the original slope considerably and obscuring the escarpment which is buried underneath it (see topographic section D, Fig. 3-18). The slope appears relatively uniform and undisturbed by channels and gullies. Only two pronounced valleys, between wells 14 and 51 and between wells 24 and 22, are apparent. This is, most probably, a reflection of the lack of control points and represents an oversimplification inherent in the data.

3. Outer slope - At about the + 100 contour line, the slopes all around the structure are reduced to about 8 degrees. Along this part of the profile, the slopes coincide with the outer, moderate flanks of the biohermal build-up (Fig. 3-2).

Diagenetic Alterations¹

Introduction

The BRM reef underwent severe diagenetic changes which altered much of the original depositional texture. The most pronounced change was dolomitization, and, as indicated earlier, the entire reef mass now consists of dolomite.

¹"Diagenesis" is used here in its broadest sense, as defined by Murray and Pray, 1965, and it pertains to all post-depositional changes (excluding metamorphism).

The study of the diagenesis of the reef rocks was focused on selected key diagenetic features pertinent to the understanding of the geological history of the reef.

The analysis documents a number of diagenetic fabrics which originated during the period of exposure to which the reef was subjected prior to the deposition of the enclosing off-reef Salina strata. The firm stratigraphic evidence for this exposure period will be presented in the next chapter. What is sought here is to unravel what independent evidence the reef rocks provide to support the postulated subaerial exposure stage.

Diagenesis was evaluated through analysis of petrographic attributes. The data and their immediate implications are presented and evaluated here. The conclusions will be integrated with other data to arrive at a comprehensive diagenetic model in a later section (section 5A).

Petrographic Observations (Plates 10, 11)

The petrographic observations suggest a sequence of diagenetic paragenesis which consists of several distinct stages of dissolution of carbonate minerals and vugular infilling.

a. Karstic solution is the first stage in diagenesis and development of secondary porosity. The generation of secondary porosity in carbonates is either selective and preferential or indiscriminant. Both fabric selective and non-fabric-selective porosities (Choquette and Pray, 1970) are present in the BRM reef. A substantial part of reef-porosity is primary intraskeletal between corals (Pls. 1/8, 2/1, 4/2), bryozoa (Pl. 2/7), brachiopods (Pl. 5/11) or stromatoporoids (Pl. 3/3, 3/5). Many intra-skeletal voids are enlarged by solution. Molds formed by the selective leaching of skeletons are an important source of porosity by total dissolution of skeletal components (Pls. 4/2, 5/8, 5/9) or partial dissolution (Pls. 3/3, 11/4). Intercrystalline and interparticle matrix porosity of the type shown in plate 10/1 is also produced by solution.

The more spectacular porosity in the BRM reef resulted from non-fabric-selective dissolution. Vugs as large as two to three inches in diameter are not uncommon (Pl. 10/2, 10/2). Some of these are enlarged molds, but for the most part dissolution removed the minerals nonpreferentially. All of the plugged vugs discussed in the next

section belong to this group. Indeed, intercrystalline matrix porosity and non-fabric-selective porosity are the predominant sources of porosity in the reef. Also common are interconnected vugs which form "channel porosity" that was subsequently plugged and only partially reopened at yet a later stage (Plates 11/3 and 10/9). Fracture porosity is another abundant type that could be related to karstic processes. Many of the smaller fractures were formed by internal brecciation following roof-collapse into karst-generated cavities (Pl. 11/10, 11/11).

b. Porosity plugging. The infilling of the pores, vugs and fractures during the complex diagenetic history of the reef was probably as pervasive as the generation of porosity. The vugs formed by the karstic leaching underwent a continuous infilling in which several stages can be discerned:

1. Vug lining by fibrous carbonate (see Plates 10/4, 10/5, 10/8, 11/4, 4/5). The first phase of vug infilling was the development of an encrusting layer of fibrous carbonate. These linings now consists of dolomite and it is impossible to determine whether calcite or aragonite was the original mineral deposited. Within the same vug the layer is continuous and of even thickness, lining the entire surface of the vug including its most intricate and irregular passageways and protrusions (Plate 10/8, 10/9). It is composed of "fibrous carbonate" (Pl. 10/10, 10/11), consisting of slender, closely packed and intergrown subparallel fibers. The fibers grew perpendicular to the walls of the vug and display a wavy crossed-polarized extinction.² Most fibers range from one to five microns in thickness, although a few coarse fibers about 0.5 mm in thickness have been observed. The crusts are invariably "cloudy" in appearance, as if contaminated by submicroscopic impurities. Many fibers are arranged in a compressed plumose triangular bundle which originates at a common apex on the cavity wall and radiates divergently into the cavity. The voids formed between the apexes along the cavity wall are infilled by equant cement which is in optical continuity. The boundaries between adjacent triangular bundles are sharp,

²Cement with such characteristics has been termed "fibrous mosaic" by Bathurst (1959, p. 511), "precipitated fibrous crust" (P. F. C.) by Folk (1965, p. 24-25) or simply "fibrous" by numerous authors (for example, Newell 1955; Wolf, 1965; Chilingar et al., 1967, Fig. 2). Dunham refers to this habit of cement as "drusy" (Dunham, 1969a, footnote 4). The "radial fibrous" texture from stromatactis vug lining described by Bathurst (1959, p. 511) was not found.

each having its own pattern of undulose extinction. Within the triangular fans, thickness of the fibers is submicroscopic. Often the fibrous texture can be discerned only in crossed polars. When crusts from opposite walls meet, the suture line is well-defined and nearly straight.

Several generations of vug linings can be discerned, expressed in concentrically arranged, successively even layers of fibrous spar (Pls. 10/4, 10/5, 10/8, 10/9, 11/1). The fibrous minerals completely fill the void space in some specimens (Plate 10/6, upper part), and plug only the periphery of the vug, leaving its central part void in others (Pl. 10/4, 10/5, 10/6, lower part). Invariably small vugs are completely infilled (Pls. 4/5, 10/7). Most fibrous cement is white to light gray in color. In certain parts of the reef a dark brown fibrous cement which completely plugs the "channel porosity" is common (Pl. 11/2, 11/3). In several samples the difference between succeeding vug lining generations is expressed by color changes - the first generation (outer lining) is light whereas the second (inner part) is dark (Pls. 10/8, 11/2).

In this connection it is highly significant to note that karstic dissolution on a larger scale is also present, as is evident from the fact that in at least three reefs (BRM, Hessen and Ray), lost-circulation zones were encountered while drilling the discovery wells in the fields (W. Mantek, written communication, June 8, 1970).

2. The central void space of many vugs, particularly the larger cavities, left unfilled by fibrous cement has been wholly or partially infilled by micritic sediment. The sediment is very dense, homogeneous, and of a dark brown, yellowish green to reddish color. In many cavities, the internal sediment occurs only as a very thin layer along the floor (Pl. 10/10). In others it completely infills the void left after the deposition of the fibrous cement (Pl. 11/4). In several specimens the internal sediment infills passageways leading into cavities (Pl. 10/9), and in larger cavities it is distinctly laminated (Pl. 11/9). The two samples of internal sediment analyzed for trace elements are distinctly enriched in insoluble material.

3. Where fibrous cementation and sediment infilling did not completely infill the cavities, the residual void space is often occupied by halite, anhydrite or ferroan dolomite. Most halite occurs as very large, transparent cubic crystals which fill

all the remaining space in the lined cavities (Pls. 10/4, 11/1, 11/3). Halite also completely infills other types of voids, including interparticle and fracture porosity in the BRM Conglomerate Member and leached interparticle and intercrystalline porosity in the reef (Pl. 10/1) Vug-filling anhydrite invariably consists of very large crystals up to 2 cm long (Pl. 11/8). Anhydrite more rarely has a felted texture (Pls. 10/11, 11/5, 11/10, 11/11) similar to but coarser than the fabric of anhydrite nodules (see Chapter 4). Anhydrite also fills voids lacking fibrous cement linings.

A few cavities are infilled with stark white dolomite (Pl. 11/7) which consists of a coarse mosaic of idiomorphic dolomite rhombs (0.2 to 0.5 mm in diameter) (Pls. 11/6, 10/10). The rhombs are distinctly zoned, containing mostly one, but occasionally more than one, dark brown to black rhombohedral frame within them. The frames are about 0.03 - 0.05 mm across. Some of the dolomite crystals have a dark colored core, also rhombohedral in outline, probably consisting of ferroan dolomite.

c. Leaching of vug infillings (second leaching phase). Many vug infillings show clear evidence of partial dissolution. This is particularly evident where irregular secondary voids have been excavated within vugs previously completely infilled by fibrous cement (Pls. 10/7, 10/8, 11/2, 11/3). Indeed, there is reason to believe that the reef owes its present porosity to this second phase of leaching.

d. Late calcite. Rarely vugs generated by the second leaching phase were later occluded by coarse crystalline, transparent, blocky calcite (Pls. 2/6, 10/8). Calcite is indeed extremely rare in the reef. All together throughout the 3600 feet of reef-core examined, only seven occurrences of calcite have been noted. One consists of very coarse euhedral-pyramidal ("dog tooth") calcite crystals projecting into a large solution cavity (Pl. 10/3); elsewhere anhedral calcite occupies void spaces generated during the second phase of leaching.

Interpretation of Diagenetic Attributes

Lithification - A question of major importance which is inherent in all discussions of carbonate diagenesis relates to the fundamental problem of lithification. The indiscriminant, non-fabric-selective dissolution clearly took place after the rocks were already lithified. That lithification of carbonates can proceed in both subaerial and

submarine environments has been thoroughly documented in recent years (Bricker, 1970; Bathurst, 1971, chapters 8, 9, 10). However, so far no petrographic criteria are known by which a categorical decision on this issue can be made. In the BRM situation, ample evidence for a subaerial exposure period is available. Yet, this still has only limited and inconclusive bearing on the problem. Consequently, a definite answer to this fundamental question will have to be deferred until unequivocal criteria to distinguish between meteoric and marine water lithification have been established.

Generation of secondary porosity - In carbonate terrain, one of the most characteristic results of subaerial weathering and of the action of meteoric water (which need not entail subaerial exposure) is the development of karstic solution. Vadose and phreatic meteoric waters of acid pH and charged with carbon dioxide are undersaturated with calcium carbonate and are prone to dissolve carbonates encountered along their path (see extended discussion in Purdy, 1968, pp. 196-203; Dunham, 1969a, pp. 161-166; Choquette and Pray, 1970; Bathurst, 1971, chapter 8 and p. 450). Solution-generated secondary porosity is extensive throughout the entire reef mass and there can be no doubt as to its karstic origin. For the time being this still leaves open the question of whether the karstic processes operated under vadose, phreatic or confined conditions.

Cavity-rimming fibrous cement - It is of prime importance to establish whether carbonate cement² fabrics are indicative of diagenetic environments.³ In a recent paper, Friedman (1968) has tried to establish a correspondence between water salinity and the mineralogy and fabric of carbonate cements. Considering the diverse conditions under which very similar looking cements can be formed (Bricker, 1971), it is at best questionable whether an unequivocal dependency does indeed exist (Bathurst,

²"The word cement is taken to include all passively precipitated space filling carbonate crystals which grow attached to a free surface" (Bathurst, 1971, p. 416). Thus, also crystals of cavity linings, which are attached only at one of their ends while their other end grows into a void are considered as cements.

³The diagenetic environments of main concern to the present discussion are the marine and the fresh water environments.

1971, p. 439; Dunham, 1969a, p. 166). Yet, despite these reservations, it must be admitted that this type of cement does find its closest Recent analog in cave deposits.

Furthermore, it should be emphasized that the question as raised here doesn't relate to the formation of fibrous cement in general but rather, to the formation of a very particular habit of fibrous cement. As far as its genetic interpretation is concerned, the most important attribute of this habit is its occurrence in solution cavities of definitely secondary and most probably of karstic origin. Reprecipitation is an integral part of karstic activity and as characteristic of it as is solution. The fact that the fibrous cement is the first cement present and it completely lines the cavities can be best explained by a simple genetic association between cavity formation and cementation. Therefore, the fibrous lining is most probably also of karstic origin. This is further corroborated by its frequent association with vadose silt. In addition, it obviates the need to look for an external source to account for the immense quantities of precipitated calcium carbonate cement. Thus, although the fibrous cement fabric in itself might not be diagnostic of any particular diagenetic environment, the habit of occurrence in secondary cavities and the scale are most probably indicative of karstic origin.

It is of interest to refer to several studies in which the possible environmental significance of similar cements has been contemplated. Dunham (1969a, p. 166) expresses the hope that "... the drusy (i. e. fibrous) habit in calcite cement will prove to be a suggestive criterion for the vadose and related shallow phreatic zone" but concludes in saying that "the habit of crystals in general is notoriously undependable." Lucia (1968, in particular Figs. 18A, 18D and 19) has documented exceedingly similar features in exposed and buried "lacy carbonate crusts" forming in the Pekelmeer Salina of South Bonaire. Their origin there is not fully analyzed. They could be related to the sabkha brines or to percolating rain waters. Using this as an analog and stressing its fresh water origin, Kendall advocates the same model for the fibrous lining of tepces (Kendall, 1969, pp. 2514-2515). Wolf (1965d) described essentially identical features and interpreted the fibrous lining to have formed in the intertidal to supratidal littoral zone, thus emphasizing subaerial exposure rather than water salinity.

On the other hand, practically all investigators who addressed themselves to the

origin of "stromatactis" and advocate the submarine origin of this feature, directly or indirectly postulate a submarine origin for the fibrous cements crusts. Cotter (1966) specifically calls for the submarine origin of the fibrous linings. However, particularly in this case, the evaluation is not entirely convincing. To account for clearly karstic diagenetic features, Cotter postulates a subsequent exposure period. There appears to be no reason why the formation of the fibrous cement, and for that matter the formation of the cavities themselves, could not be part of this stage as well. Newell (1955) presents a convincing case for the synsedimentary origin of similar crusts, but his observations pertain to primary cavities. Krebs, who favors a submarine origin of the fibrous crusts for the bulk of the Devonian fore-reef limestone in Germany, but nevertheless accepts a subaerial origin for some of them, presents many additional references in which the problem has been debated (Krebs, 1969, pp. 293-296 and Table 1).

Vadose cavity filling sediment - The internal sediment which infills the secondary cavities is distinctly different from the marine sediment which surrounds the cavities. It is also distinct from the synsedimentary geopetal infillings. The latter commonly contain fossil fragments (Pl. 1/9), which are absent in the cavity fillings. The internal sediment postdates the fibrous cement whenever the two occur together. It is enriched in insoluble residue relative to the surrounding marine sediments and is oxidized. The homogeneous clay-size composition indicates filtering, and the lamination, when present, indicates gravitational settling.

Except for its finer grain size, the internal sediment is similar in all other respects to the "vadose silt" described by Dunham (1969a) and is of identical origin. It represents a mixture of fine carbonate mud and insoluble residue, brought into suspension during the karstic dissolution, which has filtered through the intricate network of the solution channels and was trapped and deposited inside the larger cavities. Its uniform clay size was acquired by mechanical sorting along its flow path. The occurrence of the vadose sediment and its specific association with solution cavities lend support to the karstic origin of the cavities and the fibrous cement which lines them.

It is of interest to note that very similar occurrences of internal sediment, in one

form or another, have been reported in many papers dealing with the problem of stromatactis (Bathurst, 1959; Schwarzscher, 1961; Philcox, 1963, 1971; Otte and Parks, 1963; Lees, 1964; Playford and Lowry, 1966; Heckel, 1972). Similar occurrences in which the internal sediment is oxidized were reported by Krebs (1969) and by Wolf (1965d). The former suggests that the vadose sediment represents redeposited terra rossa, whereas the latter attributes it to subaerial oxidation in the intertidal to supratidal zone. Maiklen documented practically identical features from the Middle Devonian Keg River reefs of Alberta (Maiklem, 1971; compare in particular his Fig. 3 with Plate 11/9).

Cavity filling by evaporitic minerals - Halite and anhydrite presently filling the central parts of cavities were precipitated from a highly concentrated brine. It is hard to conceive that such a brine was available contemporaneously with the flourishing of the reef. As will be shown later (Chapter 4), this phenomenon is adequately accounted for by a practically unlimited supply of sabkha brines which was available during the deposition of the off-reef Salina units. These same brines were responsible for the pervasive dolomitization of the entire reef mass.

It is difficult to assert with certainty whether the idiomorphic dolomite is primary or neomorphic (Folk, 1965), but in either case, it had to be deposited from a relatively concentrated brine. The conditions required for the formation of ferroan dolomite cores and frames are a high $\text{Fe}^{+2}:\text{Mg}^{+2}$ ratio and a reducing milieu (Katz, 1971). The source of Fe-ions might be dolomitizing brines enriched with Fe-ions from an organic-algal source in the sabkha. Evidence for this is afforded by the abundance of authigenic pyrite in the A-1 Carbonate Unit (see p. 157). Alternatively, or in addition to it, Fe-ions could have been acquired from the insoluble residue within the cavity-filling vadose sediments. If the dolomite crystals grew at the expense of a previous vadose internal sediment, then ample Fe-ions were available at the site of its formation. Reducing conditions in the microenvironment of a fluid or sediment-filled cavity are not unusual, even within a vadose zone.

The dolomite rhombs furnish yet another analogy to similar occurrences linked with the so called "stromatactis" feature. Dolomite euhedra infilling the central part of stromatactis cavities have been described by Textoris (1966), Wolf (1965d), Cotter

(1966), Schwarzacher (1961), Philcox (1963) and Heckel (1972), the last three specifically mentioning the occurrence of Fe-rich dolomite. Philcox (1965) mentions the enrichment in iron oxides of similar cavity-filling blocky calcite.

Considering the abundance of brine in the reef-flanking sediments, it is reasonable to assume that during the evaporite stages most of the remaining open void spaces in the reef were plugged by evaporitic minerals. Much, but evidently not all, of the porosity was regained due to a subsequent leaching phase.

Second leaching stage - Subsequent to dolomitization of the reef and to the evaporate mineral infilling of pore spaces, the reef was again subjected to dissolution processes. During this stage, many of the previously plugged pores were reopened. To what degree the secondary leaching improved the porosity throughout the rest of the reef mass is difficult to evaluate as the two pore-generating stages are difficult to distinguish petrographically. During the second leaching stage soluble salts and carbonate cements were dissolved most likely by meteoric waters.

Vug infilling by calcite - The scarce calcite crystals were deposited in vugs formed during the second leaching phase. Their deposition took place after dolomitization of the reef was complete. Thus, excluding the entrapment of gas in the reef (if this can be regarded as part of its diagenetic history), the calcite infillings represent the last diagenetic event recorded in the rocks.

Karstic Origin of Stromatactis in the Belle River Mills Reef

In the foregoing sections attention has been drawn to certain analogies which exist between the diagenetic features in the BRM reef and a sedimentary fabric termed "stromatactis", which is attributed to karstic processes affecting the BRM reef and perhaps many other occurrences of stromatactis (Gill, 1972).

In a recent paper, Heckel (1972) reviewed the various aspects of the "stromatactis problem". He also offered a definition for this structure according to which "stromatactis is a carbonate spar filled cavity in calcilutite which has a typically flat to smoothly curved base and an irregular top that is not sheltered by larger rigid grains" (*ibid.* p. 8). This definition would probably be acceptable to most investigators who reported on stromatactis. The thesis presented here is that this definition is arbitrary and restricted since it merely defines an end member of a much more

complex and diversified family of related structures.

According to this definition, many of the cavities described above would qualify as stromatactis. Some of the "better" stromatactis are shown in Plates 11/4, 11/7, 10/7, 10/8. It should be emphasized that the examples shown in the plates represent but a very small selection of the occurrences of this fabric, which is extremely abundant throughout the reef. Consequently, the documented karstic origin of these structures in the BRM reef has immediate bearing on the origin of stromatactis in general.

The restrictive nature of the conventional definition of stromatactis lies in both the geometrical constraints of the cavity itself and in the lithofacial construction on its host rock.

The insistence on the specific form of the cavity, namely, its flat or smooth floor, its irregular roof and its isolation (the last attribute, although not part of the definition, being implied) might well be the main pitfall of the definition and the main source for misunderstandings. Many investigators have analyzed this structure only in two dimensions and consequently were content with the applicability of the geometric restrictions as quoted above. However, it is highly significant that many workers who inspected the spatial geometry of this feature have drawn attention to the fact that individual stromatactis, which in one section might be flat-bottomed, might in themselves be exceedingly irregular structures or otherwise be associated with nearby (in the same hand specimen) identical features which do not show a flat bottom. Bathurst (1959, p. 519) speaks of the "complex labyrinthine pattern" of the structure; Schwarzacher (1961, pp. 1493-1494) states that "it can be shown that practically all other (i. e., non-primary, referring to stromatactis) cavities form an intercommunication system through large volume of rock. Cavities, which in one section appear to be isolated, can be shown by serial sectioning to be part of the same system which pervades the whole hand specimen. By careful field studies it was possible to prove the continuity of the cavity system over a distance of several yards, and the actual extent is probably considerably larger." Philcox (1971) writes that "in bioherm centers stromatactis is highly irregular and extensively interconnected"; Wolf (1965d, p. 206) observes that "serial sections of oriented hand specimens reveal

that two or more "horizons" of these open space structures merge when considered in three dimensions. This indicates that some of the stromatactis are part of a complex labyrinthine network." Association with cavernous dissolution is also mentioned by Cotter (1966). The stromatactis described by Otte and Parks (1963) was disqualified by Hecken (1972, footnote 2) specifically because of their cavernous nature. In fact, Heckel (1972, p. 14 and Fig. 6) himself mentions the enlargement and interconnection of cavities, or in general, the apparent cavernous-labyrinthine overall structure of at least some of the stromatactis in the Tully limestone. In fact, I suspect that once the smooth-bottom requisite is analyzed carefully, many, if not most, so-called stromatactis will have to be disqualified.

Bathurst (1959, p. 519) and Heckel (1972, p. 14), among others, call on a subsequent, later stage "internal erosion, solution and redeposition" to account for the rugged bottom of adjacent otherwise identical features or to explain the cavernous nature of the phenomenon as a whole. One may well wonder why not to include a rugged bottom as part of the definition and regard the flat bottom as an exception lacking internal erosion or, perhaps, smoothed by internal erosion. And all together - why not regard internal erosion as an integral part of the formative dissolution process as a whole?

A flat bottom, if it is indeed consequential, can readily, and probably better, be explained by stratification controlling the karstic dissolution processes. It is reasonable to envision that the excavation of cavities will tend to be initiated along minute bedding inhomogeneities and thus be relatively smooth, whereas the tops of the cavities, being literally formed by "micro-caving in" will tend to be irregular. This is probably particularly true for calcilutite bioherms in which there are no other fabrics which might have controlled the dissolution during its initial stages. Thus, it appears that the smooth bottom attribute is strictly fortuitous and that the cavities referred to as stromatactis are either spatially directly connected or otherwise closely associated with a complex network of a cavernous solution system.

The restriction of stromatactis to calcilutite is arbitrary to a similar degree. Apparently, stromatactis in mud mounds attracted attention because they are very conspicuous in the otherwise homogeneous and featureless rocks of the mounds. Also, the explanations advanced for their origin became instrumental in explaining the origin

of the enigmatic mounds themselves. This is the source for the usage of *Stromatactis* (capitalized and italicized) as a generic, taxonomic name for an obscure, dubious soft-bodied organism (or plant) of "unknown affinity", as advocated by many authors (among them Bathurst, 1959; Philcox, 1963, 1965, 1971; Lowenstam, 1950; Lees, 1964; Playford and Lowry, 1966; Otte and Parks, 1963) following its original description from the Devonian in Belgium (see references in Heckel, 1972, p. 1): According to these interpretations, this speculative organism, through its mud-baffling or perhaps framebuilding capacity, was responsible for the erection and maintenance of the mounds. Upon its decay, cavities were formed which were later filled by calcite.

As is evident from the BRM case and from several other studies (Wolf, 1965d; Krebs, 1969; Playford and Lowry, 1966; Langton and Chin, 1968, Plate 3; Barss et al., 1970) *stromatactis s. str.* is indeed not confined to mudstones and it does occur in other types of carbonates as well.

In hand specimen scale, the karstic cavities with their complex multi-stage diagenetic history as documented from the BRM reef, probably represent the other end of the spectrum of structures of which *stromatactis s. str.* is an end member. To adequately characterize this more "mature" end member, which, for the sake of argument, can be termed "*stromatactis sensu Lato*", one would have to list the following attributes:

1. The cavities are strictly secondary, usually distinctly non-fabric-selective, of any size and form, and isolated by usually part of or associated with a complex network of a karstic cavernous solution system.
2. It might occur in all types of carbonates.
3. A fibrous (or bladed, P. F. C. or P. B. C. of Folk, 1965) carbonate cement lines the entire surface of the cavity; often several concentrically disposed successive generations of vug-lining cement are present; the fibrous cement might completely infill the cavities (which is usually the case in the smaller ones) or infill them only in part, leaving a central "residual" void space.
4. The residual void space might be subsequently infilled by one or all of the following (usually, but not necessarily, in the order listed: vadose internal sediment; precipitated equant calcite; euhedral, often ferroan, dolomite.

With the exception of the fourth attribute, these properties are common to all

so-called stromatactis s. str. As shown above, the fourth attribute, at least in part and in various combinations, is common to many. It is quite obvious that once the definition is broadened to include all the attributes listed above, the term "stromatactis" loses much of its uniqueness. On the other hand, Heckel is probably right in stating that stromatactis, in the restricted sense as defined by him, is distinctive enough to warrant a name.

The karstic origin of the stromatactis in the BRM reef is proven beyond reasonable doubt. Are all stromatactis of karstic origin? Such a generalization, if valid, is obviously of utmost importance as it furnishes a tool to decipher and recognize karst phases in the diagenetic evolution of carbonate rocks. It would be particularly useful to the evaluation of subsurface data where sample size is restricted. Because of its far-reaching implications, one has to exercise extreme caution in answering this question. As a direct consequence of the foregoing discussion, the answer is most likely positive. This is especially true at least for those cavities for which the broader definition applies.

Although I am inclined to accept the karstic origin of stromatactis s. str. as well, one further comment is in order. Several authors who advocate its submarine origin cite evidence for the early, supposedly synsedimentary genesis of this feature. Much of this evidence is not unequivocal and can be reconciled with a karstic phase as well. For example, both Schwarzacher (1961) and Heckel (1972) emphasize that stromatactis are synsedimentary on the basis of its occurrence in contemporaneous off-mound pebbles. But Schwarzacher (1961, p. 1502) specifically speaks of erosional unconformities in the mound while Heckel describes pebbles that occur in a calcarenite separating two growth stages of the mound.

Indeed, in many cases the stratigraphic and paleogeographic implications of interpreting stromatactis as of karstic genesis are not as drastic as might be thought at first. In the first place, practically all reports on stromatactis pertain to presently exposed carbonate formations. Therefore, in many of them, once the synsedimentary origin of the feature is disproved, there remains no difficulty in explaining it by a karstic phase. Secondly, it should be emphasized that since karstic processes can proceed in confined and phreatic aquifers as well (and, in fact, are sometimes better

developed under such conditions), "karst" is not synonymous with "subaerial exposure".

Thus, I propose that stromatactis, in both its restricted sense, be a criterion indicative of a karstic dissolution and reprecipitation phase in the diagenetic history of carbonate rocks.

GEOLOGY OF THE SALINA A-1 UNIT

General

The A-1 Unit envelops the reef around its entire circumference. Together with its overlying A-2 Evaporite Unit, it encloses the reef completely in non-reefal rocks (Fig. 2-9). An understanding of the environment which prevailed during the deposition of the Salina A-units is essential for the correct evaluation of several aspects of the reef history and the underlying fundamental stratigraphic relationships which can conclusively resolve the question of the time relationships between the reef and the off-reef units. The geology of the Salina evaporites has some bearing on such questions as the pervasive diagenesis of the reef rocks, and the source and migration of the gaseous hydrocarbons now contained in the reef.

The evaluation of the geology of the A-1 Unit is based on lithologic and stratigraphic information obtained from the 17 off-reef and the 10 reef-flank wells (Tables 1-2, 3-4). Of these, nineteen wells had core material, totaling 2066 feet (wells number 1, 3, 4, 5, 10, 16, 17, 23, 24, 27, 28, 34, 37, 40, 41, 44, 46, 47 and 48). The detailed lithologic logs of the cores are deposited in the Subsurface Laboratory, Department of Geology and Mineralogy, The University of Michigan. Abbreviated descriptions of the major lithofacies are illustrated for some of the wells in the cross sections (Figs. 4-6 through 4-8).

Stratigraphic Subdivision, Thickness and Distribution

The Salina A-1 Unit thickens gradually basinward from where it wedges out abruptly against the reef escarpment. The A-1 Unit attains a maximum thickness of 162 feet within a quarter to half a mile from the reef. On the southern edge of the reef, where slopes are moderated due to the accumulation of the BRM Conglomerate Member, the thinning out is more gradual. Here the upper part of the unit overlaps the reef flank (wells 4 and 7, see cross section, Fig. 3-13 and map, Fig. 4-2). The lateral contact between the Niagaran reef rocks and the A-1

Unit appears to be very sharp. Nowhere have interfingering relationships between the two rock units been observed.

The stratigraphic subdivision of the A-1 Unit consists of the A-O Carbonate, the A-1 Anhydrite and the A-1 Carbonate in ascending order (Fig. 2-12). The A-1 Unit overlies the Guelph Formation unconformably and is conformably overlain by the A-2 Evaporite Unit. The lower and upper boundaries as well as internal boundaries of subunits have distinctive radioactive log signatures. Relative to the underlying Guelph, the rocks of the A-O Carbonate are characterized by slight but consistently higher readings on the gamma-ray log and lower readings on the neutron log. The A-1 Anhydrite is readily distinguished by the consistent occurrence of very low gamma ray and neutron readings, forming a conspicuous departure pattern. Both curves approach each other again (marking a rise in response) within the A-1 Carbonate. The top of the A-1 Unit, a transition from carbonate rock to anhydrite, is recorded by a distinct drop in response on both logs.

The thickness and distribution of the various subunits is shown in Figs. 4-1 through 4-5 and Tables 3-1, 3-3 and 4-1. The A-O Carbonate is about 5 feet in thickness over most of the area, reaching 10 feet in wells 5 and 17. A total of 40 feet of core from 6 off-reef wells (wells 3, 5, 10, 17, 27 and 41) were available for the petrographic analysis of this subunit.

The A-1 Anhydrite onlaps the lowermost part of the reef flank. It is not present above the -1875 structural contour line (Figs 4-1 and 4-3). It thickens gradually away from the reef, reaching a thickness of 20 feet within a quarter of a mile from the reef (Fig. 4-1). The unit thickens basinward where it grades into salt and attains a thickness of 475 feet in the center of the Michigan basin (Ells, 1967, p.10). Core from this subunit was available from 9 wells (wells 1, 3, 5, 10, 17, 27, 34, 40 and 41), totaling 115 feet.

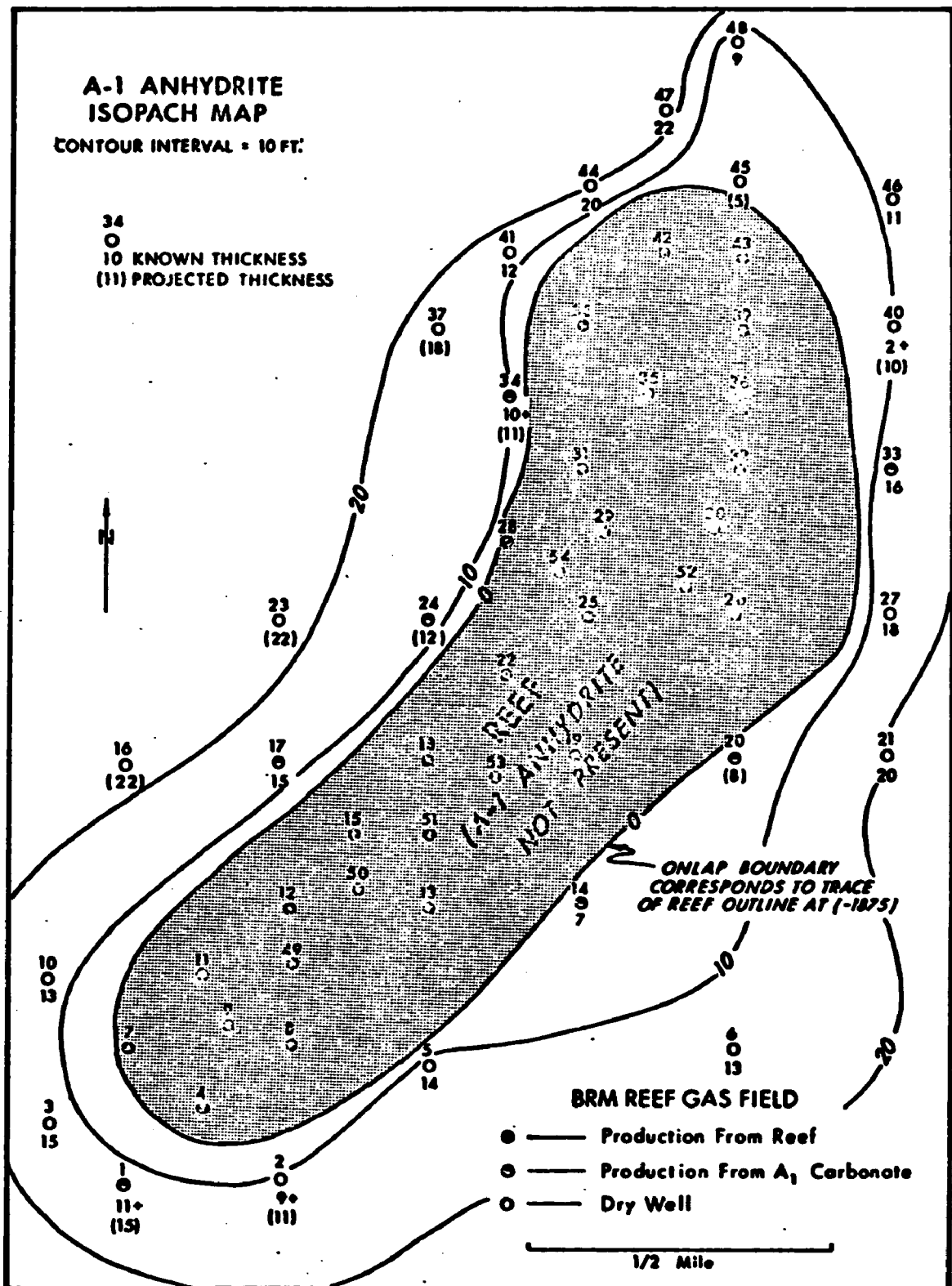


Fig. 4-1. A-1 Anhydrite, isopach map.

The A-1 Carbonate wedges out against the reef at its -1750 contour line. Reduced thicknesses, below 100 ft., are present on the southern plunge of the structure (wells 4 and 7, Fig. 4-2). Like the A-1 Anhydrite, the unit thickens away from the reef. Within the study area, its maximal thickness is 134 feet in well 47. According to Ellis (1967, p.10) this is about the thickest the unit gets as it thins towards the center of the basin. Around the margins of the basin the unit consists mostly or totally of dolomite and thus is commonly referred to as the "A-1 Dolomite." Towards the center of the basin, in areas in which the A-1 Evaporite consists of salt, the unit consists mostly of limestone (Sharma, 1966). This observation is apparently not consistent with that of Ellis (1967) who notes that even in the center of the basin the unit might be all dolomite or all limestone, or a mixture of both. Jodry (1969) maintains that regionally, including the basin margin, the unit is basically limestone and that the occurrence of dolomite is a result of local dolomitization. In the vicinity of the Belle River Mills reef the entire unit consists of dolomite. A total of 1911 feet of A-1 Carbonate core was available from 19 wells (Tables 1-1 and 3-4).

In the majority of the off-reef wells two anhydrite horizons are present in the lower half of the A-1 Carbonate. They are expressed by two prominent closely spaced "kicks" on the neutron log, with a corresponding more moderate drop in the gamma-ray response (Fig. 2-12). Their graphical expression on the neutron log resembles the shape of rabbit ears, and thus they are commonly referred to as the "rabbit ears anhydrite" (Ellis, 1967, p. 10). The distribution pattern of the "rabbit ears anhydrite" (Table 4-1) in plan view (Fig. 4-5) appears as two disconnected horseshoe-shaped bodies adjacent to the reef at the north and south ends, and absent on both sides of the central part of the reef. A similar distribution pattern is known for other reefs, such as the Ray field (Fig. 1-4). The "rabbit ears" anhydrite beds are commonly associated not only with reefs in southeastern Michigan, but are known from other parts of the basin as well (Ellis, ibid.). With the exception of wells 4 and 41, which have only one

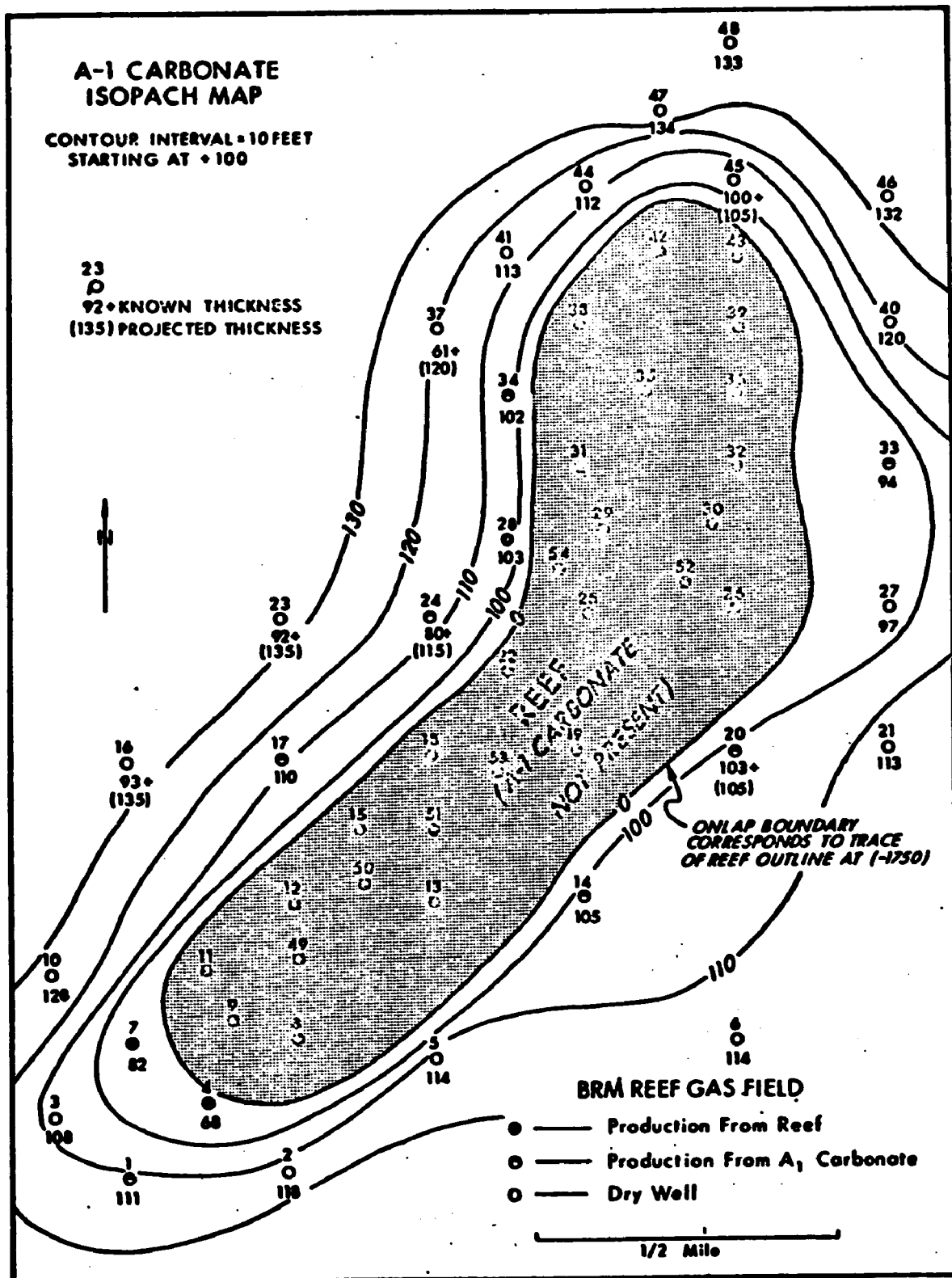


Fig. 4-2. A-1 Carbonate, isopach map.

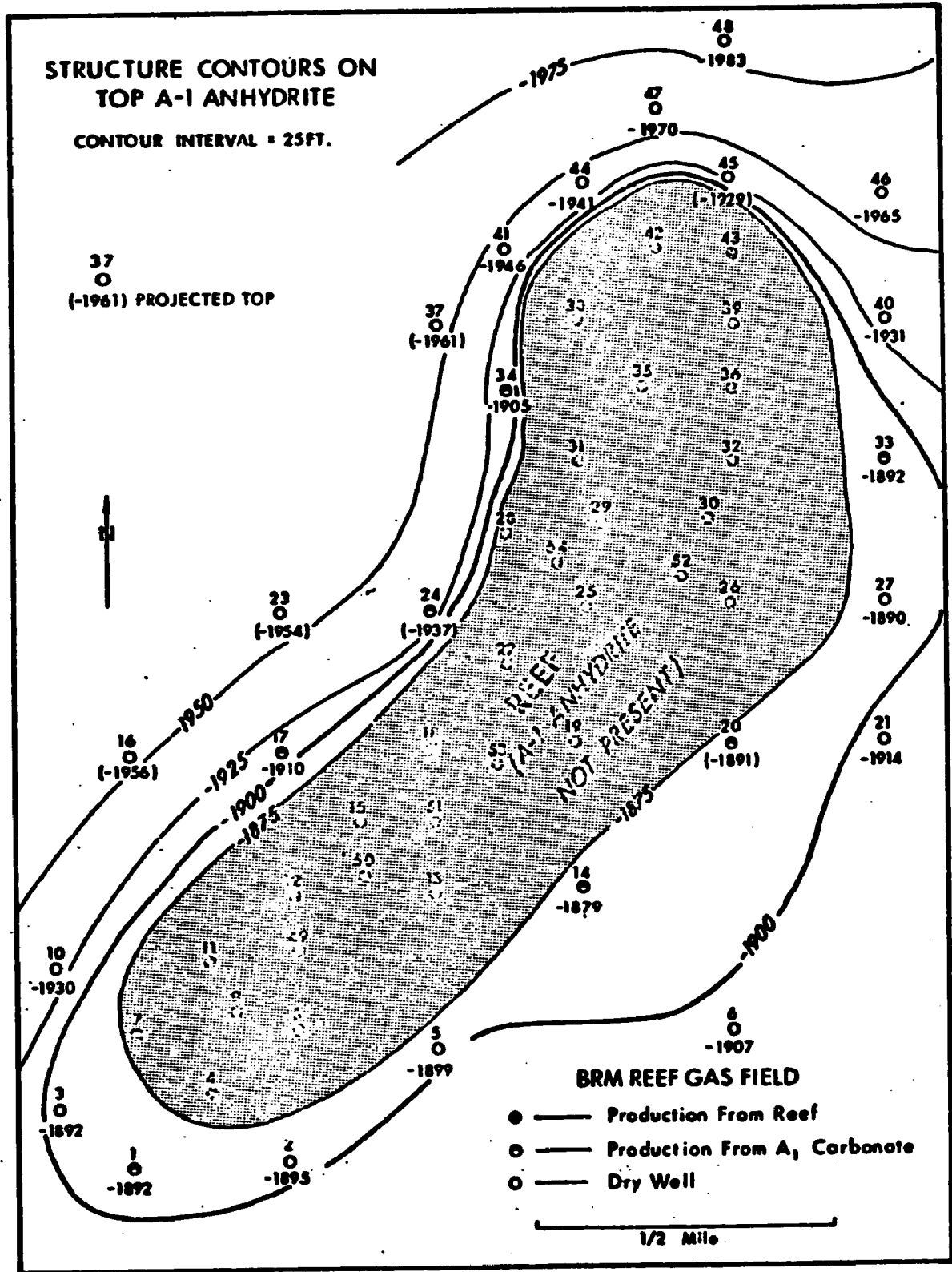


Fig. 4-3. Structure contour map on top A-1 Anhydrite.

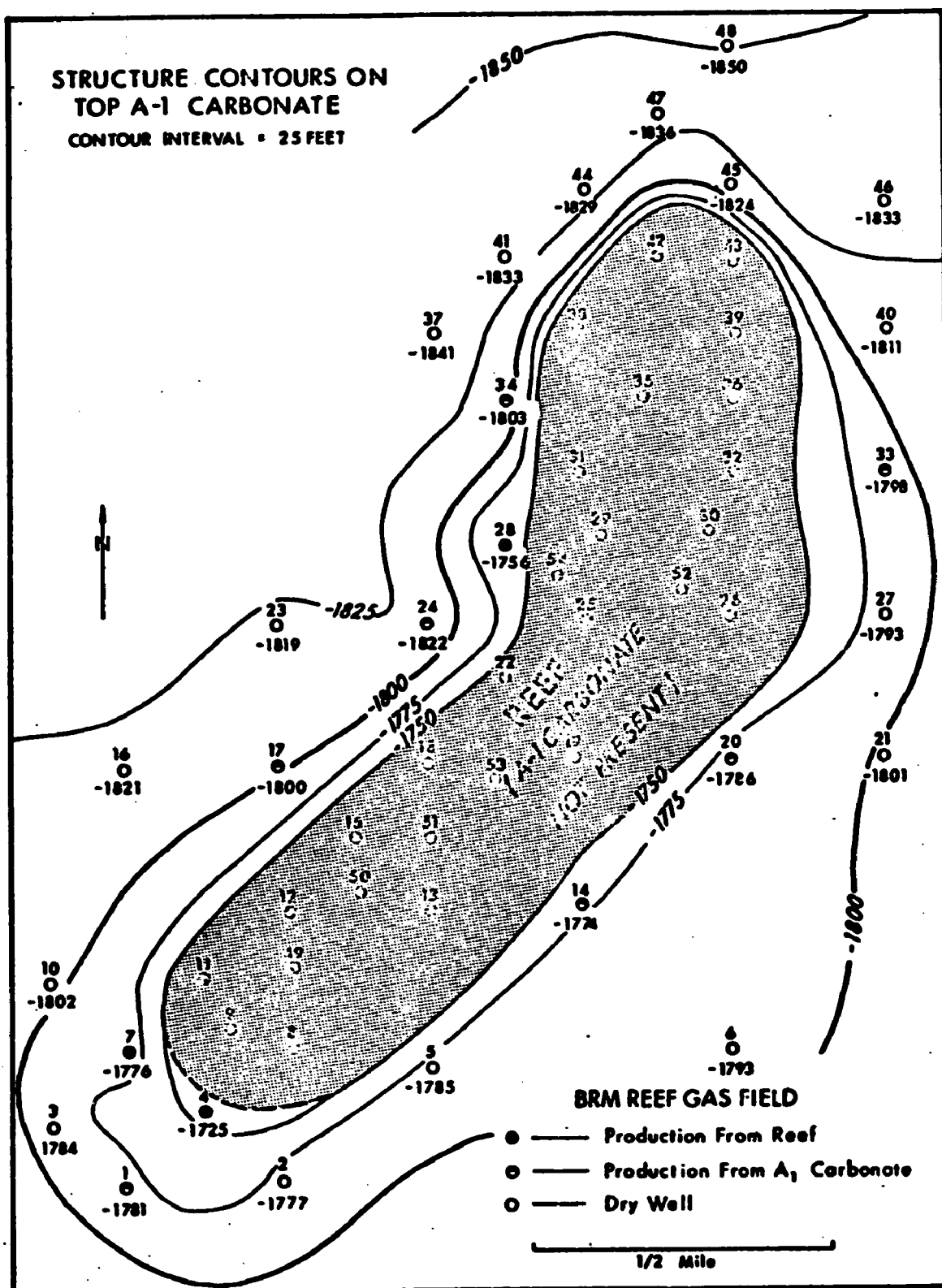


Fig. 4-4. Structure contour map on top A-1 Carbonate

Well	K. B. Elevation	Upper Anhydrite horizon			Lower Anhydrite horizon		
		top	bottom	thickness	top	bottom	thickness
1	622	2462	2473	11	2480	2488	8
2	619	2456	2468	12	2478	2482	4
3	622	2470	2476	6	2487	2491	4
4	618	2388	2394	6	-	-	-
5	613	2465	2468	3	2475	2479	4
7	622	2445	2456	11	2464	2469	5
10	623	2498	2507	9	2516	2520	4
16	619	2505	2509	4	2515	2518	3
17	616	2479	2484	5	2489	2495	6
27	603	2451	2459	8	2463	2470	7
28	619	2426	2434	8	2440	2452	12
33	605	2462	2468	6	2474	2478	4
34	620	2485	2487	2	2497	2499	2
40	607	2490	2498	8	2505	2508	3
41	621	2521	2527	6	-	-	-
44	621	2516	2523	7	2531	2535	4
45	618	2504	2514	10	2522	2529	7
46	605	2506	2514	8	2520	2524	4
47	618	2532	2542	10	2542	2549	7
48	618	2538	2546	8	2550	2557	7

Table 4-1. Stratigraphic data, A-1 Carbonate, "Rabbit Ears" Anhydrite horizons
(no anhydrite horizons present in wells not listed; figures in feet).

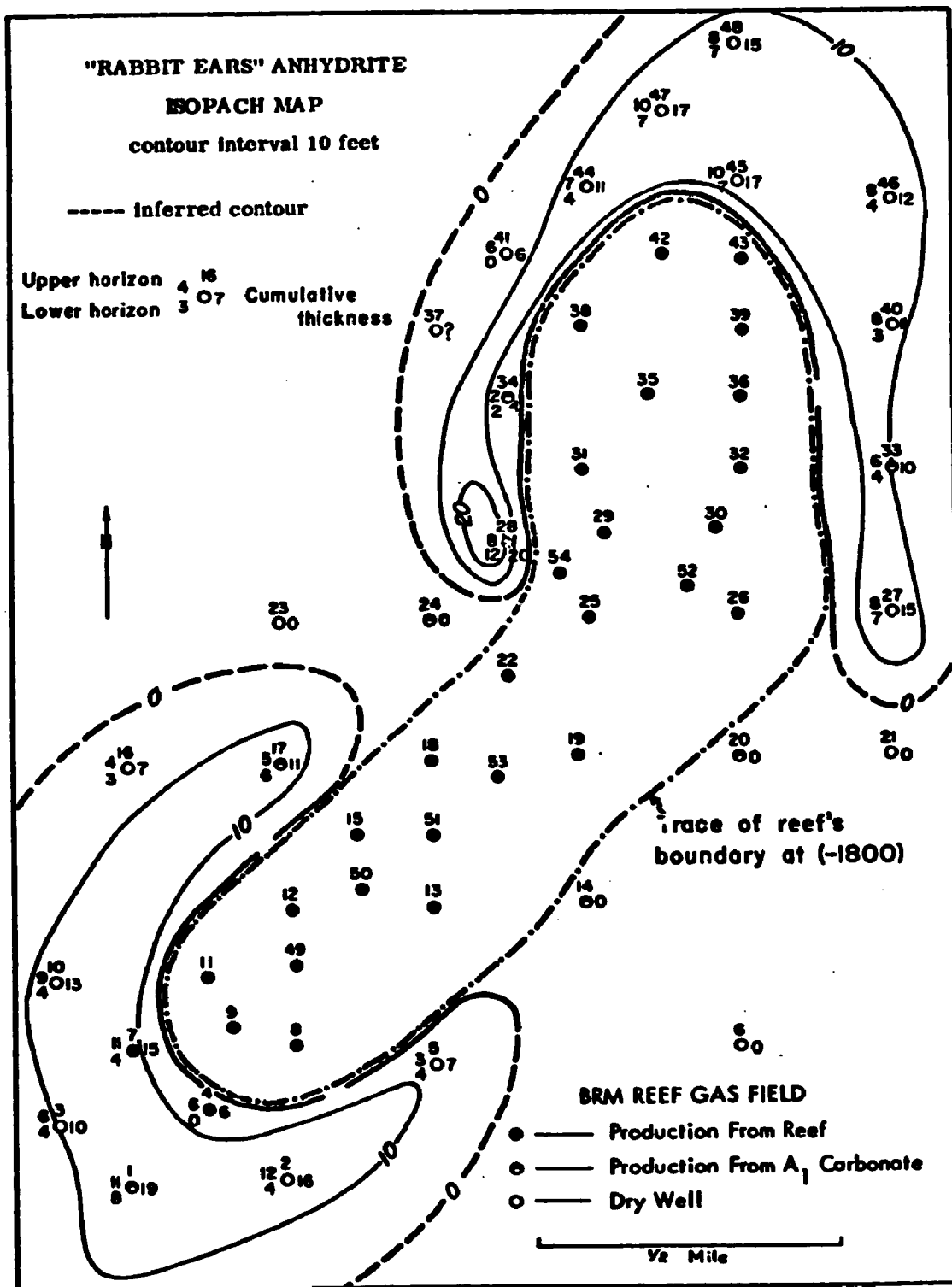


Fig. 4-5. "Rabbit Ears" Anhydrite isopach map. Cumulative thickness of anhydrite horizons.

anhydritic bed, the two anhydrites invariably occur together. The average thickness of the lower bed is 5 feet, and the upper 8 feet. The upper anhydrite pinches out against the reef at a structural elevation of about (~1800) feet. Along the reef flanks the anhydrite beds are steeply inclined, but flatten out within a quarter of a mile of the reef (Figs 3-9 through 3-13, and 4-6 to 4-8).

Structure contour maps of the tops of the A-1 Anhydrite and the A-1 Carbonate (Figs, 4-3 and 4-4) show that both units dip radially away from the reef. On the reef flanks, dips up to 30° have been observed (well 28, Pl.15/10). Bed inclination diminishes rapidly away from the reef, where dips are on the order of one to two degrees.

Petrography and Environmental Interpretation

The A-1 Anhydrite

Petrographic Description (Plate 12): The comprehensive descriptive classification for anhydrites by Maiklem *et al.* (1969) was found to be most useful for the Salina anhydrites. The classification and the proposed nomenclature is based on macroscopic fabric or structure elements of external form of the anhydrite masses within the rock, anhydrite to matrix relationships, bedding and distortion. Almost all of the 25 different fabric or structure groups recognized by Maiklem *et al.* (1969, Fig. 1) are present in the A-1 Anhydrite. The fabrics illustrated on Plate 12 are but selected samples of the more abundant fabrics present. It should be emphasized that all gradations and transitions from one fabric type to another are very frequent. A single fabric is rarely persistent vertically for more than a few centimeters. The four basic types of anhydrite fabric are:

Nodular - irregular shaped lumps of anhydrite which are approximately equidimensional and separated from one another by matrix.

Nodular mosaic - anhydrite masses which are approximately equidimensional and which are partly separated by matrix and partly in contact with one another.

Mosaic - coalesced anhydrite masses which are approximately equidimensional and in which matrix is lacking. The boundaries are partly thin films of organic or silty material and partly indistinct.

Massive - anhydrite which lacks internal structure.

Abundance of matrix material and the anhydrite to matrix relationship are the main criteria by which the above mentioned groups are differentiated from one another. Additional distinctive attributes which help to separate additional classes within the basic groups are the nature of bedding and degree of distortion.

The terminology for the microscopic description of anhydrite textures is based on crystal shape (equidimensional vs. elongate) and crystal size (Maiklem *et al.*, 1969). Some of the textural terms used in the present discussion are:

Microcrystalline - equidimensional crystals with diameters less than 0.6mm.

Subfelted - combination of microcrystalline and small lath-shaped crystals less than 0.5 mm in length.

Felted - a mass of lath-shaped crystals less than 0.5 mm in length, having a random orientation. (This texture is often referred to as "decussate" — Haney and Briggs, 1964; Shearmann and Fuller, 1969, p. 500.)

Aligned Felted - felted texture in which parts of the mass of laths are parallel or aligned, with length less than 0.5 mm.

In the A-1 Anhydrite, the prevalent type is a frequent alternation of a distorted mosaic fabric and a bedded (laminated) massive fabric.

Distorted mosaic anhydrite (Pl.12, Figs. 1-3) consists of very closely packed distorted nodules, some flattened parallel to the bedding and commonly coalescing to form a continuous mass. Only small amounts of the original matrix remain in the form of thin carbonaceous and dolomicritic seams interlaced and discontinuous between adjacent nodules, as impurities within nodules, or as irregular remnants between nodules (Pl. 12/9). Interbedded within this fabric are thin undulating laterally continuous carbonate laminations, devoid of anhydrite (Pl.12/1) which contain either single dolomicritic and carbonaceous laminae or of couplets of the above two. The anhydrite is white to pale gray in color with a bluish hue. The dolomicritic matrix and laminations are tan and the carbonaceous streaks are dark gray to black.

Petrographically, the anhydrite masses vary considerably with respect to size, shape and the distinctiveness and nature of their boundaries. Substantial portions of several thin sections can be best described as a more or less continuous, structureless mass of anhydrite with dispersed matrix. However, for the most part, the anhydrite consists of discrete bodies, completely or partially separated by matrix material from one another. Most are aggregates of crystals with irregular and diffused boundaries, displaying no preferred orientation. Some have smooth boundaries, at least along parts of their circumference, and can be recognized as nodules which are flattened and elongated parallel to the bedding. In places, adjacent nodules merge laterally. Most nodules are about one to two millimeters in size.

The anhydrite is embedded in a matrix of brown dolomicrite, 0.003 mm or less in size, constituting between 10 and 30 percent of the rock. The anhydrite has an equidimensional micro-crystalline texture. Crystals are mostly 0.005-0.01 mm in size. Parts of some nodules display a subfoliated texture (Maiklem *et al.*, 1969, p. 226), consisting of elongated lath-shaped anhydrite cleavage flakes which in places are up to 0.06 mm long. In some rocks, small aligned equidimensional crystals apparently represent disjointed remnants of originally longer laths, traces of which can still be recognized in the parallel alignment of anhydrite laths.

Laminated massive anhydrite (Pl. 12, Figs. 2-5), consists of alternations of thin carbonaceous, dolomicritic and anhydritic laminae. The carbonaceous films are dark brown in color and about 0.05 mm thick. Some are thicker due to superposition of several films. Small anhydrite nodules commonly present between films cause the films to bulge. The gray to tan dolomicritic laminae, usually about 0.5 mm thick, occur in sets of three or four, individually distinct due only to subtle hue changes, and bounded by carbonaceous films above and below. Many laminae have embedded anhydrite nodules flattened parallel to the bedding. The dolomicrite is usually riddled with minute (0.005-0.01 mm) anhydrite crystals and laths.

The anhydritic laminae are either massive or nodular. The massive laminae are nearly pure microcrystalline anhydrite, composed of equidimensional crystals 0.003 mm or less in size. The nodular laminae are composed of minute anhydrite nodules embedded in a microcrystalline anhydrite matrix. Individual nodules are 0.1 to 0.25 mm long, invariably flattened parallel to the bedding. Coalescence of adjacent nodules is common. For the most part, the nodules are composed of microcrystalline anhydrite. Some show traces of subfelted texture. The anhydritic laminae range in thickness from 0.25 mm to 2 mm, and are usually bounded by carbonaceous films. The laminated massive anhydrite fabric characterizes thin 3-5 cm intervals within other anhydrite fabrics (Pl. 12/2). However, in several wells beds up to 50 cm thick (Pl. 12/4) are entirely laminated massive anhydrite.

Other common fabric patterns include:

Distorted nodular (Pl. 12/6) - discrete nodules embedded in a dolomicritic matrix constitute about 50% of the rock. Most nodules are pronouncedly flattened and elongated parallel to the bedding. Most are 1 to 3 mm long, although some reach a length of 2 cm. This fabric is in places interbedded with very thin dolomicritic beds, consisting of suits of extremely thin even parallel laminations (Pl. 12/6, bottom part).

Nodular mosaic (Pl. 12/7) - this fabric is intermediate between the "nodular" and the "mosaic" fabrics in terms of anhydrite to matrix ratio and the degree to which nodules are separated from one another. The rock consists of nodules which are in part isolated and in part in contact with each other.

Enterolithic (Pl. 12/2, 12/3) - the term designates the presence of contortions and convolutions resembling a human intestine (Shearman and Fuller, 1969; West, 1965). The term corresponds to a fabric which Maiklem et al. (1969) designate as either "contorted mosaic" or "contorted bedded." The contortion is confined to a single anhydritic lamina and the adjacent underlying and overlying laminations do not participate in it. Enterolithic structures are fairly common in the A-1 Anhydrite. They are well developed and more abundant within sections composed of a distorted bedded mosaic fabric. However, on a microscale, they are very common in the laminated massive fabric as well (Pl. 12/3).

Highly distorted structures (Pl. 12/8, 12/9) - these include such structures as disharmonic folds, overturned micro-folds, S-shaped beds and local micro-brecciation. Unlike the enterolithic structures which are confined to single laminae, the deformed sections encompass several beds or sequences of laminae. Both the anhydrite and the interbedded carbonate material are affected by the deformation. These structures are most likely the result of plastic flowage induced by compaction at a rather early (prelithification) diagenetic stage.

The anhydrite in the deformed sections has a distinct subfelled texture and typically contains authigenic quartz. The quartz shows three modes of development: (1) Isolated individual crystals (quartz poikilotopes) - mostly euhedral with well developed crystal faces, up to 0.5 mm long. The crystals often contain specks of anhydrite inclusions. (2) Closely packed aggregates of coarse, subhedral crystals, riddled with minute anhydrite inclusions. (3) Chalcedony or chert nodules - highly

irregularly shaped, usually with well defined contacts but in places sending thin linear extensions into the surrounding anhydrite matrix. Some nodules are up to 6 mm in diameter. The nodules are composed of anhedral crystals and of spherulites and show a porphyrotopic texture. Smaller crystals, about 0.01 mm in size, enclose clusters of coarse crystals, some of which are up to 0.12 mm in size. The spherulites and the coarser crystals consist of radially arranged fibers. They typically show a radial and wavy extinction. The chalcedony fibers have a positive elongation ("length-slow"). This crystallographic property is apparently indicative of authigenic chalcedony in many ancient evaporite deposits (Folk and Pittman, 1971). The nodules are very dense and have no porosity. The quartz crystals are tightly packed and only minute amounts of intercrystalline anhydrite are present. In several thin sections of the highly distorted structures, a peculiar anhydrite texture is developed. It consists of a network of polygonal cells which are in part interconnected and in part isolated. The cells have a diameter of 2 to 3 mm. Their boundaries consist of coarse acicular anhydrite laths, about 0.5mm long, which are arranged in a parallel to subparallel array, perpendicular to the circumference of the cell. In places, this orderly arrangement is disturbed by swellings of the cell boundaries, consisting of aggregates of anhydrite laths radiating at random. The authigenic quartz, wherever present, occurs within the small bulges. The interior of the cells consists of microcrystalline anhydrite.

Algal laminated dolomicrite layers within the A-1 Anhydrite are horizons composed predominantly of extremely finely laminated dolomicritic layers separated by very thin carbonaceous films, with no intervening anhydritic laminae. The laminites are flat lying or undulated, locally containing small domal structures. Desiccation cracks (Pl. 12/10), and fenestral fabrics with anhydrite infillings (Pl. 12/11) are fairly common. Locally brecciated laminite horizons form small, flat and angular intraclasts embedded in an anhydrite matrix (Pl. 12/11).

Environmental Interpretation: From the above petrographic description, the following observations appear particularly pertinent to the environmental interpretation of this facies:

1. Practically all the fabrics described are essentially modifications of a basic nodular texture. Even the laminated massive fabric contains many lamina which have an internal nodular structure. Microscopically, the nodules have a felted (decussate) texture. Perhaps equally significant is the fact that the units lack an orderly varvitic structure. Furthermore, the arrangement of fabrics within the unit is rather erratic and fabrics can not be correlated in adjacent wells.
2. Of particular significance is the groundmass or matrix within which the anhydrite nodules are emplaced. This has been shown to be a dolomitic, rich with carbonaceous matter. In places it is still possible to discern that the original host rock consisted of an algal laminated sediment. Other sedimentary indications which testify to the shallow water origin of the original sediments include the presence of desiccation cracks, fenestral fabric and intraformational conglomerates.

Recent studies of Holocene settings in which evaporites are presently forming show that sulfatic minerals have essentially two modes of formation, which can be termed "basinal" and "Sabkha" (see Buzzalini *et al.*, 1969). Most authors agree that the two types can be recognized in the sedimentary record on the basis of their distinctive fabric attributes. Disagreement still prevails with respect to the water depth at which each of the two types is forming. Thus, while there appears to be agreement concerning the fundamental processes involved, opinions still differ as to the exact environmental setting in which each of the processes operates. "Basinal" evaporites form by the primary chemical precipitation of minerals from supersaline brines in a barred basin (Briggs, 1958). Their most characteristic feature is their regular varvitic nature which appears to persist uninterruptedly over large areas. Classic examples of this type of evaporite deposition include the Permian Castile Formation in the United States (Anderson and Kirkland, 1966) and the Zechstein

basin in Europe (Richter-Benbun, 1955, 1957.) Although the authors cited above envision a rather deep basin as the site of formation of "Basinal" evaporites, this view has been recently challenged by several authors (Fuller and Portér, 1969a; Shearman, 1965, 1970) who propose that also varvitic evaporites can be formed in extremely shallow inland seas. At any rate, since the A-1 Anhydrite is clearly not varvitic, the resolution of this controversy is of no immediate concern to the problem at hand.

Sulfates deposited under Sabkha conditions, on the other hand, are diagenetic in origin and typically result in nodular and interolithic fabrics. Our understanding of the origin and environmental significance of nodular anhydrite can be attributed to the pioneering studies of Curtis et al. (1963), Kerr and Thompson (1963) and Murray (1964), and to the more recent studies by Shearman (1966, 1969) who developed and convincingly showed the applicability of his concept of the sabkha cycle of sedimentation and early diagenesis to the interpretation of ancient sediments.

Curtis, Erans, Kinsman and Shearman (1963) investigated the phenomena in the Recent of the Trucial Coast from which area the term "Sabkha" and its related concepts originate. Their study was followed by a number of investigations conducted and reported upon by a number of geologists, including G.P. Butler, G.G. St. C. Kendell, Sir P.A. Skipwith, L.V. Illing, A.J. Wells and J.C.M. Taylor, who provided much new data and greatly improved our understanding of the sabkha environment. Kerr and Thompson (1963) and Murray (1964), who advocate a similar process for the formation of nodular anhydrite, base their observations on the Holocene sediments of Laguna Madre, South Texas. Kinsman (1969, p. 836) cites yet another locality - supratidal flats along the Northwestern shores of the Gulf of California in Baja California - where Recent anhydrite nodules are forming.

All of these studies have shown that nodular anhydrite forms as an early penecontemporaneous diagenetic product within the capillary zone of unconsolidated sediments in the exposed parts of supratidal flats of arid regions ("Coastal

Sabkhas"). Due to the aridity and the proximity of the Sabkha to the sea, its ground water is primarily derived by "flood recharge" (Butler, 1969, p. 72) of marine water. These rise into the capillary zone above the water table where they are further concentrated by intensive evaporation. A concentrated interstitial brine is thus formed, the geochemistry of which has been described by Butler (1969) and Kinsman (1960). As a first stage in nodule growth, individual anhydrite laths crystallize from the connate brine. These are emplaced within the unconsolidated host sediment. Further nodule growth is brought about by displacive forces, exerted by growing anhydrite laths during their incorporation into the aggregate, in a manner first proposed by Withington (1961) and described in detail by Shearman and Fuller (1969, Fig. 3). Shearman further demonstrated (*ibid.*, p. 503-505) that the enterolithic structures are primary in the sense that they form concurrently with the emplacement and growth of the nodules. Thus the "displacive emplacement" growth mechanism satisfactorily accounts for the decussate textures of the nodules and the enterolithic structures, both of which are common in both ancient and Recent anhydrite beds.

The A-1 Anhydrite Unit is petrographically very similar, if not identical, to many other ancient nodular anhydrites reported upon in the literature. Quoted below are some additional occurrences which seem to be particularly relevant to our discussion either because they appear in sections which resemble the entire A-1 Unit or because they have some bearing on the general question of reef-evaporite juxtaposition which will be discussed later.

Well documented examples of nodular anhydrite have been described from the Devonian of Michigan (Haney and Briggs, 1964); the Purbekian in England (West, 1955; Shearman, 1966); the Permian of the Delaware Basin (Kerr and Thompson, 1963); the Miocene of Sicily (Hardie and Engster, 1971); the Jurassic of Abu Dhabi (Wood and Wolfe, 1969) and from the Visean of Ireland (West *et al.*, 1968). References pertaining to the problem of "evaporite encased reefs" (see Chapter V) which also include extensive mention of nodular anhydrite deposits include studies from two geological provinces, the Winnipegosis (Ratner member) and Keg River Formations of the Middle Devonian Upper Elk Point basin in

Alberta and Saskatchewan (Fuller and Porter, 1969a,b; Shearman and Fuller, 1969; Klingspor, 1969; Wardlaw and Reinson, 1971; and Maiklem, 1971), and the Pennsylvanian of the Paradox basin (Gray, 1967, Choquette and Traut, 1963; Peterson, 1966; Peterson and Hite, 1969; Elias, 1963; and Hite, 1970).

In summary, the A-1 Anhydrite represents a palaeogeographic setting similar to the large supratidal flats of the Sabkhas of the Trucial Coast. This interpretation is further and independently supported by the other compatible and complementary lithofacies with which the A-1 Anhydrite is associated. The original sediment prior to the emplacement of the anhydrite was most probably an intertidal algal laminated sediment similar to lithofacies 2.

The A-0 Carbonate and the A-1 Carbonate

The A-0 Carbonate and The A-1 Carbonate units are very similar lithologically, being predominantly microlaminated dolomicrites. Both units lack invertebrate skeletal remains, although "trace" fossils in the form of faecal pellets, burrows, and algal mat structures are characteristic and abundant. Common also are relatively widespread anhydrite in a variety of textural forms, and authigenic pyrite. Stylolites are ubiquitous.

Six carbonate rock lithotypes have been differentiated;

Lithofacies 1: Microlaminated mudstone.

Lithofacies 2: Flat algal laminated sediment (planar stromatolite).

Lithofacies 3: Pelletal wackestone.

Lithofacies 4: Indurated crusts.

Lithofacies 5: Intraformational breccia and flat pebble conglomerate.

Lithofacies 6: Nodular anhydrite.

Lithofacies 1: Microlaminated mudstone - Petrographic

Description (Plates 13,14): The microlaminated mudstone consists primarily of carbonate mud, now dolomite, with subordinate amounts of carbonaceous matter in the form of thin films, seams and flakes. Other accessory components and

fabrics which introduce subtle modifications in lithologic aspects include subordinate amounts of pellets, various forms of anhydrite and local indications of burrowing activity. The degree of development and the mode of lamination are the main attributes which vary constantly within this lithofacies.

Typically, the rock is composed of very dense and homogeneous dolomicrite, 0.003 mm or less in size. Characteristic porosity and permeability values for this type of matrix are on the order of 1-3% and 0.01 millidarcy, respectively. In several wells this lithology still consists of undolomitized or slightly dolomitized limestone. Neutron log indications of a tighter section (well 17, 2423-32; well 24, 2441-47; well 28, 2381-85; well 34, 2424-89; well 37, 2465-81; well 41, 2460-82, 2487-2521, 2542-56; well 44, 2455-70) correspond to the limy intervals, which are usually denser and finergrained than the dolomitized ones. Although a micritic matrix predominates and is fairly uniform, there are thin zones in which dolomitization resulted in a "grain-growth" recrystallization into a xenotopic microsparitic mosaic of 0.01-0.02 mm anhedral crystals (neomorphic, equant, finely crystalline of Folk, 1965). Such sections have a higher porosity and permeability. Porosities of 5-10% and permeabilities of up to 15 millidarcies are not uncommon. All the porosity is intercrystalline. Infilling of pores with heavy tar and with coarse, blocky anhydrite crystals is fairly common.

Lamination patterns (Campbell, 1967) alternate frequently throughout this lithofacies, the dominant mode being even discontinuous parallel and subparallel laminations (Pl. 13/1, 13/2). Wavy discontinuous parallel to subparallel lamination is also abundant (Pl. 13/3). Zones of well developed, even parallel and continuous laminations (Pl. 13/4) are interbedded with the above two types but occur in subordinate amounts. In this type individual laminae are between 0.15 mm to 1.5 mm thick, usually of even thickness, continuous, planar, even, and parallel. For the most part, the rock consists of very dense homogeneous micrite. In places, however, the varves are composed of microdolospar. Within each laminae crystal size is more or less uniform although slightly different in adjacent laminae. Since the finer grained laminae are usually slightly darker in hue (all laminae having various shades of tan to brown color), subtle variations in

crystal size appear to have a distinct effect on the definition and distinctiveness of the laminae. The combined effect of the presence of several linear elements contributes to the laminated appearance of the rock. The exact nature of most of these elements becomes apparent only through the examination of thin sections. Macroscopically, the lamination is due to the presence of minute darker colored discontinuous carbonaceous streaks commonly interlaced into continuous "horse tail-like" seams (Pl. 13/1). In thin sections the seams appear as dark brown colorations along horizontal, planar and slightly undulating filamentous microthreads, only about 0.05 mm thick (Pl. 13/5). Commonly, the filaments develop into somewhat thicker minute partings or microstylolites, typically 3 to 7 threads in one vertical millimeter of section. Although discontinuous and segmented, the striations are closely spaced into more or less continuous laminae. Commonly, clusters and arrays of such filaments give certain laminae a darker hue, thereby introducing subtle color banding which accentuates the lamination. Residual insoluble material accumulated along planar stylolites and along condensed, multiply superimposed microstylolites enhances the laminated appearance (Pl. 13/1, 13/2).

• Although rather rare, very thin dark gray to black shaly partings separate groups of laminae into "beds" or "laminae-sets".

Thin carbonaceous flakes also produce planar laminae (Pl. 13/6). The term "mat chips" is appropriate for these flakes, presumed to be disintegration products of a once continuous algal mat. The mat chips are dark gray to black, larger ones being 1 to 2 cm in length, up to 0.5mm in thickness, and invariably planar and uniform in thickness. No internal filamentous or cellular structure could be discerned. Finer chips are much more abundant. These are usually between 0.25 and 1.0 mm long and only about 0.02 mm thick (Pl. 13/7). In places, they tend to cluster along very thin horizons, thereby forming darker colored laminae. Where the small chips are very thin, they can not be differentiated from the horizontal filamentous microthreads, described earlier.

Linear, horizontal microsparitization of an original uniformly-sized micrite matrix is an additional mechanism which enhances the lamination. In places, variations in grain, size were introduced diagenetically in the form of very thin horizontally discontinuous streaks of microspar. The streaks represent grain-growth recrystallization of original micrite, typically along boundaries between laminac. They are commonly lighter in color (Pl. 13/6), and only one or two crystal layers in thickness, but nevertheless an important contribution to the laminated aspect of the facies.

Anhydrite is a characteristic accessory component in the laminated lithofacies. It occurs sporadically throughout the microlaminated mudstone lithofacies, being very abundant at some horizons where it comprises up to 10 per cent of the rock. Most commonly anhydrite occurs as small isolated nodules (Pl. 13/8), 15/1). 1-2 mm long, elliptical, and elongated parallel to the lamination. Internally, the nodules consist of anhydrite laths arranged in a felted to an aligned felted texture. Less commonly anhydrite occurs as isolated, coarse crystals ("crystalloptic" texture of Maiklem, *et al.*, 1969), scattered in a micritic dolomitic ground mass, being either elongate acicular crystals up to 2 mm long, or equidimensional, blocky crystals about 0.1 to 0.2mm across. The crystals do not show a preferred orientation, but commonly occur in clusters in which several laths radiate from a common vertex (Pl. 13/9, 14/11.) A third textural type occurs where anhydrite fills vugs and cracks, and is probably epigenetic in origin. Unlike the felted texture in the nodules or the acicular habit of the disseminated individual crystals, vug-filling anhydrite is very coarsely crystalline. Crystals with a width of 1mm are quite common. The dimension of individual crystals is, for the most part, determined by the shape and size of the available pore space since often the entire space is occupied by a single anhydrite crystal. In addition to occupying some of the intercrystalline pores mentioned earlier, this type of anhydrite more rarely infills epigenetic (post-lithification) cracks (Pl. 13/10, 14/4).. Some of these cracks, up to 0.5cm in width, extend vertically for about one foot. Some are minutely micro-faulted.

Other noteworthy features of the microlaminated mudstone include disseminated halite, micrite pellets, and pyrite. The halite is very fine grained and it can not be discerned by regular binocular examination of the core slabs. However, when wetted with water, the salt dissolves and upon drying it recrystallizes into transparent cubes on the surface of the slab. Small, well-rounded micrite pellets, although rather rare, are nevertheless characteristic of this lithology in some wells. Some of the pellets are associated with bioturbation fabrics, such as local disruption of laminated patterns or well-defined, highly irregular or regular, cylindrical burrows (Pl. 14/1).

Framboidal pyrite is a common accessory component in all A-O and A-1 Carbonate lithologies. It is most abundant as minute black dots, disseminated throughout the matrix (Pl. 14/2). Another typical occurrence is in association with anhydrite nodules (Pl. 15/1). The pyrite is confined to the nodules and appears to have replaced them. Pyrite also occurs as thin aggregates, concentrated along boundaries between laminae, in association with algal mat debris (Pl. 16/10), and as infillings of cracks.

Lithofacies 1: Microlaminated mudstone - Environmental Interpretation:

It can be argued whether or not the petrographic properties of lithofacies 1 are diagnostic enough to attribute it to a unique environment. A microlaminated, unfossiliferous carbonate mud can be deposited in deep water, well below wave turbulence, or in tidal and supratidal flats along protected shores or in quiet water lagoons. However, some of the more specific aspects of this facies can not be reconciled with a deep water origin. Furthermore, when evaluated in the context of the other facies with which it is intimately interbedded and associated, it becomes evident that Lithofacies 1 can be only a product of shallow water deposition.

The environmental interpretation of specific properties of the microlaminated mudstones are as follows:

Carbonaceous films - The carbonaceous films and seams, which are ubiquitous throughout this lithofacies, represent incipient algal mat formation. This mat is distinctly different from the well developed mats which characterize the intertidal zone, further landward (Lithofacies 2). It consists of short, thin segments which probably never coalesced to form a continuous surface. The subtidal environment thus appears to be less favorable for the establishment of a firm mat. This is probably due to the presence of mat grazing and burrowing organisms which feed on algae and destroy the mat and to less intense penetration of sunlight.

Microlamination - Algal films are the prime source for the laminated structure of this lithofacies. The rudimentary mats, as poorly developed as they are, nevertheless are effective in trapping and binding the available fine-grained carbonate mud (see further discussion in next section). However, as the laminae are not totally confined by algal films, their formation and preservation at least in part is attributed to normal deposition of a very fine grained carbonate mud sediment in an environment of very low hydrodynamic energy.

Origin and source of carbonate mud - The lithofacies comprising the A-O and A-1 Carbonate units consists of micrite, mostly dolomicrite, typical of the major Recent shallow water carbonate environments where similar sequences have been described (e.g., The Bahamas, Florida, Persian Gulf, Western Australia). However, beyond this general similarity, the Salina carbonate rocks afford no direct evidence as to the origin or source of the mud. Three processes have been put forth to explain the origin of carbonate mud, including spontaneous inorganic chemical precipitation, biochemical precipitation, and physical breakdown and destruction of skeletal material (see Bathurst, 1971, p.204; p.212, p.276.) . The first two processes probably are dominant in Recent environments of the Trucial Coast and the Bahamas. This interpretation is also favored for the A-O and A-1 Carbonate muds. It is further strengthened by the fact that the A-1 Carbonate Unit, even further basinward, does not contain contemporaneous skeletal lithotopes from which the mud could have been derived.

Pellets and burrows - Because of their pronounced elongation, the rod-shaped pellets are presumed to be of faecal origin. They are very similar to pellets produced by crustaceans (Davies, 1970, Fig. 18c), sea cucumber (Baars, 1963, Fig. 3) and many other bottom feeders. Their frequent association with burrowing tubes and with disrupted and disturbed laminae probably the result of bioturbation, further supports this interpretation. If the pellets indeed are of organic origin, they constitute the only evidence for invertebrate animal life during deposition of the A-O and A-1 Salina units.

As Lithofacies 1 is totally devoid of skeletal remains, one is forced to conclude that the burrowing and pellet-producing organisms in question were soft-bodied. As mentioned earlier, these organisms might have been responsible for the inhibition of algal mat formation (Garrett, 1970). Burrowing organisms and pelletal muds are quite abundant in intertidal and subtidal tidal flats of temperate regions, but in arid regions they are more prevalent in the subtidal zone. Therefore, the presence of an organic community in the Salina evaporitic sequence constitutes important evidence for the subtidal origin of this facies.

Anhydrite and Halite - The mode of formation of nodular and acicular anhydrite has been discussed in detail in the previous section. Anhydrite in this form is indicative of early penecontemporaneous mineralization in a sabkha environment. The same applies to halite (see also Smith, 1971), although halite generally will not be preserved owing to its high solubility. Thus these minerals could mark short periods of subaerial exposure brought about by intermittent, temporal sea level oscillations. The formation of the anhydrite and halite is generally linked to the process responsible for the almost pervasive dolomitization of the A-O and A-1 units, about which more will be said later on. However, it should be added at this point that the mineralization (including dolomitization) does not necessarily require subaerial exposure. It could have resulted from the downward and lateral migration of supratidal brines in a manner essentially similar to the "seepage refluxion" process (Adam and Rhodes, 1960), which could adequately explain

also the origin of the coarse crystalline anhydrite in veins and in intercrystalline pores. This anhydrite is epigenetic, having formed after dolomitization was complete and the rock lithified. It precipitated in open voids and cracks from a concentrated brine indigenous to the A-1 Carbonate or, alternatively, derived by refluxion from the overlying A-2 Evaporite.

Significance of pyrite - The pyrite in the microlaminar mudstone is clearly authigenic and indicative of the reducing conditions which prevailed within the carbonate mud soon after its deposition. The formation of pyrite in sediments is ascribed by Berner (1970, 1971, p. 202-208) to entail four reactions: reduction of dissolved sulfate by anaerobic bacteria to form hydrogen sulfide (H_2S), reaction of H_2S with iron to form ironmonosulfide (FeS), generation of elemental sulfur and reaction between elemental sulfur and ironmonosulfide to form pyrite (FeS_2). The availability of organic matter under reducing conditions appears to be an important prerequisite. In the absence of abundant detrital iron, the iron contained in organic matter is practically the only iron available. Furthermore, the sulfate-reducing bacteria need the organic matter for their metabolism. Thus, the pyrite in Lithofacies 1 indicates both prevalence of reducing conditions and abundance of organic matter, both important prerequisites for source rocks of the hydrocarbons. Their presence makes the A-1 Carbonate a likely source rock for the hydrocarbons contained in the reef and in the adjacent A-1 Unit.

Lithofacies 1 is in many respects similar to other microlaminated dolomiticrites which have been ascribed to supratidal deposition (Table 4-4). However, the general sparsity of fenestral and desiccation fabrics, along with its other attributes, tends to disfavor such an interpretation for Lithofacies 1.

On the basis of these considerations, the microlaminated, occasionally pelletal, mudstone of Lithofacies 1 is interpreted to represent sediments deposited in the very shallow subtidal marginal environments in broad, protected embayments of an inland sea, or lagoons adjacent to coastal sabkhas in a

paleogeographic setting similar to the present-day Trucial Coast of the Persian Gulf.

Lithofacies 2: Flat algal laminated sediment (Planar stromatolite) -

Petrographic Description (Plates 14,15): This lithofacies consists of regular alternations of couplets of dark gray to black carbonaceous films and light gray to tan carbonate mud laminae. The carbonaceous streaks, which are most probably the remains of algal mats, are continuous and flat with only small scale undulations of very low amplitude. The density and spacing of successive organogenic laminae as well as the overall ratio of these to the clastic algal bound intermat muddy sediment are among the more characteristic factors which vary slightly and determine the general physical appearance of the rock. Algal mats average about 30% of the rock. Individual algal films are about 0.01 mm thick, and in densely packed sections, 10 to 15 algal films might be present in one millimeter of vertical section (Plate 14, Figures 3-5). In places algal mats overlies one another without an intervening intermat sedimentary layer, thereby forming thicker black carbonaceous laminations (Pl. 14/3). The intermat layers were originally carbonate mud, diagenetically altered in some layers to dolomicrite, whereas in others the dolomicrite has been recrystallized into a decimicron-sized anhedral dolomite crystal. Generally the intermat layer in each couplet is thicker than the mat layer, the thickness varying considerably within 0.05 mm to 3 cm (Pl. 14/3, 15/3, 15/4).

A fenestral fabric is very common in the intermat mud laminae. Fenestrae, between 0.05 mm and 0.3mm in diameter, most commonly are horizontally aligned in the upper part of individual laminae ("limnoid fenestral" fabric of Tebbutt et al., 1965), elsewhere, fenestrae are distributed uniformly throughout entire laminae. Commonly, fenestrae are either completely or partly filled with blocky anhydrite (Pl. 14/8) that is texturally distinct from the felted anhydrite that characterized the anhydrite nodules. Blocky anhydrite is also abundant in intercrystalline pores of coarser grained layers, where it is in crystals of decimicron-size. In places, minute anhydrite nodules are

present in the intermat layers (Pl. 14/10). Although rather rare, intralaminar desiccation cracks have been observed in several samples (Pl. 15/4). Additional evidence for desiccation and probably prolonged subaerial exposure is provided by micro-unconformities (Pl. 15/2) which show an irregular contact between algal laminated sediments and overlying faintly laminated mudstones of Lithofacies 1. Desiccation cracks in the upper part of the algal laminated sediment have been enlarged, probably by subaerial erosion, and later infilled by the succeeding sediment.

A special form of the flat algal laminated facies, referred to in Michigan as "Poker chips" lithology, is almost invariably developed near the base of the A-1 Carbonate Unit. This type is composed of a very orderly succession of even parallel laminations, 1 mm or less in thickness, consisting of alternations of dark, slightly argillaceous, algal streaks and layers of pelletal wackestone and dense mudstone (Pl. 15/5, 15/8). The pellets in the intermat layers are elongated, well-rounded spherical bodies, some up to 2 cm in length and 2 mm in diameter (Pl. 15/7). Due to parting which develops along the mat horizons, cores of this facies often split horizontally into very thin, well-rounded discs, hence the designation "poker chips."

Additional structural features of this lithofacies that provide diagnostic criteria for their algal mat origin include disturbed mats, disintegration products of dessicated algal mats, and perpetuation of algal substrate irregularities. Enrolled and overturned mats (Pl. 15/6) represent a relatively thin succession of several mat and algal bound intermat mud layers that have been bent into a tight recumbent fold. The space surrounding the enrolled mat was occupied by a muddy sediment, rich with algal mat debris and small upended or otherwise disoriented flat lithoclasts, probably fragments of contemporaneous thin indurated crust layers. Disintegration products of desiccated mat appear as 2 to 5 mm long, flat mat chips and slightly curled, concave saucer shaped forms, abundant throughout this lithofacies (Pl. 15/3, 15/4). Such disintegration products are commonly concentrated in large numbers in relatively thick layers (3 to 8 cm), bound by well defined flat

algal mat horizons. Within the layers, the desiccated mat fragments usually assume an orientation which is parallel with the bedding. Small acicular anhydrite laths, similar to those described in lithofacies 1 (Pl. 13/9), are a common accessory component in the desiccated mat layers (Pl.14/11).

Perpetuation of substrate irregularities is preserved in several samples; the contact between an algal laminated sequence and its underlying substrate is irregular. The first algal laminae covers the substrate conformably and the irregularities in this contact are perpetuated, and sometimes even exaggerated, by the succeeding algal laminations. The same applies to surface irregularities formed within the mat itself, whenever an otherwise conformable algal laminated sequence is interrupted by horizons of disturbed or desiccated mat. (Pl. 14/11).

Lithofacies 2: Flat algal laminated sediment (Planar stromatolite) -

Environmental Interpretation: Algal constructed flat laminated carbonates are in effect a morphologic end member of stromatolites. They can thus be referred to as "planar stromatolite." Stromatolites are organo-sedimentary structures which consist of alternating algal-rich and sediment-rich lamellae. In certain environments living blue-green algae form dense carpet-like mats which cover large areas. The living algae secrete adhesive, gelatinous organic substances which form a mucilaginous membrane on their upper surface. On these sticky surfaces, sedimentary particles agglutinate. The algal filaments grow through the newly formed sedimentary layers and a new mat is reestablished at the surface. Stromatolites are formed thus by the binding and trapping of detrital or precipitated sedimentary (usually carbonate) grains by algal mats (Logan et al., 1964). They grow by vertical accretion in a pattern which results in the formation of laminated structures. A recent comprehensive discussion on the origin, classification and other attributes of stromatolites, as well as a review of much of the previous literature on the subject, can be found in Hofmann (1969).

In Recent marine environments stromatolites are known from the shallow littoral and adjacent coastal zone in a wide spectrum of environments and subenvironments, ranging from the shallow subtidal to the supratidal and including sea marginal and terrestrial supersaline, brackish and fresh water bodies. Locally specialized growth forms developed which are indicative of specific environments. In the discussion that follows only the environmental significance of planar stromatolites will be evaluated.

Most Recent algal flat laminated sediments are confined to or otherwise best developed in intertidal and supratidal environments. This is especially true of algal flat laminated sediments of Holocene age which exhibit a vertical succession of planar stromatolites rather than a single surface mat. The importance of making the above distinction relates to the potential of the structures being preserved and incorporated into the geological record. In Bermuda subtidal sediments down to a depth of about 10m are covered by a surface mat (Gebelein, 1969), although the lamination is rarely more than one layer thick. Grazing and burrowing organisms digest and leave no trace of the subtidal mat on Berry Island, Bahamas, soon after its formation (Bathurst, 1971, p. 122-126). Similar observations were made by Neumann and others (1970) and by Garrett (1970). Thus, the subtidal zone is most probably not a likely environment for the formation of planar stromatolites. Indeed, as shown by Garrett (1970), the distribution of stromatolites appears to be governed primarily by ecologic factors, viz., stromatolites are preserved in those areas which are inhospitable to grazing and burrowing animals which would otherwise feed on the mat and destroy it. These can be either water bodies with abnormal salinities (relative to sea water) or marginal marine areas which experience transient marine and terrestrial conditions. Evidence for intermittent exposure in Lithofacies 2 is afforded by microconformities, mud cracks and a fenestral fabric common to intermat layers. As shown by Shinn (1968), Kendall (1969), Illing (1959), Fischer (1964), Tebutt *et al.* (1965), fenestrae form by dessication, shrinkage, and trapping of gas bubbles in exposed unconsolidated fine-grained carbonate sediments. The frequent interbedding of disintegration products of desiccated mat with features such as overturned torn

mat also are indicative of subaerial exposure. Similar features occur in the Florida Keys (Gill, 1971).

Planar stromatolites strikingly similar to lithofacies 2 from Recent intertidal and, to a lesser extent, also supratidal settings have been reported from the Bahamas (Black, 1933), Florida (Ginsburg *et al.*, 1954; Gebelein and Hoffman, 1968; Muller, 1969), Shark Bay, Western Australia (Logan, 1961; Davies, 1970) and from the arid Trucial Coast, Persian Gulf (Illing *et al.*, 1965; Shearman, 1966; Kendall and Skipwith, 1968, 1969). Most compelling in their resemblance to the A-1 Carbonate are some algal laminated sediments of Shark Bay (Davies, 1970, Figs. 10, 12a, 17 and 18c, cf. Pls. 14/3, 15/6, 15/4 and 15/7 of the present study).

A representative contemporary analogue of Lithofacies 2 should account for specific as well as the general attributes including desiccation features, fenestral fabric, acicular anhydrite, occasional anhydrite nodules, micro-unconformities and complete dolomitization. In addition, the Recent environment with planar stromatolite should be closely associated with the supratidal anhydrites, crusts and breccias of the A-1 Anhydrite and lithofacies 4, 5 and 6, and with lagoonal muds and pelletal muds (lithofacies 1 and 3). These added constraints practically eliminate most Recent occurrences except the present day Trucial Coast of the Persian Gulf. Therefore, the flat algal laminated sediments of Lithofacies 2 were most likely formed in the intertidal zone of an arid, hot tidal flat environment similar to the present Persian Gulf.

Lithofacies 3: Pelletal Wackestone - Petrographic Description:

Pellets, having a well rounded, spherical to oval cross section (Pl. 15/9), constitute between 20 to 30 percent of the rock. Some are pronouncedly elongated. In top view they appear as elongated spherical rods (Pl. 15/7). Larger ones are up to 2 cm long and 2 mm in diameter. However, most pellets are smaller, the majority having a diameter of between 1 and 2 mm.

In places the larger rod-shaped pellets have been cracked and bent, and the gap thus formed infilled with coarse crystalline anhydrite. The pellets are for the most part composed of very dense micrite and are darker in color than the enclosing matrix (Pl. 15/9). Rarely (well no. 34, 2513' - 2518') preferential recrystallization of pellets relative to the micrite matrix produces a dense hypidiotopic mosaic of decimicron-sized dolomite crystals. In places, particularly where pellets are concentrated in thin laminae, the pelletal grains are in mutual contact (Pl. 15/10). However, for the most part, the grains are suspended in and supported by a micritic mud matrix. In parts of this lithofacies (notably in well no. 4, 2361'-2389') only traces of the original micritic mud have been preserved. Most of the matrix, now dolomite, has been recrystallized into a xenotopic to hypidiotopic equigranular mosaic of very fine dolomite crystals, about 0.01 mm in size. Well developed idiopathic dolomite rhombs are scattered throughout the matrix. This lithofacies is the most porous rock type in the A-1 Carbonate Unit. Porosity values of 5 percent are common and locally porosities as high as 10 to 15 percent occur. Mostly intercrystalline, the pore space locally is infilled by coarse anhydrite crystals. Molds formed by the partial or complete leaching of pellets form additional porosity. Some pellets have been totally leached and distinct ghosts of micritic envelopes outline the original pelletal grain. Some molds are later infilled by coarse anhydrite crystals, in others, scalenohedral dolomite crystals line the inner circumference of the mold.

Discontinuous poorly developed faint lamination is the dominant bedding type (Pl. 15/9), in which laminae thicknesses vary from a few millimeters to 4 or 5 cm. Thin undulating short carbonaceous films locally form the boundaries between laminae. Distinctly laminated pelletal wackestones consist of numerous alternations of pelletal wackestone and mudstone devoid of pellets (Pl. 15/10). Lamination is continuous, planar and parallel. The pelletoidal laminae commonly consist of a single layer of densely packed grain-supported pellets. In the interbedded mudstone laminae, desiccation cracks are locally present. Anhydrite, in the form of small nodules and lath shaped crystals, similar to the ones described from lithofacies 1 and 2, are present in minor amounts throughout this lithofacies as well.

Lithofacies 3: Pelletal Wackestone - Environmental Interpretation:

The pelletal wackestone, subfacies of Lithofacies 1, probably represents the outer depth range of the shallow subtidal zone, containing more abundant soft bodied benthos which generated the pellets, and destroyed the algal mats which are very poorly developed in this subfacies. The interbedding of facies 3 with desiccated mudstone which is devoid of pellets indicates frequent sea level oscillation and periodic shallowing.

Lithofacies 4: Indurated Crusts and Lithofacies 5: Intra-formational Breccia and Flat pebble conglomerate - Petrographic Description (Plate 16):

Dark brown layers, distinct in color and fabric from the other lithofacies thus far described, occur in various stratigraphic levels throughout the A-1 Carbonate Unit. These layers, 2 to 3 cm thick, consist either of unlaminated, very dense and homogeneous dolomicrite, or microlaminated mudstone (Lithofacies 1). Most commonly, the brown layers are horizontally bedded (Pl. 16/1, 16/2). In some samples they are bent and draped over irregularities of their immediate substrate (Pl. 16/3). Typically upper boundaries are sharp and well defined, whereas lower boundaries pass irregularly and gradationally into the underlying sediment through a thin, lighter brown horizon. The bottom contact of the brown layers is often irregularly incised, marked by small wedges and irregularly shaped small projections of brown coloration penetrating the underlying sediment. Individual crust layers usually maintain a constant thickness but some show irregular lateral thickness variations within the 4-inch width of the core slab. Desiccation cracks, characteristic of this lithofacies, are usually normal to the bedding and confined in their vertical extent to an individual crust layer (Pl. 16, Figs. 1-3, 15/4). Complete fragmentation of crusts by closely spaced desiccation cracks and joints is quite common. Thus, the thinner crust layers represent undisplaced microbreccias (Pl. 16/5), interbedded with the intraformational breccia of Lithofacies 5.

Intraformational breccias are intimately associated and interbedded with rocks of both Lithofacies 4 and Lithofacies 2. Lithoclasts generated by the brecciation of the indurated mud crusts are either small, equidimensional

angular fragments (Pl. 16/4), or flat and elongated ("flat pebble" type). They are usually unsorted. The smaller equidimensional fragments are mostly 1 to 5 mm in diameter. Some of the larger "flat pebbles" are several centimeters long and 0.5 to 1.0 cm thick (Pl. 16/5). The lithoclasts are suspended in a micritic matrix, commonly in mutual contact, which produces considerable interparticle porosity (Pl. 16/4, 16/5). The solution-enlarged vugs, some of which are up to 2 cm in diameter, commonly are infilled by halite (Pl. 16, Figs. 1, 3, 5), a phenomenon unique to the intraformational breccia zones.

The algal laminated sediments of Lithofacies 2 through desiccation and brecciation contributed flat pebbles and other lithoclasts to the sedimentary environment. These are commonly very thin, consisting of a single, or at most two or three mat-sediment couplets, and they are usually interbedded in an algal laminated sequence (Pl. 15/3, 15/4, 16/2, 16/10).

Lithofacies 4 and 5 - Environmental Interpretation: The indurated crusts and the intraformational breccias are genetically interrelated, indeed, recognition of Lithofacies 4 as "indurated crusts" rests primarily on the evidence that Lithofacies 5 was derived from lithoclasts of contemporary origin. Until recently, cementation and early lithification of carbonates was thought to be exclusively a subaerial process. If this were indeed so, the environmental significance of the indurated crusts would have been clear cut. However, in the light of more recent studies, it is now clear that the process can and does take place in a wide range of submarine environments as well (Bricker, 1971; see also Bathurst, 1971, chapters 9 and 10). Therefore, in order to build a strong case for the supratidal-subaerial interpretation favored here, one has to show that the contending alternative interpretations do not apply. The model to be adopted should adequately account for the following aspects of Lithofacies 4 and 5: the indurated crusts form a continuous surficial layer; they are dolomitized and desiccated; the pebbles consist both of crust material and of planar stromatolite fragments; and finally, the two lithofacies are intimately associated and occur in an overall

context of a sabkha type complex. These considerations preclude most Recent submarine occurrences of early lithification as likely analogues. Among the reports on Recent submarine lithification, the closest analogue to Lithofacies 4 can be found in the crusts now forming in the shallow subtidal of the Persian Gulf (Shinn, 1969; Taylor and Illing, 1969; De Groot, 1969), but this example too fails to match some of the above criteria. On the other hand a striking resemblance exists between Lithofacies 4 and 5 and indurated crusts and flat pebble conglomerates reported from Andros Island (Shinn et al., 1965; Shinn et al., 1969; Rohel, 1967), the Florida Keys (Shinn, 1964), Bonaire (Deffeyes et al., 1965) and Shark Bay (Davies, 1970). It is not incidental that the reports by Shinn and Deffeyes and co-workers also pertain to the formation of Recent dolomite.

In Bonaire, Florida, and the Bahamas these lithofacies are limited to the supratidal zone, whereas in Western Australia they are forming in the higher part of the intertidal zone as well. The formation of the crusts is apparently similar to the formation of caliche (Friedman and Sanders, 1967, p.287) and is related to the same processes which lead to the emplacement of early diagenetic sulfates (see discussion in previous section) and dolomitization in supratidal sediments. Marine derived ground water is further concentrated by evaporation by capillary rise in the vadose zone within exposed supratidal sediments. The interstitial hypersaline brines thus formed are apparently capable of cementing the unconsolidated mud at or near the sediment-air interface (see also "evaporative pumping" model of Hsu and Siegenthaler, 1969). The carbonate mud layers themselves were probably eroded from subtidal sediments and deposited above the high water mark by abnormal severe "catastrophic" storms, similar to that recorded in Florida after Hurricane Donna in 1960 (Ball et al., 1967; see also Perkins and Enos, 1968), during which a two-inch thick storm layer was deposited over vast supratidal flats on the keys and on the Florida mainland as well. The crusts desiccate and crack upon drying, producing unattached flat lithoclasts. The clasts are reworked and transported within the supratidal and subtidal zones by abnormally high spring and storm induced tides. As many breccias can be reconstructed

and pieced together, it is evident that reworking and redistribution of clasts did not always take place. The fragments of the planar stromatolite, which are often interbedded with the crust pebbles, originate by the desiccation of the algal laminated sediments (lithofacies 2) in the intertidal zone, largely in the transitional belt between the higher intertidal and lower supratidal zones. Clasts do not necessarily indicate early lithification. Rubbery algal mats retain enough cohesiveness to remain intact even when reworked and redistributed after initial fragmentation by desiccation.

In summary, the indurated crusts of Lithofacies 4 are thought to represent the early lithification (and dolomitization) of mud layers deposited by storms in the supratidal zone. The flat pebbles of Lithofacies 5 were derived from desiccated algal mats redeposited by storms within the supratidal, intertidal or subtidal zones. Their angularity indicates short transport distance and deposition in close proximity to their site of formation.

Lithofacies 6: Nodular Anhydrite ("Rabbit Ears" Anhydrite) -

Petrographic Description (Plate 16): Each of the two anhydrites is composed of varying proportions of white to bluish anhydrite embedded in a tan to light gray groundmass of flat algal laminated and microlaminated mudstone in thin beds, only several centimeters thick (Pl. 16/6). Either might be dominant within the anhydritic zones. Intensive anhydritization commonly completely masks the nature of the original host sediment.

The "Rabbit Ears" anhydrite displays a wide range of fabrics, all variants derived from anhydrite nodules.

The nodules have a felted texture similar to that in the greater part of the A-1 Anhydrite and Lithofacies 1 and 2 of the A-1 Carbonate (Pl. 16/7). Most do not exceed 1 or 2 mm in diameter and are flattened parallel to the bedding (Pl. 16/6). Considerably larger nodules, with diameters of 1 to 3 cm, are commonly present in the middle part of each of the two anhydritic layers.

Coalescence of adjacent nodules and lateral merger of anhydritic masses, all at the expense of the original carbonate host sediment, is expressed in a variety of fabrics grading from "nodular" and "distorted nodular" to "nodular mosaic", "bedded nodular mosaic", "mosaic" and "distorted mosaic" (Maiklem et al., 1969) (see Pl. 16, Figs. 6, 8-10). Several or all of the fabrics might occur together adjacent to one another in frequent and unsystematic sequence (Pl. 16/8, 16/9). Enterolithic structures, although rather rare, are present in both anhydrite horizons.

Lithofacies 6: Nodular Anhydrite - Environmental Significance:

The environmental significance of the "Rabbit Ears" anhydrite is similar to that of the nodular anhydrites in the A-1 Anhydrite, discussed earlier.

Facies Distribution

The distribution of the various lithofacies in the A-1 Carbonate Unit and the stratigraphic relationships of the A-O Carbonate, A-1 Anhydrite and A-1 Carbonate are portrayed in Figs. 4-6, 4-7 and 4-8. Cross section L-L' (Fig. 4-8) shows the lateral facies variations in a section which runs perpendicular to the presumed depositional strike, section K-K' (Fig. 4-7) along the west, basinward, side of the reef and section J-J' (Fig. 4-6) along its east or landward side.

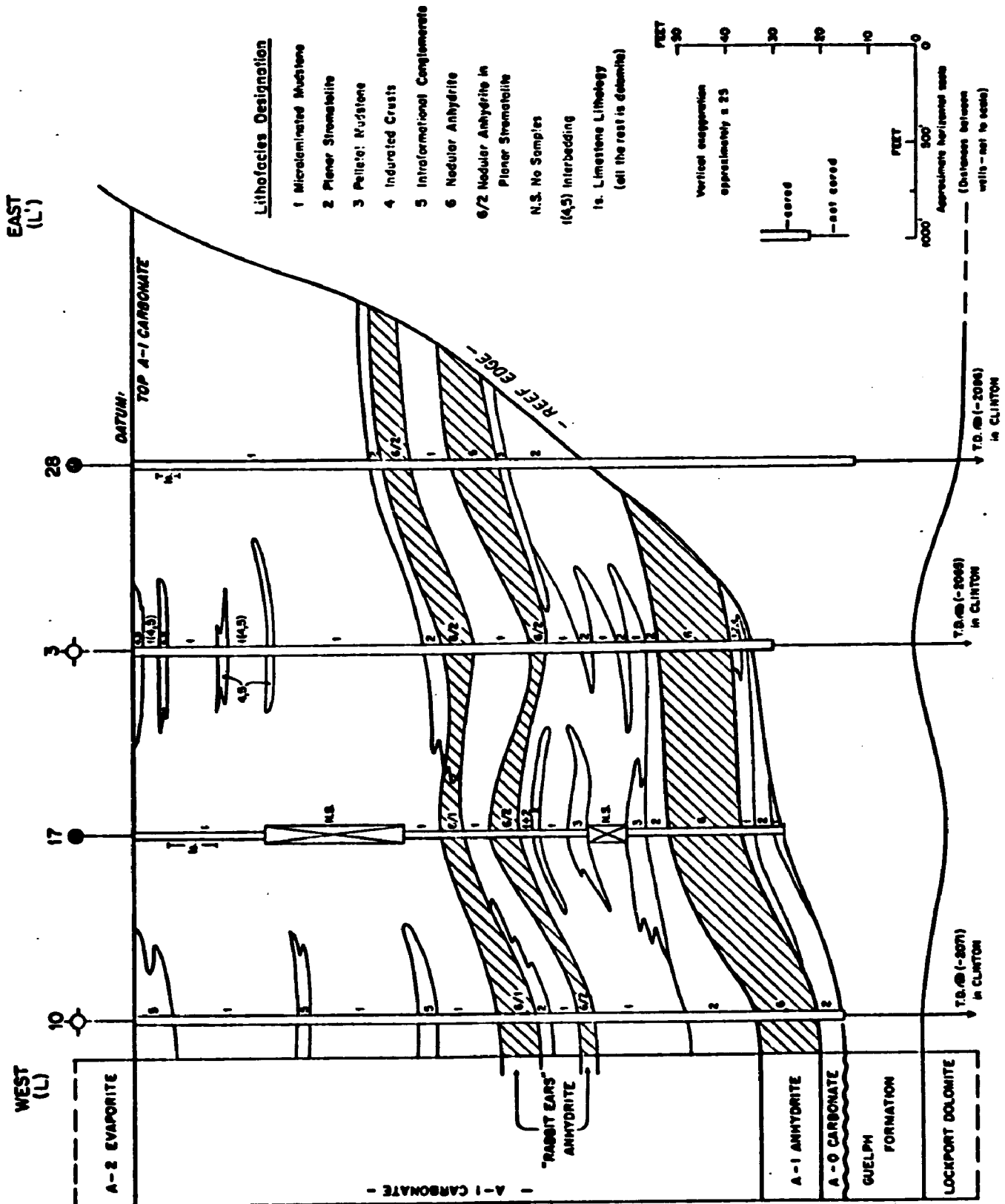
With respect to the internal stratigraphy of the A-1 Carbonate Unit, all three sections show essentially the same relationships which are well represented in well no. 3, chosen as the type section (Fig. 2-12). The lower part of the A-1 Carbonate up to and including the upper "Rabbit Ears" Anhydrite, shows many vertical facies changes. In contrast, the upper part consists of essentially a continuous uniform section of microlaminated dolomite (lithofacies 1) only sparsely interbedded with very thin streaks of the other lithologies.

The lateral facies transitions along the paleodepositional slope (section L-L', Fig. 4-8) appear to be systematic whereas those along the strike of the beds (section K-K', Fig. 4-7; section J-J', Fig. 4-6) are much less regular and predictable. The dominant pattern in the lower part of the section is the interfingering between microlaminated mudstone and planar stromatolite (lithofacies 1 and 2). The less shallow water environment of lithofacies 1 prevails and dominates the sections farther away from the reef, whereas the shallower environment of lithofacies 2 (intertidal flat) dominates along the reef edge and its immediate vicinity. The same pattern repeats three times, below the "Rabbit Ears" anhydrite and in each of the two anhydrite layers within the "Rabbit Ears" Anhydrite (in the lower R.E. this interfingering probably occurs farther basinward, west of well no. 10). The ubiquitous planar stromatolite (lithofacies 2) which immediately overlies the A-1 Anhydrite is thickest near the reef (well no. 28, Fig. 4-8) and gradually thins out basinward (wells no. 17 and no. 10) through a zone of frequent interfingering with lithofacies 1 (well no. 3). In the upper part of the section (lithofacies 1) the microlaminated mudstone is fairly uniform, in a few places being interbedded with layers of flat pebble conglomerate which were probably washed into the lagoonal area during strong storms. In well no. 47 (Figs. 4-6, 4-7) the uppermost part of the section is dominated by planar stromatolite. This intercalation of intertidal sediments indicates shoals in the bottom topography, a feature which is more pronounced and better expressed in the strike sections.

In contrast to section L-L', the strike sections (Figs. 4-6 and 4-7) show a rather unsystematic distribution of facies. This is in part a reflection of the fact that the sections do not run exactly parallel to the depositional strike, which in turn, reflects the rather complex and irregular bottom topography of the depositional site. Lateral gradations between lithofacies 1 and 2 indicate deeper and shallower water respectively. These can be related to downslope deepening, tidal channeling within the intertidal flats and shoaling within the subtidal lagoon. In general it is an expression of

FD. 4-4. A-1 UNIT LITHOFACTS CROSS SECTION J - J.

FIG. 4-7. A-1 UNIT LITHOPACED CROSS SECTION E-E.



the complex configuration of the paleostrandline at any given time, as well as of its spacial shifting through time. The discontinuity in the distribution of the "Rabbit Ears" layers and their absence on both sides of the central part of the reef (Figs. 4-5, 4-6, 4-7) can be similarly attributed to a local depression bounded by elevated shoals. West of the reef this same area remained relatively deeper during most of A-1 Carbonate time where only the microlaminated mudstone was deposited.

The distribution pattern of undolomitized limestone shows no systematic pattern within the microlaminated mudstone. The limestones may represent lithologies in which dolomitization was impeded due to transmissibility barriers within the formation.

Environmental Synthesis

A Depositional Model for the A-1 Unit

In the preceding sections, the environmental significance for each of the lithofacies comprising the Salina A-1 Unit was evaluated in detail. The lithologic attributes of each lithofacies and its postulated environment of deposition are summarized in Table 4-2. Recent analogues to each lithofacies on which much of the paleo-environmental interpretation is based, and their corresponding environments, are listed in Table 4-3. Already at the individual lithofacies level it became apparent that, with the exception of lithofacies 4 and 5, every facies, quite independently of the others, finds its most satisfactory Recent analogue in one of the interrelated environments comprising a sabkha complex. It therefore follows that when we come to integrate all the individual lithofacies into a unifying depositional model, the one afforded by the Recent sabkhas of the Trucial Coast becomes the most suitable choice. It should be stressed that although, in its limited application, the term "sabkha" denotes only a "salt encrusted supratidal flat", it is used here in a broader sense, as a one-word designation for a particular suite of environments. These include the subtidal-lagoonal and the intertidal and

Lithofacies	Lithologic Attributes*	Environment
1) Faintly microlaminated mudstone	Carbonate mud, microlaminated; films and seams; mat chips; occasionally pelletal, burrowed; few limestones and slightly dolomitized limestone horizons; anhydrite nodules and laths (rare); finely disseminated halite (rare); authigenic framboidal pyrite.	Shallow subtidal
3) Pelletal Wackestone	Pelmicrite, mud and grain supported; laminated; anhydrite nodules and laths (rare).	
2) Flat algal laminated (planar stromatolite)	Laminated; alternating organic-rich and dolomicrite laminae; limnoid fenestral fabric; intralaminae desiccation; microunconformities; enrolling and overturning of mats; curled desiccated mat; anhydrite nodules in intermat (rare); authigenic framboidal pyrite.	Intertidal flat
6) Nodular anhydrite (including A-1 Anhydrite)	Nodular anhydrite in a multitude of interrelated fabrics; enterolithic structures; felted and aligned felted texture; framboidal pyrite replacing nodules.	Supratidal flat
4) Indurated crusts	Dolomicrite; massive or microlaminated; 1-3 cm thick; dessicated; in situ brecciation.	
5) Intraformational breccias and flat pebble conglomerates	In situ brecciated crusts; flat lithoclasts of planar stromatolite and indurated crust; salt infilling of voids (rare).	Supratidal to subtidal

* Attributes common to all carbonate lithofacies: dolomicrite composition, total absence of skeletal remains and secondary void filling by coarse crystalline anhydrite.

Table 4-2. Lithofacies and postulated environments of the Salina A-1 Unit.

A-1 Lithofacies	Recent analogue	References
(1) Microlaminated mudstone	Subtidal (lagoon), Trucial Coast	Kendall and Skipwith, 1968; 1969; Shearman, 1966.
(2) Planar Stromatolite	Intertidal, Trucial Coast. Intertidal, Shark Bay. Intertidal, Cape Sable, Florida. Supratidal, Florida Keys. Supratidal marsh, Bahamas.	Illing et al., 1965; Kendall and Skipwith, 1968; 1969; Shearman, 1966. Logan, 1961; Davies, 1970. Geblein and Hoffman, 1968. Ginsburg et al., 1954; Multer, 1969; Gill, 1971, Shinn et al., 1969.
(3) Pelletal Wackestone	Subtidal, Bahamas. Subtidal-Intertidal, Bahamas. Subtidal-Intertidal, Trucial coast.	Purdy, 1963. Shinn et al., 1969. Illing et al., 1965 (p.93).
(4) Indurated Crusts	Supratidal, Bahamas. Supratidal, Florida Keys. Supratidal, Bonaire. Intertidal, Supratidal, Shark Bay.	Shinn et al., 1965; Shinn et al., 1969. Shinn, 1964. Deffeyes et al., 1965. Davies, 1970.
(5) Flat pebble conglomerate	Supratidal, Bahamas. Intertidal, Shark Bay. Supratidal, Florida Keys.	Shinn et al., 1969; Rohel, 1967. Davies, 1970. Personal observations.
(6) Nodular Anhydrite	Supratidal, Laguna Madre. Supratidal, Baja California. Supratidal, Trucial Coast.	Kerr and Thompson, 1963. Kinsman, 1969. Numerous authors.

Table 4-3. Recent analogues to the lithofacies in the Salina A-1 Unit.

supratidal flats which are associated with Recent coastal sabkhas in hot and arid regions. The various aspects of this environmental setup, encompassing physiography, climate, lithofacies, water chemistry and depositional and diagenetic processes, have been described in numerous articles. (Many of these articles have been already cited in earlier sections. For comprehensive lists of references see in particular Butler, 1969; Evans et al., 1969; and Bathurst, 1971, p. 178 and p. 216.)

The analogy to lithofacies 4 and 5, which do not have matching counterparts in the Trucial Coast, can be found in other provinces of Recent carbonate deposition (Table 4-3) which are similar in many respects to the Persian Gulf. On the basis of these descriptions, it becomes possible to construct a corresponding depositional model for the lithofacies of the Salina A-1 Unit and to reconstruct its depositional history and paleogeographic evolution.

Figure 4-9 is a schematic representation of the depositional model envisioned for the various lithofacies present in the A-1 Unit in the Belle River Mills area. The A-1 Unit was deposited in very shallow water within the supratidal, intertidal and subtidal environmental zones. The Niagaran reefs in the "pinnacle reef belt" (Fig. 1-2) were exposed islands during the entire deposition of the A-1 Unit (See below). The "outer slope" of the reef (see p. 117) provided the depositional slope upon which initially the three environments were differentiated. The subjection of areas to subaerial exposure as supratidal flats was more contingent upon basin-wide sea level fluctuations than upon depositional processes. Due to the very gentle slope of the depositional interface, every relatively minor drop in sea level could result in the emergence and exposure of extensive areas. Sedimentation in this zone was limited to thin veneers of carbonate mud, washed onto the supratidal flats by periodic storms. The most characteristic attribute of the supratidal facies is its distinct penecontemporaneous diagenesis, leading to early dolomitization, dolomitic surface crusts and growth of anhydrite nodular and entrolithic fabrics within the unconsolidated carbonate muds. These

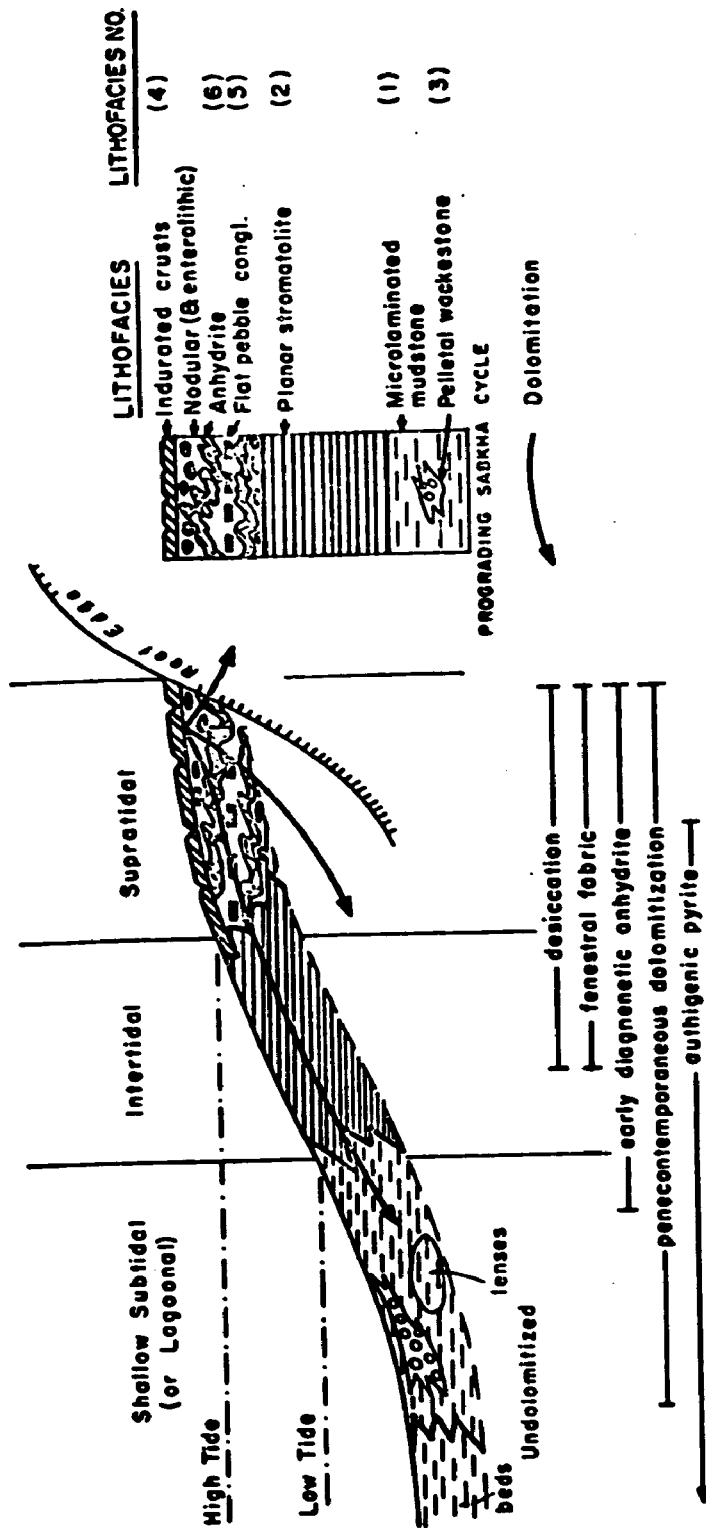


Fig. 4-9: Depositional model for the A-1 Unit (ancient sabkha analogue, diagrammatic).

processes are interrelated and connected to the geochemical evolution of the interstitial brine (see below).

The dolomitic crusts on the surface of the supratidal flat crack by desiccation. The flat pebbles thus formed, when in place, give rise to intraformational breccias and when relocated - to flat pebble conglomerates (lithofacies 5). The former is diagnostic of the supratidal whereas the latter marks storm deposits commonly transported to nearby environments.

The intertidal zone is characterized by the development of algal mats, which through their capacity to bind sediments, produce the planar stromatolite (lithofacies 2). Prolonged periodic exposure, brought about by minor drops in sea level, forms mud and shrinkage cracks in the intermat layers and disintegrates the mat itself. Storms are recorded in the interbedded flat pebble conglomerates and in the tearing and overturning of mats. Due to the low depositional slope, the intertidal zone was essentially flat and it covered extensive areas.

In the subtidal zone, due to deposit feeders, inhibited light penetration and constant, even though very slight, agitation, only rudimentary development of mats is possible. Apparently, the only fauna was soft bodied benthos which produced the pelletal mud (lithofacies 3). As indicated by the fundamentally laminated nature of this facies (lithofacies 1), and in the absence of well developed mats to stabilize the sediment, the water energy must have been very low. Thus the subtidal facies was most likely deposited in very shallow water in the distal part of a broad lagoon or a protected embayment.

Dolomitization of the A-1 Unit

The penecontemporaneous diagenetic changes to the A-1 Unit include emplacement of anhydrite and almost pervasive dolomitization. The formation of nodular anhydrite was discussed in detail in pp. 147 - 150. Postulated

mechanisms for the dolomitization process will be discussed here in brief (for exhaustive treatments of the subject see Bathurst, 1971, Chapter 13; Berner, 1971, p. 148-157; Friedman and Sanders, 1967, p. 287-289; Fisher and Rodda, 1969; Adam and Rhodes, 1960; Deffeyes et al., 1965; Shinn et al., 1965; Illing et al., 1965; Shearman, 1965; Kinsman, 1966; Butler, 1969; Hsu and Siegenthaler, 1969).

During deposition of the A-1 Carbonates, the water table underneath the supratidal flat approximates the high diurnal tide mark, the ground water being derived essentially from the sea. Due to aridity the contribution of meteoric water is negligible. The paucity of skeletal fossil remains in all lithologies suggests that the salinity of the sea was higher than normal. Water loss due to evaporation in the vadose zone is replenished by both lateral tidal recharge and by flood recharge - the downward percolation of sea water washed onto the supratidal flats during spring and storm induced tides. These surface waters are concentrated by evaporation and dissolution of previously formed evaporitic crusts. Waters rising by capillary forces, or by "evaporative pumping" (Hsu and Siegenthaler, 1969), into the vadose zone are also concentrated by evaporation. In this manner the vadose zone becomes saturated with a brine concentrated enough to precipitate saline minerals and induce other diagenetic changes in the host sediment. Theory and field observation suggest a series of probable chemical reactions between the sediment and its interstitial brine. An early possible reaction is the crystallization of calcium carbonate from the brine in the form of aragonite crystals, leading to partial cementation, the formation of a crust layer at or close to the sediment air interface, and, upon subsequent dolomitization and further lithification, development of the indurated crusts of Lithofacies 4. The second chemical reaction involves the reaction of calcium carbonate (aragonite or calcite) with sulfate ions in the brine, leading to crystallization of lath-like anhydrite and/or gypsum and their clustering into nodules which displace the original host sediment as they grow. Crystallization of both calcium carbonate and calcium sulfate depletes the connate brine in Ca, and enriches the brine both in the absolute Mg content and the ratio of

Mg:Ca. This Mg-rich brine is responsible for the early pervasive prelithification dolomitization of the originally aragonite carbonate muds in the supratidal zone.

Since other lithofacies of the A-1 Carbonate representing tidal and subtidal environmental zones are thoroughly dolomitized, penecontemporaneous dolomitization was not confined to the supratidal zone alone. That is to suggest that the dolomitizing fluids rich in magnesia entered adjacent zones through gravitational fluid flow through permeable strata (Fig. 4-9).

The concentrated brine in the supratidal sediments had a much higher density than the connate water in contiguous sediments, including the lithified sediments of the Guelph reef, the underlying older A-1 sediments which might have already been lithified and the still unconsolidated contemporary facies further down the depositional slope. Dolomitization would proceed where physical flow was not obstructed by permeability barriers and as long as the supply of brine lasted. Dolomitization prior to lithification of the contemporary facies is suggested by their fine-grained unaltered texture and displacive early diagenetic growth fabric of anhydrite nodules which could occur only in unconsolidated sediments. No doubt much of the dolomitization and the pore-filling by evaporite minerals within the reef itself must have occurred at the same stage. These same dense, highly saline fluids provided coarse crystalline, late diagenetic, anhydrite in intercrystalline and fenestral voids and cracks, the halite disseminated in limited parts of Lithofacies 1, and the coarse salt infilling observed in Lithofacies 5.

Ancient Analogues

Ancient analogues for the A-1 Anhydrite and Carbonate Units have been reported in recent years in ever increasing numbers. Some of these are summarized in Table 4-4. Selection of the analogues was based primarily on recent publications in which at least two matching lithologies have been documented by detailed petrographic analyses. Also listed are several

Analogue	Lithofacies	1	2	3	4	5	6	Suppt. paraco dol.	no foss	Recent analogue
Silurian, Michigan, basin (present study)		D(C)s	Di	De	Dp	De-p	P	+	+	Sabkha cycles
Ordovician, Williston basin (Rohol, 1967)		Dp	Dp		Dp	Dp	P	+	+	Sabkha
Ordovician, Maryland (Matter, 1967)		Cl, P		Cl, P	Dp	Cl, P		+	+	Sabkha, Bahama
Ordovician, New York (Braun and Friedman, 1966)		De	Di	De	Dp	Dp		+	+	Bahama
Silurian, Ohio (Textoris and Carozzi, 1966)		Dp	Dp	Cl		Cl		+	+	Sabkha cycles
Devonian, New York (Laporte, 1967)			Di			Dp	P	+	+	
Upp. Devonian, Alberta (Fuller and Porter 1969a)			Dp	Ca, 1		Cp		+	+	
Mississippian, Mar. Prov. (Scheck, 1967, 1968)		C, Di	C, Di			Dp	P	+	+	Sabkha
Mississippian, Ireland (West et al., 1968)		D	Di			P	P	+	+	Sabkha
Pennsylvanian, Paradox basin (Gray, 1967)			Di, 1			P	P	+	+	Sabkha
Permian, Gaudalupe Mts. (Kendall, 1969)			Di	C, Di				+	+	Sabkha
Triassic, Calcareous Alps. (Fischer, 1964)					Dp	Di		+	+	Sabkha cycles
Triassic, Calcareous Alps. (Gorman, 1969)		Di, s	Di	C, Di, s		Dp	P	+	+	
Jurassic - L. Cr., Abu Dhabi (Wood and Wolfe 1968)										
Off-reef carbonate members within the Middle Devonian, Upp. Elk Point Group, Muskog and Prairie evaporites of Alberta and Saskatchewan										
Ratner Mbr. (Winnipegosis Fm.) (Wardlaw and Reinson, 1971)			Db				b			basinal
Ratner Mbr. (Winnipegosis Fm.) (Shearman and Fuller, 1969)			Di				P			Sabkha
Ratner Mbr. (Winnipegosis Fm.) (Fuller and Porter, 1969a)			D				P			Sabkha
Upper Keg River Mbr. (Klingspor, 1969)			Db				b			basinal
Zama Mbr. (McCamie and Griffith, 1968)	D		D				+			
" " (Fuller and Porter, 1969a)			Di				P			Sabkha

Legend:

Mineralogy: D-dolomite; C-calcite

Environment: b-basinal; s-shallow subtidal; l-lagoonal; i-intertidal; p-supratidal

Table 4-4. Summary of Ancient A-1 Anhydrite and A-1 Carbonate analogues.

analogues of ancient sabkha deposits, interbedded or overlain by thick evaporite sequences that enclose juxtaposed organic reefs similar to the Guelph-Salina relationships. The Middle Devonian Muskeg and Prairie formations of Alberta and Saskatchewan are particularly pertinent to the Guelph-Salina setting.

Most, if not all, of the papers cited, report lithologies practically identical to these of the A-1 Unit. The identity extends to all aspects of visual appearance, sequence and lateral facies variations and general geological and environmental setting. Indeed, similarities even in minute detail are truly astounding.

Stratigraphic Implications of the Depositional Model (Reef Exposure During Lower Salina Time)

The controversial question of the time relationship between the Salina A-1 Unit and the Guelph reef (see p. 45) actually finds its conclusive solution with the discovery of the fact that the BRM Conglomerate Member of the Guelph Formation underlies the A-O Carbonate Unit (see p. 110). This observation clearly demonstrates that the A-1 Unit postdates the Guelph. Nevertheless, it is of interest to examine whether the same conclusion is corroborated or disputed by the additional, independent evidence afforded by the environmental interpretation of the A-1 lithofacies.

Sabkha complexes and reefs represent incompatible environments. They contrast in being partly terrestrial vs. entirely marine, with different environmental settings of salinity, water depth and energy, availability of nutrients, temperature, and contrasting sedimentary facies associations. The closest proximity of living reefs to sabkhas exists in the Trucial Coast where fringing coral reefs flourish on the inner shelf of the Persian Gulf, seaward of coastal lagoons above which the sabkhas exist (Kinsman, 1964a, Fig. 3; Kinsman, 1966, Fig. 2; Kendall and Skipwith, 1969, Figs. 2 and 22). The reef biota exhibit a tolerance for relatively high salinities (up to 46 parts per thousand) and large seasonal temperature variations (Kinsman, 1964b). However, even with these somewhat unique conditions, sabkha and living coral reef are not contiguous.

Thus the environmental interpretation of the A-1 lithofacies supports the earlier conclusion that the entire Salina section must postdate the Niagaran Supratidal Island Stage. The base of the A-O Carbonate lies some 430 feet below the crest of the reef. As these earliest Salina rocks were deposited near mean sea level, sea level in the Michigan basin dropped by at least this amount at the beginning of Salina deposition in the Early Cayugan relative to its high stand at the termination of Guelph reef growth at the end of the Niagaran. At the beginning of the Salina deposition, the entire vertical extent of the reefs was subaerially exposed.

The A-1 Unit as a Source Rock for Hydrocarbons

The A-1 Carbonate around the BRM Reef is producing small quantities of gas (Table 1-2, Fig. 1-6). Stratigraphically, over the entire basin, the unit is overlain and underlain by impermeable evaporites of the A-1 and A-2 Units. Faulting, which could conceivably bring the A-1 Carbonate in contact with potential source beds is unknown in the area. The only contact with non-evaporitic rock is where the A-1 Carbonate onlaps and wedges out against the Guelph reef.

The gas in the A-1 did not come from the reef. Clearly, any hydrocarbons indigenous to the reef would have been destroyed during its exposure, prior and during the deposition of the A-1 Unit. Moreover, the hydrocarbons must have migrated into the reef reservoirs after the deposition and at least partial consolidation of the A-2 Evaporite, which forms the seal to the upper part of the reservoir. Any alternative model is contingent upon there being an adequate source bed which fits the spatial and temporal constraints of the situation. Apparently no suitable alternative source bed seems to exist. Sharma (1966) suggested the underlying Clinton and Lockport as potential source beds, but even if these were adequate source beds, which as yet has not been demonstrated, they fail to fulfill other requirements of the model.

Hydrocarbons in the A-1 Unit may be indigenous to the A-1 Unit because of similarities to the A-2 Carbonate Unit where hydrocarbons must be indigenous. Differential compaction over the rigid Guelph reef masses forms small anti-clinal traps in the overlying A-2 Carbonate which are productive in some areas (Ells, 1967, p. 12). The A-2 Carbonate is petrographically similar to the A-1 Carbonate and it, too, probably represents sabkha deposits. As the A-2 Carbonate is completely encased above and below by evaporites, there can be little doubt that its hydrocarbons are indigenous. Thus, the A-1 Unit is the only reasonable source rock for the gas and oil now contained in the Guelph reefs and in the A-1 Unit itself.

In addition to the specific stratigraphic relationships which favor the A-1 as a source bed, it is evident that the A-1 Unit possesses several general attributes characteristic of potential source rocks for hydrocarbon:

- 1) Abundance of organic matter: Lithofacies 1 and 2, which volumetrically constitute the greater part of the unit, have abundant carbonaceous material of algal origin. Chemical analyses were made to determine total organic carbon content. First, carbonate carbon was removed by dissolution in concentrated HCl. Second, the organic carbon content of the insoluble residue was determined by combustion. In a few samples analysis was made of the content of chloroform soluble hydrocarbons in the range $C_{15}-C_{37}$. Extraction of hydrocarbons from the ground core samples followed procedures developed by B.M. Van der Weide (unpublished reports of the Société Nationale des Petroles d'Aquitaine). All the analyses were performed by the Geochemical Laboratory of the Institute for Petroleum Research and Geophysics, Israel, results of which are presented in Table 4-5 and summarized in Table 4-6.

The average organic carbon content of ancient non-reservoir carbonate rocks ranges between 0.27 - 0.24 percent (Hunt, 1967, Table 8; Gehman, 1962). The average hydrocarbon content of

Lithofacies	Sample (well/depth)	Insoluble residue (%)	%Organic Carbon in insoluble residue	Organic Carbon (%)	Chloroform Soluble Hydrocarbons	
					(%)	% of total organic carbon
(1) Micro- laminated mudstone (Limestone) (Lst. Oil stain) (Limestone)	3/2500.5	9.1	5.4	0.5	0.160	30
	5/2479	6.0	7.2	0.4		
	24/2452A	5.6	5.9	0.3		
	24/2452B	9.2	5.3	0.4		
	27/2430	3.4	4.9	0.2	0.022	10
	28/2381	10.0	5.3	0.5	0.055	10
	40/2434	5.4	6.2	0.3		
	41/2465A	4.9	6.0	0.3	0.030	10
	41/2465B	4.7	5.8	0.3		
	44/2547	18.3	5.0	0.9		
	48/2480	10.6	5.8	0.6	0.088	15
	48/2513	3.8	6.2	0.2		
	17/2430				0.041	
	48/2480.5				0.097	
(2) Planar Stromatolite (Spropellic) (Oil stained) (Oil stained)	4/2460A	2.9	7.8	0.2		
	4/2460B	1.9	8.5	0.2		
	5/2489	8.9	7.5	0.6	0.207	35
	5/2510A	7.1	9.4	0.6		
	5/2510B	6.2	8.7	0.5		
	5/2479	37.8	7.0	2.5		
	17/2521A	4.1	17.5	0.7	0.267	38
	17/2521B	4.1	13.5	0.5		
	44/2550.5	19.5	5.3	1.0	0.105	10
	10/2537				0.495	
	40/2522				0.202	
(6) Nodular anhydrite (A-1 Anhy. Nodular mosaic) (Nod. Anhy.)	5/2520	73.5	0.7	0.5	0.016	3
	10/2553	66.0	0.6	0.4		
	10/2559	54.4	0.5	0.2	0.016	8
	10/2564	32.0	0.5	0.2	0.013	7
	41/2573	70.0	0.8	0.6	0.010	2
	41/2576				0.005	
	17/2528	11.7	5.4	0.4		

Table 4-5. Insoluble residue, Organic Carbon and Hydrocarbon content in selected samples from the A-I Unit.

	Lithofacies 1	Lithofacies 2	Lithofacies 6 and A-1 Anhy
Organic Carbon Content (%)			
Range	0.2 - 0.9	0.2 - 2.5	0.2 - 0.6
Mean	0.4	0.64	0.4
Hydrocarbon Content(%)			
Range	0.02 - 0.16	0.202 - 0.495	0.013 - 0.016
Mean			
(%) of total organic carbon	10% - 30%	10% - 38%	2% - 8%
Insoluble residue (%)			
Range	3.4 - 18.3	1.9 - 37.8	11.7 - 73.5
Mean	7.6	10.2	51.2
Organic carbon in insoluble residue (%)			
Range	4.9 - 7.2	5.3 - 17.5	0.5 - 5.4
Mean	5.7	9.4	1.4

Table 4-6. Summary of organic chemistry analysis of the Salina A-1 Unit

ancient carbonate rocks is 0.034 percent (Hunt, 1967). The corresponding values are significantly higher for the lithofacies of the A-1 Unit, except for the hydrocarbon content of the nodular anhydrite samples.

Thus, chemical data on organic hydrocarbons indicate that the A-1 Unit contains sufficient organic carbon to support the idea that it was a principal source bed for the oil and gas in the Salina-Niagaran reservoirs.

- 2) Reducing conditions: Prevalence of reducing conditions is a necessary requisite for the preservation of the organic precursors to petroleum hydrocarbons. The presence of authigenic pyrite in all the lithofacies of the unit indicates that reducing conditions prevailed in the sediments soon after their deposition (see discussion in page 157). . . . Abundant authigenic pyrite may indicate abundant organic matter, as organic matter acts as a source for the iron and for energy needed for anaerobic sulfate-reducing bacteria which produce the pyrite.

- 3) Compaction: Migration of fluids from source bed to reservoir is an essential stage in the accumulation of hydrocarbon. As the A-1 Unit compacted by overburden loading, connate fluids were expelled and forced to migrate laterally into more porous beds. Lateral rather than vertical migration was dictated by the confining evaporitic beds. Evidence for the compaction is both petrographic and structural, in the form of stylolites, which are formed by pressure solution (see reviews in Bathurst, 1971, Chapter 11; Park and Schot, 1968a, 1968b; Trurnit, 1968), steep dip of strata, shearing and flattening of the anhydrite nodules adjacent to the rigid reef boundary.

It is apparently a common misconception that shallow marine-marginal tidal flats are in general oxidizing environments and thus unfavorable for the preservation of organic matter (see for example Ingerson, 1968). While this is generally true of the sediment water interface, it is not necessarily true for the conditions below this interface.

One of the most characteristic and consistent attributes of the Recent tidal flat sediments in the Big Pine Key area, Florida (Fowler *et al.*, 1970; Gill, 1971) is their strongly reducing nature throughout the full range of environments from shallow subtidal, to intertidal and supratidal flats, marshes and ponds. In all, reducing conditions dominate the interstitial material just centimeters below the sediment surface, characterized by generation of hydrogen sulfide and in the formation of "incipient peat" which accumulates in shallow karstic depressions and in discontinuous patchy layers only inches below the sediments surface. The sediments are extremely rich in organic matter provided by algal mats, black and red mangroves and by marine grasses. All available oxygen is consumed rapidly by decaying organic matter and aeration is retarded by the high rate of deposition and by the fine grained nature of the sediment. Prevalence of reducing conditions in similar Recent settings has been reported from the Ojo de Liebre Lagoon, Baja California (Phelger, 1969, p.828), Shark Bay (Davies, 1970, p. 186), the Trucial Coast (Illing *et al.*, 1965, p. 107) and the subtidal zone of Andros Island (Shinn *et al.*, 1969). Sever and Parker (1970) recently reported on the hydrocarbons found in present day algal mats.

Thus, marginal marine carbonate sediments including those of sabkhas, appear to be reasonable source beds for hydrocarbons.

In emphasizing the hydrocarbon generation potential of the A-1 Carbonate, one should not overlook the same potential of evaporites (Woolnough, 1937; see in particular extended discussion in Peterson and Hite, 1969, p. 904-906). Therefore, the A-1 and A-2 Evaporites might have contributed hydrocarbons to the reefs as well. An analogous stipulation, of the Muskog evaporites being

the source beds for the Rainbow reefs reservoirs, has been proposed by Ilrishevich (1966, p. 252; see page 203). However, the A-1 Carbonate appears to have been the principal source bed for the hydrocarbons in the Belle River Mills reef, because of its most favorable stratigraphic and structural position, organic geochemical properties, and environmental attributes.

Sabkha Cycles

The Sabkha complex, as portrayed diagrammatically in Fig. 4-9, is a characteristic suite of contemporaneous, laterally juxtaposed facies. As sea level fluctuates with time, isofacies belts migrate laterally. Discounting any abnormal breaks in sedimentation, the laterally juxtaposed facies will be found superimposed on each other ("Walter's law of superposition of facies", see translated quotation in Textoris and Carozzi, 1966, p. 1386). Depending on the pattern of sea level oscillations, different vertical sequences or facies succession will be formed. In the A-1 Unit as in Recent sabkhas, the prevailing facies in the subtidal, intertidal and supratidal zones are lithofacies 1, 2 and 6 respectively. A regressive phase, during which the supratidal zone progrades basinward at the expense of previously submerged facies, will be marked by a 1-2-6 sequence. The sequences mentioned above define a complete, uninterrupted "Sabkha cycle of sedimentation and early diagenesis" (Shearman, 1966, p. B211; Wood and Wolfe, 1969, Fig. 4; Fuller and Porter, 1969a, p.912). Truncated or partial cycles caused by sudden changes in sea level also are possible. For example, a 1-6 sequence, where the supratidal sediments directly overlie subtidal, denotes sudden emergence, whereas a 1-2-1 succession marks a truncated cycle which was submerged before achieving supratidal conditions.

It is important to stress that the supratidal facies in part is not a depositional record, but rather the product of emergence and diagenesis of a previously deposited facies. Recognizing the original, pre-diagenetic, facies is essential to the correct evaluation. A 1-6 sequence is indeed truncated only if the nodular anhydrite replaces facies 1, if it replaces facies 2, the sequence

is comparable to a complete 1-2-6 cycle. As the emplacement of anhydrite often destroys the identifying features of the original facies, a precise evaluation is not always possible.

The applicability of the concept of Sabkha cycles to the geological evolution of the A-1 Unit is shown in the following section.

Paleogeography and Geologic Evolution of the Salina A-1 (and A-O) Unit

Commencing with the Middle Silurian, the Michigan basin became an intracratonic depression bound by positive tectonic elements around its entire circumference. During the Niagaran, the definition and isolation of the basin was accentuated by the construction of a continuous belt of carbonate banks around the basin's margins (Fig. 1-1). The banks constituted the physical barrier which separated the Michigan basin from the open ocean and controlled its hydrographic regime all through the Cayugan (Alling and Briggs, 1961). The continuous growth construction of reefs during the Niagaran marks a gradual rise in sea level and the maintenance of a delicate balance between reef growth and subsidence. However, there were signs of reversal in this trend already near the end of the Niagaran. Upward growth of the organic reef stage terminated when the reef reached the supratidal island stage. The succeeding BRM Stromatolite Member reflects both periodic exposure as well as a rise in salinity. All of these are early manifestations of basin barring and the commencement of evaporitic conditions, both of which were the dominant factors which controlled the geology and paleogeography of the Michigan basin during the entire Upper Silurian.

The deposition of the Salina Group in Michigan is one of the classical examples in the geological literature of the evolution of evaporite basins. The new information afforded by the environmental interpretation of the A-1 Unit adds some insight which pertains only to the deposition of the basal part of the Salina on the margins of the basin. While these observations have only limited bearing on the question of evaporite deposition as a whole, they nevertheless

lead to paleogeographic conclusions which are at variance with previous interpretations.

The beginning of the Cayugan is marked by a drastic drop in sea level. In the Belle River Mills reef area, which is representative of the pinnacle reef shelf belt in general, (Figs. 1-2), sea level dropped by at least 430 feet. The entire reef structure was subaerially exposed down to the level of the inter-reef BRM Conglomerate Member. Therefore, the entire circular shelf zone on the periphery of the basin from the pinnacle reefs shoreward was exposed as well. This is in disagreement with the recent evaluation by Matthews (1970) who postulated that the entire basin was submerged at least throughout the completion of the A-2 Evaporite cycle. The drastic drop in sea level appears more likely to be the result of water loss by net evaporation ("evaporative drawdown", Maiklem, 1971) rather than the result of tectonic emergence or global eustatic changes, in view of the fact that the basal part of the Salina consists of 475 feet of rock salt (the A-1 Salt). The Cayugan basin inherited its configuration and bathymetry from the preceeding Niagaran stage. It is reasonable to assume that at least during the early Salina A-1 phase the central part of the basin was deeper relative to its flanks. Therefore, regardless of the exposure of the basin's flanks, it is still quite plausible that the A-1 chloride and potash facies (Anderson and Egleson, 1970; Matthews, 1970), were deposited in the deeper waters of the basin center. It appears that the A-1 salts filled up the deeper part of the basin and that towards the end of the A-2 Evaporite phase, the major depth differences within the basin were eliminated, since the A-2 Anhydrite laps entirely over the barrier reef in places.

Regionally, the A-1 Carbonate is thickest in the pinnacle reef belt (135 feet in the BRM area) and thinner towards the basin's center (Ells, 1967, p. 10) being 70 feet in Sanilac County (Felber, 1964, p.27). According to Jodry (1969) and Felber (1964), the lithology of the A-1 in the interior of the basin all is limestone, whereas Ells (1967) mentions that it consists of either limestone, dolomite or both. Beyond these general descriptions, no detailed

petrographic data are available. The type section of the Salina A-1 Unit (Fig. 2-12) represents the superposition of four sabkha cycles (Fig. 4-10). The A-O Carbonate and the A-1 Anhydrite constitute the first cycle. The nodular anhydrite beds of the "Rabbit Ears" terminate the succeeding second and third cycles and the A-2 Evaporite terminates the fourth cycle. The cyclical nature of the deposition is related to oscillatory fluctuations superimposed on a gradually rising sea level.

Relative to the first three cycles, which were of short duration and show frequent lateral and vertical facies variations, the fourth cycle is remarkably uniform. It consists of a continuous section of Lithofacies 1, with only minor intercalations of lithofacies 4 and 5. It indicates persistence of subtidal conditions during the later half of the A-1 Carbonate deposition. Following the third cycle, as greater parts of the basin became filled up with sediments, the basin's strand line was further shifted to the east and south as it continually transgressed the previously exposed higher margins of the basin.

During the deposition of the sabkha cycles, the reefs in the pinnacle reef belt constituted islands in a very shallow sea. Around each of these islands, a sabkha profile, like the one shown diagrammatically in Fig. 4-9, developed in a radial fashion. The sea between the islands was very shallow. At no time during the deposition of the unit did water depth exceed just a few meters. Relatively minor sea level drops exposed large areas around the reef islands and in subtidal shoals to supratidal conditions. These were resubmerged during subsequent sea level rises.

The aerial distribution of facies (see pp. 168-173) suggests an irregular bottom topography around the reefs, the immediate surroundings being consistently shallower. The intertidal belt was frequently interrupted by channels, whereas in the subtidal zone away from the reefs, local shoaling likely produced local facies variations.

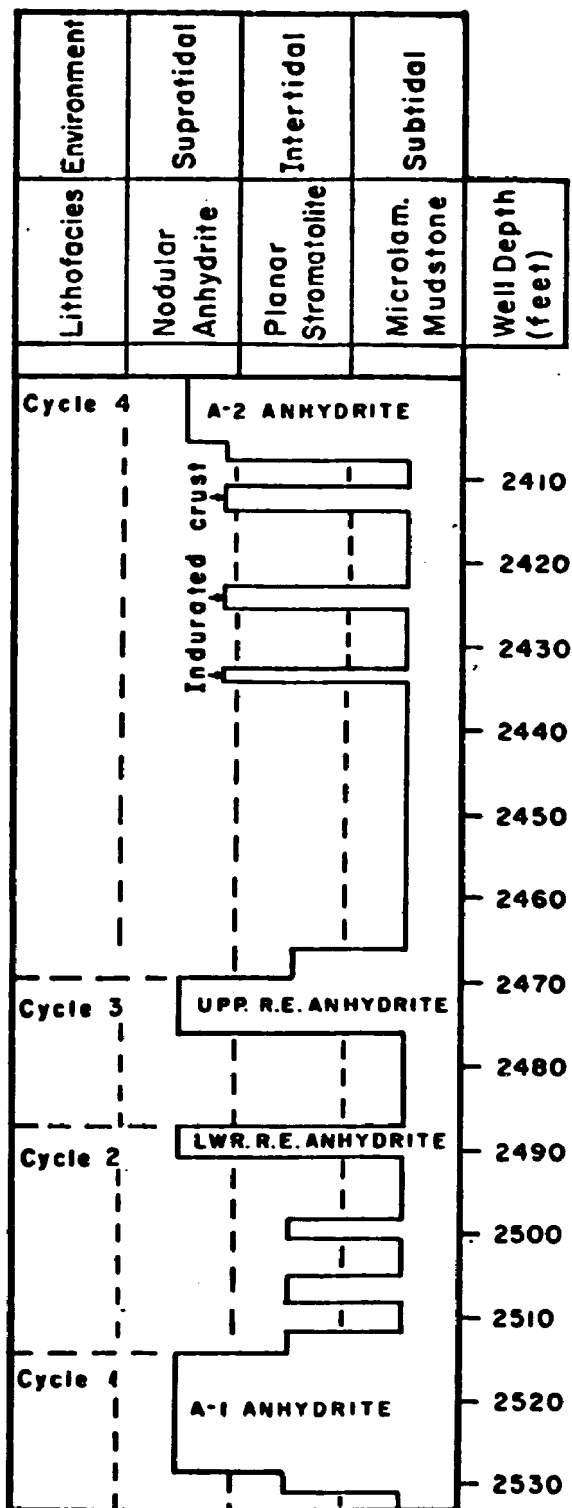


Fig.4-10: Sabkha cycles in the Salina A-1 Unit
(Type section well no. 3)

The Greenfield Dolomite in Northwestern Ohio shows many attributes typical of sabkha deposits. Ulteig (1964, p. 19) mentions the presence of anhydrite layers within the unit in the subsurface. Kahle described outcrops of the formation which he interpreted as representing supratidal deposits (Kahle, 1968; Kahle and Floyd, 1968). In the Maumee Stone Company quarry near Maumee, Ohio, a stromatolite mound, covered by thinly laminated dolomite beds, is well exposed. The entire exposure has been correlated to the Greenfield Dolomite by several authors (Alling and Briggs, 1961, p. 539; Textoris and Carozzi, 1966; Summerson, 1963b, p. 44) and consequently interpreted as evidence for the contemporaneity of reef-growth and salt deposition. Since the stromatolite mound is remarkably similar to the BRM Stromatolite Member, probably the mound represents the stromatolite member of the Guelph, and only the upper "evaporitic dolosiltite unit" of Textoris and Carozzi (1966, Fig. 3) belongs to the Greenfield Dolomite.

The Greenfield Dolomite is usually correlated with both A-1 and the A-2 Carbonate units (Ulteig, 1964, Pl. 1). However, the geology of the pinnacle reefs shows that during deposition of the lower three sabkha cycles of the A-1 Carbonate, the northern flanks of the Findlay arch were sub-aerially exposed. Whether the fourth cycle left deposits this high on the basin margins is highly questionable. Therefore, the Greenfield Dolomite seems correlative only to the A-2 Carbonate, a possibility suggested by Ulteig (1964, p. 22, Pl. 1). Further support for this interpretation is afforded by the distribution of the A-2 Evaporite which overlaps the preceding A-1 Carbonate. The zero isopach at the outer edge of the A-2 Evaporite lies largely within the Niagaran barrier reefs in the Michigan basin (Briggs, 1968, Fig. 16).

The deposition of the A-2 Evaporite terminated the fourth sabkha cycle, as the A-1 Evaporite did the first cycle, with renewed extreme aridity. Rapid tectonic sinking continued, the central basin accommodating approximately 475 feet of salt (without potash) at the basin's center. The pinnacle reefs, still exposed during the early A-2 Evaporite stage, were eventually covered over

by the late A-2 Evaporites (Figs. 3-9 through 3-13; Fig. 6-2).

Erosion of the reef masses during exposure probably was not extensive. The reef mass became lithified through cementation, mineral stabilization and dolomitization. This minimized the effects of physical and chemical weathering. Secondly, the paleogeographic setting was one of isolated pinnacle islands in a shallow sea in an arid climate, thus, an effective fluvial erosion system could not develop. Thirdly, in terms of geologic time, the duration of the exposure period was probably very short. From published data on the rate of deposition of carbonates in comparable environments it appears that a rate of 0.5 mm per year is a very conservative estimate. Bathurst (1971, p.281), quoting Cloud's data for Bahamian carbonate muds (Cloud, 1962), arrived at an estimate of about 0.8 m/year. Fischer (1964), regarding algal laminations as annual accretions, quotes a rate of 1.2 mm/year for the laminites. Ginsburg *et al.*, (1954) give an estimate of 1.6-2.0 mm/year for algal laminated sediments in the Florida Keys and 6mm/year for storm deposits. Hurricane Donna deposited 5 cm of sediment in one day in Crane Key. However, the 8 feet of sediments on the Key took 4000 years to be deposited, yielding an overall average of only 0.6 mm/year for supratidal flats (Ball *et al.*, 1967). Gebelein (1969) found that couplets of algal/sediment laminae, about 1 mm thick, are forming in the subtidal of Bermuda at a rate of one per day, yielding the startling figure of 365mm per year.

Allowing for a compaction factor of 2, it can be assumed that the original thickness of the A-1 Unit was twice as much as it is presently, or on the order of 220 feet. At a rate of 0.5 mm/year, the A-1 Unit would require 132,000 years to be deposited. The rest of the off-reef section consists of the A-2 Evaporite, most of which is salt, for which a rate of deposition of 10mm/year is again a lowermost underestimate (Schmalz, 1969, p. 820). Assuming an original thickness of about 220 feet, the A-2 Evaporite would require an additional 6600 years to form.

Thus even with these conservative estimates, the entire exposure period might have lasted only 140,000 years. Based on data on the durability of Pleistocene reefs, which have been exposed for at least that length of time (personal observations on reefs in the Sharm el Sheikh area, Southern Sinai Peninsula and several examples of Pleistocene reefs in various areas (Bloom, 1970)), such a short period is insignificant as far as reef erosion is concerned even in areas where erosive forces are more effective.

ANCIENT ANALOGUES

DISCUSSION OF THE "EVAPORITE ENCASED REEFS" PROBLEM

It is of interest to compare the Belle River Mills "story" (in its broadest sense) with analogous situations for several reasons. Analogous situations, separated in time and space from the one analyzed here, afford additional perspective to evaluate the validity of the present interpretation. Analogous cases, particularly if similarly interpreted by other investigators, lend support to the present interpretation. Furthermore, in its broadest sense, the main problem with which the present study has been confronted is the resolution of the stratigraphic and sedimentological relationships between the organic reef and its enclosing evaporite deposits. This problem of "evaporite encased reefs" has been, and still is, a controversial and much debated subject. The conclusions arrived at here have immediate bearing on this problem and are therefore, particularly if corroborated and born out by other studies, of more than local interest. I wish to emphasize that my interpretation has evolved independently, and in essence, was in no way influenced by the examples cited below.¹

Situations analogous to the BRM case can be cited from two other widely separated geological provinces: The Pennsylvanian Paradox basin of the Four Corners area, U.S.A. and the Middle Devonian Upper Elk Point basin of western Canada. In the following discussion only the Rainbow reefs of Alberta, which provide the better analogy of the two, will be analyzed in detail. Pertinent descriptions of the Paradox basin example in which the reef-evaporite relationships have been explicitly discussed include the studies by Peterson (1966), Peterson and Hite (1969), Hite (1970), Gray (1967), Ellias (1963) and Choquette and Traut (1963), who discuss in particular the Ismay and Desert Creek zones in the upper part of the Middle Pennsylvanian Paradox Formation.

The Middle and Upper Devonian of Western Canada were most remarkable reef-building periods. At least three extensive reef growth phases are present. From

¹For the most part, the main conclusions of the present study were already formulated in writing in April 1969 (Gill, 1969). The corroborating interpretations of the Canadian Middle Devonian analogues appeared later.

bottom up these include the Middle Devonian reefs, which are the subject of the following discussion, the Middle to Upper Devonian Swan Hills reefs and the well known Upper Devonian Leduc reefs. Oil and gas production from these reefs made western Canada one of the most important oil-producing provinces in North America.²

The Rainbow Member reefs³, also known as the "Keg River reefs" (Alberta) or the "Winnepegosis reefs" (Saskatchewan), developed in the eastern and northern shelf areas of the very large Upper Elk Point basin, which extends southwest for a distance of about 1000 miles from the Presquile barrier reef in northwest Alberta, through Alberta and Saskatchewan to North Dakota (Fuller and Porter, 1969a, Figs. 7, 10; Bassett and Stout, 1967, Fig. 9).

The remarkable similarities between the Rainbow and the Niagaran reefs extend to the following aspects:

1. Reef evolution, facies and morphology - A most detailed description of the Rainbow reefs was published by Langton and Chin (1968). Like their Niagaran counterparts, the Rainbow reefs are mesa-like pinnacle reefs (see also Barss *et al.*, 1970, Fig. 8). The two are comparable in areal dimensions but the Rainbow reefs, attaining a height of 750-800 feet, are about twice as tall as the Niagaran reefs. The larger atoll-shaped reefs are apparently absent in Michigan. Steep reef flanks in the upper part of the profile (25 degrees in Rainbow, somewhat higher in Michigan) and moderate ones in the lower parts are found in both. In both cases, the facies present, their distribution pattern and the overall pinnacle shape came as a response to the rapidly subsiding substrate with which organic growth had to compete (McCamis and Griffith, 1968, p. 1915). Similarities in lithofacies are present between Langton and Chin's lithofacies 2, 3, 4, (6, 8, 9), 7, 13, 14, 5 and the correlative BRM lithofacies 1, 2 (Branching Bryozoa), 5, 4, 3(?), 7, 9 and 13. These extend to both constituents, ecology and position within the reef (compare, for example, Fig. 3-9 with Langton and Chin's Fig. 8). The vadose deposits of lithofacies 8 find their Devonian analogue in the

²Pertinent literature includes Bassett and Stout, 1967, for an overall review of the stratigraphy and the most outstanding reef studies by Fischbush, 1968, Leavitt, 1968, Murray, 1966, Jenik and Lerbeckmo, 1968 (Swan Hills) and Andrichuk, 1958, and Klován, 1964 (Leduc).

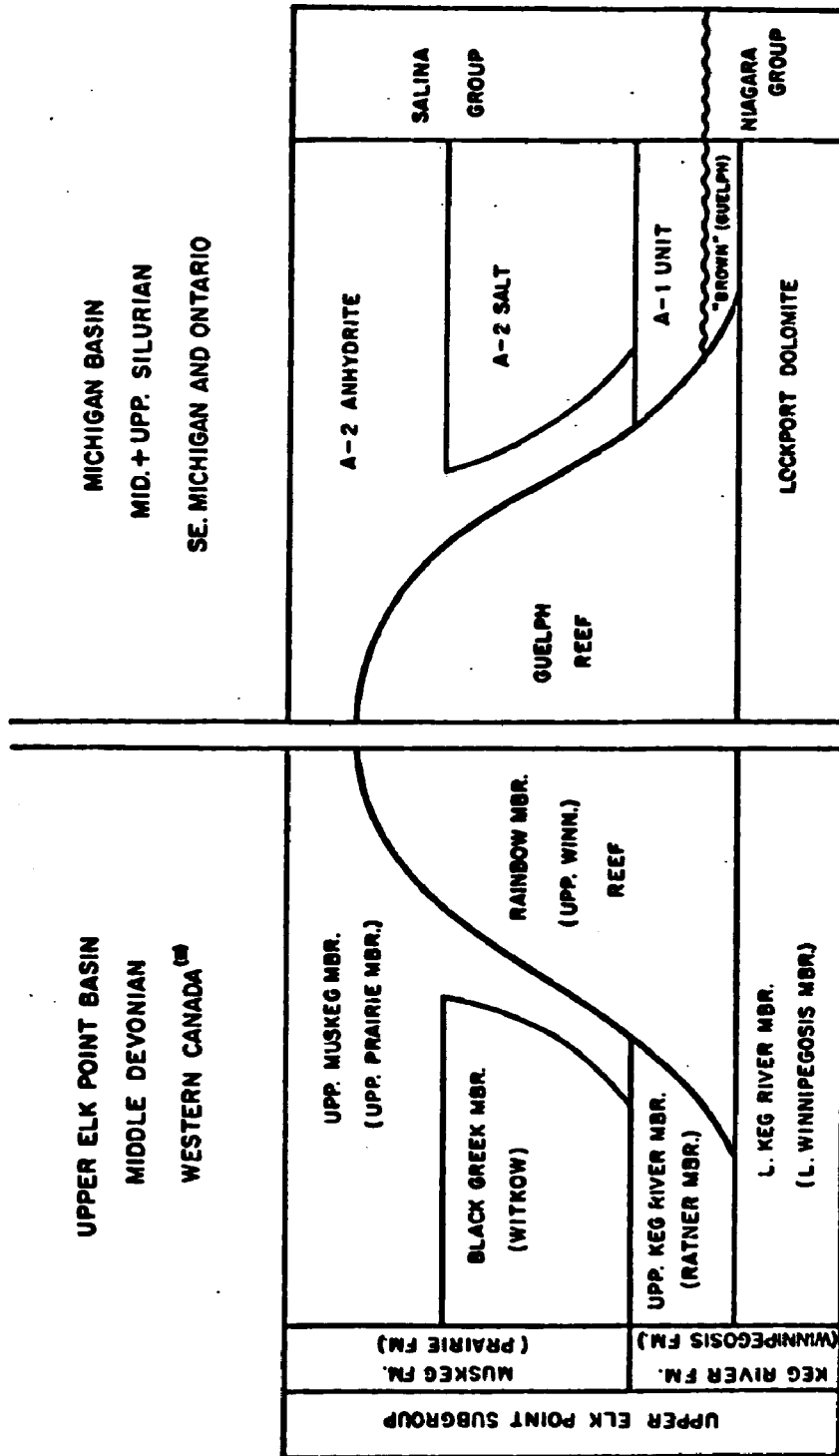
³Stratigraphic terminology after Hriskevich, 1966.

"pisolite cap" of the Winnipegosis reefs (Wardlaw and Reinson, 1971, Figs. 11, 12) and in an additional Keg River reef (Maiklem, 1971, Fig. 5). Both reefs have their foundations in crinoid mud mounds, develop into an organic reef stage in which stromatoporoïds and corals are the main framebuilders and terminate in shallow water, partly supratidal deposits.⁴ Thus, the overall reef building style, morphology, facies and lithofacies distribution pattern and reef evolution are essentially alike.

2. General stratigraphic framework - The remarkable similarities in the off reef succession of facies and in its relationship to the reefs is best appreciated with the aid of Figure 5-1. With the exception of the Zama area, the situation as shown is representative of the lower two formations of the Upper Elk Point subgroup throughout the basin. It is based on the following sources: Heriskevich (1966, Fig. 4 and 1967, Fig. 18); Langton and Chin (1968, Fig. 7, Rainbow Lake area); Wardlaw and Reinson (1971, Fig. 1, Central Sask.) and Fuller and Porter (1969a, Fig. 8); Klingspor (1969, Figs. 14, 16, Elk Point basin in general). The Zama Member, which directly overlies the reefs in the Zama area (McCamis and Griffith, 1968), but which elsewhere is separated from the reefs by anhydrites ("thrice anhydrite", Fuller and Porter, 1969a, Fig. 8), is not shown. It is apparently not present in the Rainbow subbasin (Barss et al. 1970, p. 30). The halite and potash salts, present in the Upper Prairie in Saskatchewan (Wardlaw and Reinson, 1971, Fig. 1) are also not shown. These minor simplifications are inconsequential and do not distort or bias the analogy in any way.

3. Off reef facies - The Upper Keg River Member in the Rainbow Lake and Zama

⁴With regard to the supratidal complex capping the reefs some elaboration is in order. Langton and Chin interpret their Laminite facies (no. 14) as a supratidal to intertidal deposit. In their sections this lithofacies appears in the upper part of the pinnacles and is very extensive in the central part of the atoll reefs. Fuller and Porter (1969a, p. 918 and 1969b, p. 187 and Fig. 5(2)) specifically mention the presence of a laminite on the top of the reefs, which they apparently regard as a part of the Winnipegosis reef proper. If I understand their presentation correctly, this unit, which is confined to reefs only, is in turn overlaid by an identical unit, but which extends laterally to the off reef area as well (stage 5, in Fuller and Porter, 1969a, Fig. 9. This later unit is apparently the Zama Member). If this is the case, the analogy to the BRM Stromatolite Member, which caps the Niagaran reefs, is strengthened. Klingspor (1969, p. 934) also recognizes the basic threefold zonation of the reefs and states that the upper zone consists of laminated algal deposits.



¹ Stratigraphic nomenclature after Hristovich 1966

In parenthesis — Sask. nomenclature after Wardlaw and Reinson 1971

**FIG. 5-1. STRATIGRAPHIC FRAMEWORK OF REEF/OFF REEF RELATIONSHIP,
MID. AND UPP. SILURIAN, MICHIGAN BASIN AND MID. DEVONIAN, WESTERN CANADA—
A DIAGRAMATIC COMPARISON (NOT TO SCALE)**

areas is interpreted as a relatively deep water facies, deposited in the off reef contemporaneously with reef growth (Langton and Chin, 1968, p. 111; McCamis and Griffith, 1968, pp. 1906-1907). It is thus quite different from the A-1 Unit in Michigan (but is analogous to the "Brown Niagaran" in inter-reef areas). However, over the rest of the basin, the first off-reef unit which floors the basin is distinctly and significantly different. This unit, the Ratner Member of Wardlaw and Reinson (1971, also known as the Upper Winnipegosis Member in Sask. and the Upper Keg River Member in Alberta (Klingspor, 1969)), with its nodular anhydrite and planar stromatolite dolomite "laminite" beds, is typical ancient sabkha deposit (Table 4-5). It is regarded as such by Shearman and Fuller (1969) and by Fuller and Porter (1969a, b) who convincingly elaborated on this matter. On the other hand, Klingspor, and Wardlaw and Reinson, regard the Ratner as a basinal, relatively deep water facies. The former's main objection rests in his belief in the "Layered solution model" (Sloss, 1969) as being the correct explanation to reef-evaporite juxtaposition. He also finds it hard to conceive that great thicknesses of salts and anhydrites were deposited in sabkhas. However, as far as I can see, this later objection should have nothing to do with the Ratner proper. Wardlaw and Reinson, although recognizing an exposure phase at the reef tops (the pisolite cap, *ibid.* p. 1779, which they regard, however, as a lateral equivalent of the Quill Lake and thus post Whitkow in age), and although regarding the Muskeg as post reef in age, still find it hard to accept the sabkha origin of the Ratner, primarily because the individual laminations are remarkably consistent over large areas and "continuity of individual millimeter laminations over a distance of miles is difficult to conceive in an intertidal, or even very shallow subtidal situation" (*ibid.* p. 1775, p. 1784). However, Fuller and Porter (1969a, p. 924) have already argued that the persistency of laminations can be attributed to the protective cover, afforded by the algal mats.

The similarities between the succeeding salts and anhydrites are obvious and do not require further elaboration.

4. Reef diagenesis - Information about diagenetic aspects appeared only in the studies by Langton and Chin (1968), McCamis and Griffith (1968) and Maiklem (1971). Consequently, it might be questionable whether a generalization about reefs in other

parts of the basin is justified. With this qualification, and in the absence of information to the contrary, it appears that the main diagenetic aspects of the Rainbow reefs can be summarized as follows:

a. The main source of porosity is secondary solution. Extensive leaching, both selective and non-selective, was reported by Langton and Chin. McCamis and Griffith mention lost circulation zones in cavernous sections (*ibid.* p. 1923).

b. Vug lining by carbonate material is extensive. Although not referred to as such by the authors, many of the facies illustrated contain stromatactis (e.g. Langton and Chin, 1969, Plates 2/10, 3/3, 3/4, 3/10, 3/9, the last one with multiple generations; McCamis and Griffith, 1968, Fig. 8). Furthermore, at least in some of the illustrations mentioned above, the cement is distinctly fibrous. Barss *et al.* (1970, p. 22) specifically mention the presence of *Stromatactis* (capitalized and italicized) in Upper Keg River crinoid banks. In the dolomitized reefs these cement crusts now consist of dolomite.

c. Cavity infilling by vadose internal sediment is mentioned by Maiklem (1971, Figs. 3, 4). Porosity plugging by anhydrite is described in all three studies referred to above.

d. Dolomitization of the reef rocks is apparently typical throughout the entire basin, and when present is pervasive (thus post-dating the vug lining and vug lining stages). However, some of the smaller pinnacles in the Rainbow Lake area are undolomitized. In view of the otherwise total dolomitization, the presence of limestone reefs is perplexing. Langton and Chin attribute the dolomitization, at least in part, to a more or less synsedimentary seepage refluxion by concentrated brine originating in the intertidal to supratidal laminite on the reef crest. The facies is absent in the smaller pinnacles and hence the lack of dolomitization. However, since they recognize a late diagenetic dolomitization phase as well, how did these reefs escape it? The Guelph reefs diagenetic model cannot account for this anomaly either, hence the adjective "perplexing" above.

5. Off reef salt solution - Near-reef salt solution is ubiquitous wherever the Black Creek salt is present. Salt solution is implied in practically all cross sections appearing in the articles cited above. As it is immediately apparent on seismic records (Heriskovich, 1970, Fig. 17), it is a major reef exploration aid. Due to the

observed draping of higher strata over reef flanks, most authors interpret it as a post Black Creek salt phenomenon, citing late Muskeg to, in some cases, post-Mississippian as the time interval during which salt solution processes were operative (Langton and Chin, 1968, p. 112; Klingspor, 1969, p. 934; Heriskevich, 1970, p. 2270; Robertson, 1969; Barss et al., 1970, pp. 44-45, McCamis and Griffith, 1968, pp. 1908-1909). Although none of these authors explicitly discusses the mechanism responsible for salt solution, most imply that it should be attributed to post-depositional compaction. Maiklem (1971, p. 498) is the only investigator who advocates a syndimentary timing for the dissolution of the Black Creek salts and who offers a specific mechanism to account for it. He attributes it to artesian flow of normal marine water through the reefs, in connection with the post Rainbow Member subaerial exposure period. It should be added that if the Rainbow reefs were ever completely plugged by evaporitic minerals, which is quite conceivable under the circumstances (but not contemplated by the Canadian investigators), this mechanism would account for their reopening.⁵

As far as the origin of the hydrocarbons in the reefs is concerned - Shearman and Fuller (1968, p. 513) draw attention to the source rock attributes of the Ratner Member whereas Hriskevich (1966, p. 252), in addition to contemplating an indigenous source, which would in itself be insufficient, considers the Muskeg as a likely source as well.

The interpretations of the Middle Devonian reef-evaporite juxtaposition situation can be classified into three groups:

a. Interpretations which advocate the contemporaneity of reefs and evaporites (whether subscribing to the density stratified model, or otherwise) and hence, at least by implication, accept the deep water origin of the Muskeg. Klingspor's arguments

⁵In this respect it is of interest to somewhat diverge and consider the following speculation: In the search for Rainbow analogues for the salt plugged reefs in Michigan, several possibilities exist: 1) The Rainbow reefs were never completely plugged. 2) Their reopening was more efficient and there are no plugged ones left. 3) Plugged reefs do exist further in the basin, in as yet unexplored areas or, alternatively, 4) Plugged reefs do exist but due to the lack of salt solution around them they are inconspicuous on seismic records and the Canadians have been spared the embarrassment and frustration of "discovering" them.

have been reviewed and debated under (3) above. Schmalz, in his paper on the deep water origin of evaporites (1969), cites the Elk Point basin as one of his examples (*ibid.* p. 819), but as he does not discuss any of the specific aspects outlined above at all, his analysis pertains only to the section above the Ratner Member. Sloss (1969), while developing his "evaporite deposition from layered solutions" model had the Rainbow example (as well as the Michigan and Paradox basins) in mind (*ibid.* p. 776, 779). Incidentally, despite his disclaimer as to the water depth implications of his model (*ibid.* p. 786), accepting his model inevitably implies that the Muskeg evaporites (and particularly the Ratner Member) were deposited at a water depth of several hundred feet.

b. Workers in the Rainbow-Zama area (Hriskevich, Langton, Chin, Barss, Copland, Richie, all of Banff Oil Ltd. and hence unanimous (?), but also McCamis and Griffith), who are not confronted with the interpretation of the Ratner Member which is apparently missing in this area, essentially agree that the Muskeg is younger than the Rainbow (Langton and Chin, 1968, pp. 111-112). Barss *et al.* (1970, p. 41) conclude that the supratidal complex at the top of the Rainbow reefs is contemporaneous with the evaporites at its base, whereas McCamis and Griffith (1968, p. 1915 and Figs. 20, 21) allow for a brief exposure of the very top parts of the reefs prior to the deposition of the Muskeg. Thus, all of these, by not explicitly deducing the full scale exposure of the reefs, concede (mostly implicitly but also explicitly - Barss *et al.*, 1970, p. 41) to a deep water origin of the Muskeg evaporites. Wardlaw and Reinson, specifically because they interpret the Ratner as a basinal facies ((3) above), subscribe to a similar interpretation.

c. A third interpretation, which in all essential respects fully accords with the one advanced for the Guelph reefs, might be assembled from the contributions of a number of investigators, each relating to a different aspect of the problem. These interpretations were apparently prompted by Shearman and Fuller's (1966) study of the Ratner, in which they demonstrated its close analogy to modern day sabkha deposits. Fuller and Porter (1969a, b) and Shearman (1970, and personal communication) continued by "exploiting" their finding and deduced the full consequences directly called for by this interpretation, namely, that the entire vertical extent of the reefs must have been sub-aerially exposed prior to the deposition of the Ratner Member. Fuller and Porter

(1969a, p. 918) further predict that evidence for exposure should be found in the reefs themselves. In my opinion, as shown earlier, the evidence was already provided by Langton and Chin's study. Maiklem (1971) provided additional evidence by documenting karstic breccias, vadose pisolites and internal sediments from a Rainbow Member reef. In fact, Maiklem, in developing his "evaporative drawdown" model, and in exploring its paleogeographic, hydrodynamic and diagenetic consequences, effectively presents a model, which except for its utilization of marine water rather than fresh water, is uncannily identical to the Guelph one. Finally, J. W. Keith, a geologist with King Resources Co. Calgary, Alberta, following the public presentation of the BRM evolutionary and diagenetic model (Gill and Briggs, 1970), and based on his long experience with the Rainbow reefs, voiced full support for its applicability to the Middle Devonian reefs as well (written communication July 17, 1970).

The case histories analyzed above vary in some details but the similarities between them are without doubt too large to be fortuitous. If one model can account for all the situations described, its credibility is obviously strengthened. It appears that after verifying its applicability to the Elk Point basin, this is the case with the Guelph model.

The problem of "evaporite encased reefs" actually embodies two separate questions. One relates to the time-stratigraphic relationships between the reefs and their enclosing evaporites. In this respect, the BRM case is to some degree unique in that the BRM Conglomerate Member offers a clue which is usually unavailable elsewhere. The other relates to the overall paleogeographic framework which controlled the situation.

In the absence of absolute dates or paleontological and unequivocal stratigraphic means to resolve the time-stratigraphic problem, its solution must be derived from the same criteria which aid in the resolution of the paleogeographic aspects. These have been shown to be sedimentological-paleoenvironmental and diagenetic considerations.

The main and essential aspects of the Guelph model can be summarized as follows: While the reefs grew to their full height, very little relatively deep water carbonate sedimentation took place in inter-reef areas; Reef growth kept pace with, and eventually surpassed, a rapidly subsiding substrate which was the controlling factor in

determining the external pinnacle geometry and the internal facies distribution of the reefs; reef growth was terminated upon surfacing and subsequent emergence; due to "evaporative drawdown", the full vertical extent of the reefs was subsequently exposed; at least the basal part of the off reef sequence consists of sabkha deposits whereas the rest of the enclosing evaporites might be of sabkha or other origin; the diagenesis of the reef rocks and salt solution in the enclosing strata are a consequence of the exposure and the related ensuing hydrodynamic regime which prevailed in the basin as a result of it. Common aspects pertaining to the post burial history include mainly reopening of plugged pores and entrapment of hydrocarbons derived from the enclosing sabkha, and possibly evaporite, source beds.

This model does not embody any conclusive implications which pertain to the more general questions of evaporite, particularly halite and bittern salts, deposition. Several authors carried the analogy further in suggesting that the latter could be the products of a sabkha-type environment as well (Fuller and Porter, 1969b, p. 189; Shearman, 1970). Although this interpretation is very appealing, I do not regard it as an infallible derivative of the model. The mode of deposition of the succeeding evaporite body is not uniquely linked to this model in any way. That is, the Guelph model can accommodate a number of different evaporite deposition models (Briggs, 1958, Sloss, 1969 or even Schmalz, 1969, to cite but a few, each with proper but minor amendment and/or modifications) and be consistent with the facts and situation it was designed to account for. In fact, once the lack of contemporaneity between reefs proper and evaporites proper is accepted as a premise, and the reefs and organogenic carbonate banks regarded simply as part of the basin's substrate or "basement" with respect to the succeeding evaporites, many evaporite deposition models would be improved and much more acceptable.

Thus, the main contribution of the Guelph model to the problem of evaporite enclosed reefs lies in the fact that it corrects an apparently deeply entrenched misconception, namely that the multistage (i. e. Guelph model), in contrast to the synchronous, interpretation does imply the deep water origin of the enclosing evaporites (Sloss, 1969, p. 776). "Multistage" is not synonymous with "deep water evaporites" nor is it synonymous with "shallow water evaporites" ("evaporites" meaning halite and potash salts, not nodular anhydrites and interbedded planar stromatolites).

Quite to the contrary, if anything, the opposite might be regarded as a more natural consequence of each of the models in question.

SUMMARY AND CONCLUSIONS

In accordance with common usage in Ontario and northern Ohio, the Middle Silurian Niagara Group is subdivided in the subsurface of southeastern Michigan into three formal formations in ascending order: the Clinton Formation, the Lockport Dolomite and the Guelph Formation (Fig. 2-1). The Guelph Formation overlies the Lockport Dolomite conformably. An unconformity separates it from the overlying Salina Group. In the pinnacle reef belt, the Guelph is fully developed only within the reefs. It is proposed to recognize the Guelph Formation as the formal lithostratigraphic name for these reefal buildups of Niagaran age. In the BRM reef the formation attains a maximum thickness of 431 feet and it has been divided into four members, corresponding to distinct growth stage in the evolutionary history of the reef (Figs. 2-9 to 2-11). In inter-reef areas, the Guelph consists of crinoid biomicrite termed the "Brown Niagaran" and is very much reduced in thickness.

The Niagaran Guelph reefs exemplify evaporite-encased reefs, remarkably similar in all essential aspects to analogous reef complexes known from the Pennsylvanian of the Paradox basin and the Middle Devonian of the Upper Elk Point basin. Resolution of the stratigraphic problems involving the reef-evaporite relationships is contingent upon the sedimentological, paleoenvironmental and diagenetic attributes and their interpretation. Corroborating evidence disputes the concept of evaporite deposition being synchronous with reef growth. On the contrary, the evaporite-encased reefs are a product of diachronous, multistage geological evolution entailing three distinct stages of reef growth, interrupted and followed by reef exposure and subsequent onlap and complete burial by carbonate rocks, anhydrite and salt, at least the lower part of which is of sabkha origin. The geologic model developed for the Guelph reefs hinges on the recognition that the superjacent off reef carbonates and anhydrites are sabkha deposits and that the diagenetic fabrics of the reef are the product of vadose and concurrent sabkha related processes.

The evolutionary history of the reef can be summarized as follows (Fig. 6-1):

1. Pre-reef - The Lockport Dolomite, a slightly argillaceous crinoid biomicrite, which constitutes the reef's substrate, was deposited in a broad carbonate shelf

platform below wave base.

2. Biohermal Stage (BRM Skeletal Wackestone Member) - The biohermal mound developed to maximal height of 245 feet in relatively quiet water, below wave base, as is indicated by the dominance of carbonate mud and the prevailing organic community. Three main lithofacies (with six different lithotypes) comprise the mound: Skeletal biomicrite (consisting of crinoid biomicrite, crinoid-bryozoa biomicrite, the latter in places with scattered tabular stromatoporoids and tabulate and rugose corals); Bioherm core ("Knoll", with a tabular stromatoporoids and corals lithotype and branching bryozoa lithotype) and Skeletal-lithoclast wackestone. Mound construction is attributed to the mud trapping capacity of the intricate crinoid root system and the dense population of bryozoans, with the additional constructional support afforded by tabular stromatoporoids and tabulate corals, forming more rigid knolls and biostromal horizons. The distribution of facies, more robust branching bryozoans and the Skeletal-lithoclast facies being more prevalent in the upper part, marks the gradual elevation of the mound into a zone of wave-induced water turbulence. Biohermal buildup exceeded the rate of subsidence and upon reaching wave base level, a new environmental and ecological regime, more suitable for the development of an organic reef was established.

3. Organic reef stage (BRM Boundstone Member) - A true wave resistant organic reef flourished during the next growth stage. It is superimposed and centered about the biohermal (+100 feet thickness) contour. Competing with continuous subsidence, it was confined to vertical growth and added an average of 150 feet of steeply inclined slopes to the structure. The basic mode of reef growth and the resultant facies distribution pattern was a rather simple central reef core surrounded by an apron of a fore-reef detritus. The sites of active reef proliferation shifted spatially with time and the reef raised itself up over its own debris. Four main lithofacies (with 10 more specific rock-types) have been differentiated. The main framebuilding organisms were massive, encrusting and digitate stromatoporoids, to a minor extent tabulate corals and possibly algae (Reef-core facies). Organisms in growth position comprise only about a third of the Reef-core facies, its bulk consisting of fragmented stromatoporoid debris, further attesting to the turbulent conditions in which active

reef growth took place. In between and within more rigid reef-core zones, protected pools were formed in which more delicate species of brachiopods, crinoids, bryozoa and small cup corals found shelter (Reef dwellers facies). Reef-core zones are intimately interbedded and flanked by a facies consisting of coarse stromatoporoid and coral debris which form an apron around the entire reef's circumference (Reef detritus facies). Further down the slopes of the structure, a reef-rubble conglomerate accumulated in small fans (BRM Conglomerate Member, lower part). The reef is steeper on the west and north flanks, possibly indicating that prevailing winds came from the Northwest. The structure gradually elevated itself into shallower water. Towards the end of this growth stage shallow lagoons formed throughout the crestal area. Laminated and massive pelletal and burrowed mudstones, with occasional ostracods, fenestral fabrics and algal laminations were deposited in them (Lagoonal facies). The reefal buildup, now rising to about 350 feet above the contemporary sea floor, eventually reached the water surface at which stage active reef growth was terminated.

4. Short episode of subaerial exposure - The laminated calcite, vadose pisolites, pisolitic caliche and vadose veins and breccias of Lithofacies 8 (Subaerial and vadose deposits facies) testify that following the termination of reef growth, the uppermost part of the structure emerged above the water and was exposed to subaerial weathering. This exposure episode was apparently short-lived and its diagenetic effects were confined only to the upper 30 to 50 feet of the BRM Boundstone Member.

5. Supratidal Island stage (BRM Stromatolite Member) - During the final stage of its evolutionary history, the structure constituted an island in the late Niagaran sea which was subjected to minor sea level fluctuations, resulting in alternating supratidal, intertidal and shallow subtidal deposits. In marked contrast to the massive nature of the two lower members, this member is well stratified. Due to a superficial resemblance in radioactive logs, the member has erroneously been correlated with the A-1 Carbonate. The BRM Stromatolite Member consists of four lithofacies. Intertidal planar and closely spaced LLH stromatolite is the predominant facies. The shallow subtidal deposits of the Burrowed mudstone and the Pelletal wackestone facies, mark a short inundation in the middle part of the member, during which the

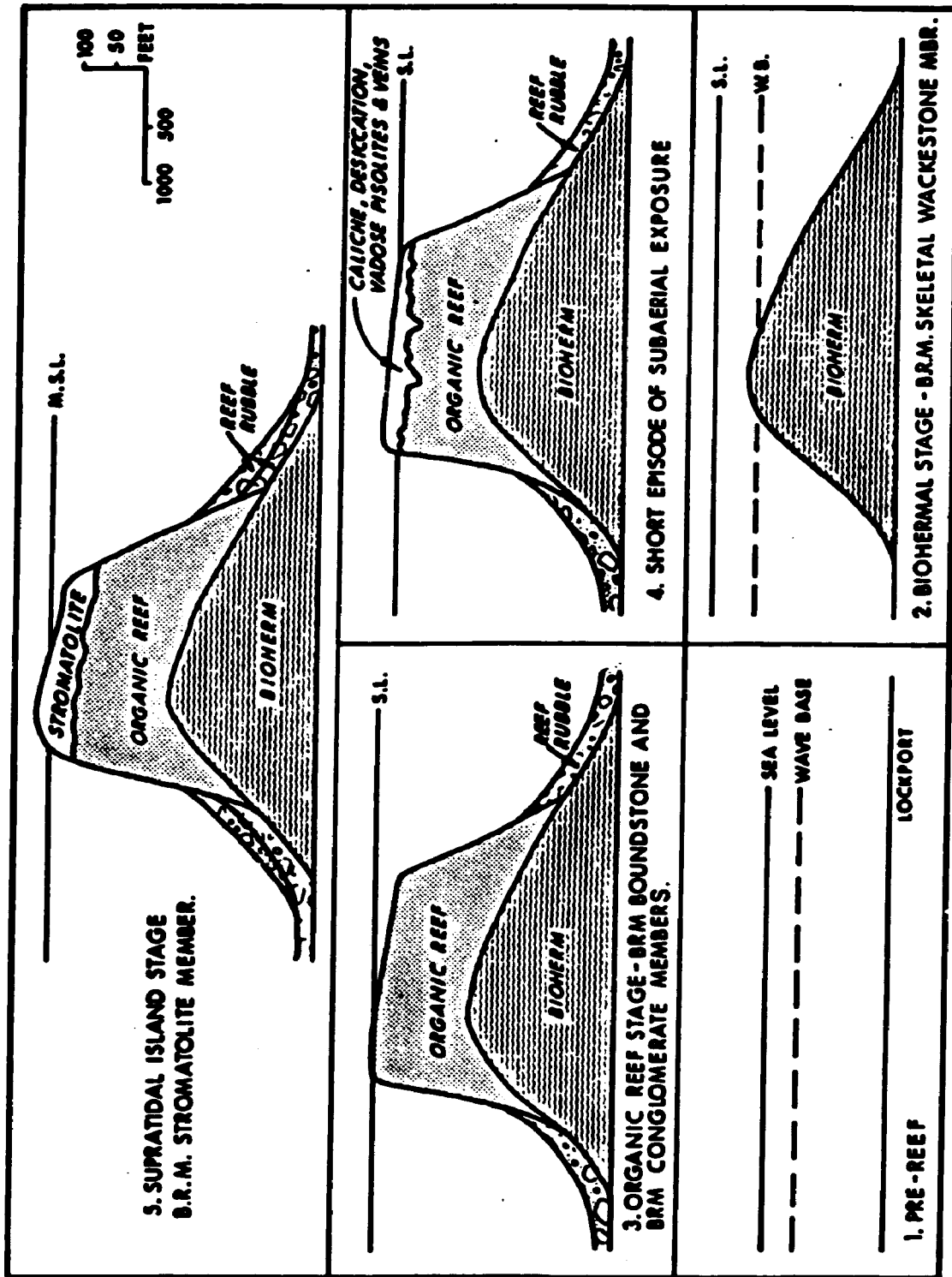


Fig. 6-1: EVOLUTION OF B.R.M. REEF DURING GUELPH FORMATION (LATE MIDDLE SILURIAN) TIME

island was submerged. The Flat pebble conglomerate facies indicates early induration and subaerial desiccation. It was formed during periods of receding sea level, while the island was subaerially exposed. The storms, which relocated pebbles on the reef's crest, transported substantial amounts of stromatolite debris to the off-reef periphery. This rubble constitutes the upper part of the BRM Conglomerate Member. As it underlies the overlapping Salina A-1 Unit, it provides an unequivocal stratigraphic evidence for dating the entire Salina Group as post Guelph reef in age.

The BRM Stromatolite Member attains a maximal thickness of 75 feet. It is truncated at its top. At the end of Guelph time, the highest point on the reef's crest stood at least 430 feet above the surrounding sea floor.

The occurrence of early diagenetic anhydrite and the absence of indigenous fauna indicate a rise in water salinity. These were early manifestations of the barring of the basin and the commencement of evaporitic conditions, both of which were the dominant factors which controlled the geology and paleogeography of the Michigan basin throughout the succeeding Upper Silurian period. The deposition of the Guelph Formation terminated as a result of intensive evaporation, which at the beginning of the Cayugan, had lowered the water level drastically and exposed the entire reef structure to the air.

Sedimentation and diagenetic alterations during the lower Salina Group time and subsequent post-burial changes leading to hydrocarbon entrapment are shown diagrammatically in Fig. 6-2 and summarized in the following paragraphs.

6. Subaerial exposure stage - The entire reef mass became subaerially exposed at the beginning of the Cayugan. Reef exposure was continuous during the time interval represented by the deposition of the A-0 Carbonate, A-1 Anhydrite, A-1 Carbonate and probably the lower part of the A-2 Evaporite as well, estimated to have lasted only approximately 140,000 years. Corroborating evidence for the exposure period is stratigraphic - the A-0 Carbonate post-dates the Guelph Formation; paleoenvironmental - the lower Salina units are sabkha deposits and diagenetic - the karstic diagenesis, dolomitization and void filling by evaporite minerals in the reef.

The major diagenetic fabrics which now dominate the reef rocks are attributed to this exposure period and to the concurrent sabkhaic processes which operated during

the deposition of the superjacent Salina A-1 Unit.

The reef rocks were further lithified and consolidated through carbonate mineral stabilization and cementation. Karstic dissolution and reprecipitation operated under vadose conditions. A complex cavernous network of interconnected cavities and vugs was formed. Much of the dissolved carbonate was reprecipitated in the form of cavity rimming fibrous cement linings. Often several concentrically disposed successive generations of vug lining are present. Vugs and passageways were further occluded by the internal deposition of vadose sediments, set into suspension by dissolution and sorted during its percolation through the network. It consists of homogeneous reddish and greenish clay-sized carbonate particles and is enriched in oxidized insoluble residue components. "Stromatactis s. str." is among the more prevalent diagenetic fabrics present. It is considered to be a geometric end member of the fabric described above ("stromatactis s. l."). It is therefore proposed to recognize stromatactis as a diagenetic fabric, diagnostic of ancient karst in carbonate rocks.

7. Salina A-1 Unit sabkha cycles - The A-1 Unit, comprising the A-0 Carbonate, A-1 Anhydrite and A-1 Carbonate (Fig. 2-12), consists of six lithofacies, representing three depositional environments: Faintly microlaminated mudstone with carbonaceous films and algal mat chips; Pelletal wackestone (Shallow subtidal); Planar stromatolite with limnoid fenestrae, interlaminae desiccation cracks, and curled and overturned mat sheets (intertidal); Nodular anhydrite, with enterolithic structures and a felted internal texture (the A-1 Anhydrite displaying a multitude of additional interrelated fabrics); Indurated crusts (supratidal) and Intraformational breccia and flat pebble conglomerates (supratidal to subtidal). All carbonate facies, with very limited local exception, consists of dolomicrite, are completely devoid of skeletal remains, contain early diagenetic anhydrite and authigenic framboidal pyrite and are extensively stylolitized. The unit was deposited in a sabkha ~~and~~ of environments and represents the superposition of three sabkha cycles (Figs. 4-9, 4-10). As the enclosing lower Salina units accumulated around the reef, its exposed part was gradually reduced until it was eventually completely buried by the upper part of the A-2 Evaporite.

Concentrated Mg-enriched brines, formed in the supratidal flats, were responsible for the penecontemporaneous dolomitization of the A-1 carbonates. The sabkhas,

in direct lateral contact with the reefs, furnished an abundant supply of brine to dolomitize the reef rocks as well. This source was available and active during the entire exposure period (Fig. 6-2, stages 7 and 8). As sediments accumulated around the reef an equivalent level of reef rocks became saturated with brine and dolomitized. It is conceivable that brines rose by capillary forces within the reef to dolomitize rocks above the intake level as well. The pervasive and indiscriminant dolomitization of the reef was probably most intensive during the deposition of the A-1 and "Rabbit Ears" anhydrites and the A-2 Evaporite in the off-reef areas.

8. Salina A-2 Evaporite - The A-2 Evaporite was not investigated petrographically and consequently it was not established whether it was deposited in a sabkha environment, in which case reef exposure continued into this stage as well, or in deeper water which might have submerged the reef. The first alternative is, however, more plausible. Towards the end of A-2 Evaporite time, the reef became completely enclosed and effectively sealed by evaporite deposits.

Although pore plugging by evaporite mineral precipitation could have taken place concurrently with dolomitization all through the exposure period, it was probably most effective during the deposition of the A-2 Salt. During this interval the reef was in direct lateral contact with solutions from which halite was precipitating in the inter-reef areas. This dense and heavy brine must have saturated the entire reef mass by lateral and downward migration. Therefore, possibly the entire accessible void space in all the pinnacle reefs in the area, was completely plugged by evaporitic minerals at this stage.

The stratigraphic relationship between the A-2 Salt and the BRM reef is not clearly understood. In many other reefs in the pinnacle reef belt of southeastern Michigan and Ontario, the salt passes laterally into anhydrite in the immediate proximity of reefs¹ (Adams, 1965, Fig. 1; Mantek (unpublished report on the Lenox reef); Kiddoo, 1962, Figs. 4, 6; Grieve, 1955, Fig. 7; Koepke and Sanford, 1966, Fig. 26;

¹It should be noticed that reference is here made strictly to the relationships as they exist in the lower part of the A-2 Evaporite around the reef's flanks. The upper part of the A-2 Evaporite consists uniformly of anhydrite, over reef's crests and in off-reef areas as well.

Hewitt, 1962). Inasmuch as the A-2 Salt extends all over the reef belt (Briggs, 1968, Fig. 16), this interpretation implies a halo of A-2 Anhydrite replacing salt around the Guelph pinnacle reefs. Such anhydrite halos could result from either synsedimentary dilution or from post-depositional salt solution. Synsedimentary dilution of the brine otherwise uniformly depositing halite around the reefs could be due to a fresh water lens contained in the top of the reefs. Post-sedimentary salt solution could be the result of relatively fresh ground water circulating within the reefs. Both alternatives are best accounted for as consequences of the reef exposure and, in fact, would be difficult to explain otherwise.

The entrapment of gas in the BRM reef was contingent upon several post-burial changes involving reopening of plugged pores, maturation of hydrocarbons in the source beds and their migration into the reefs.

9. Reopening of plugged pores - The petrographic evidence suggests that the reefs owe their present porosity to a second dissolution phase which postdated the diagenetic events so far discussed. Since its porosity must have been acquired prior to hydrocarbon entrapment, an event subsequent to which no significant diagenetic changes could have occurred, the last diagenesis prevailing in the reefs involved fresh water flushing.

That this process did not operate uniformly on all the Guelph reefs is evident from the present distribution of productive and nonproductive reefs in the area (Fig. 1-4), oil and gas entrapment being largely dependent upon re-solution of the pore filling minerals. From the basin circumference inward, three roughly concentric arcuate zones delineate reefs in which the voids have been extensively reopened (outermost), partly reopened (middle) and essentially unopened (innermost).

The following hydrodynamic scheme, shown diagrammatically in Fig. 6-3, accounts for the regional pattern by fresh water flushing. The reefs were completely sealed by the Salina evaporites. Fluids could enter the reefs only through their base in the Lockport Dolomite, a confined aquifer for ground water originating in rainfall along the more elevated Algonquin (Ontario) and Findlay (northern Ohio) arches in which the Lockport was subaerially exposed. Outflow was somewhere in the opposite end of the basin to the west, where the Lockport was outcropping subaerially

or submarinely, at a lower absolute elevation. The regional piezometric surface of the Lockport was above the crest of the reefs. Water flowing within the Lockport will attempt to saturate the entire accessible porosity up to the piezometric surface. Outside of the Lockport itself, accessible porosity existed only in the Guelph reefs. Therefore, water flowing in the Lockport was forced to enter the reefs as well. Closer to the intake areas the water was still fresh. This water entered the reefs and dissolved the salts contained in them, thereby reopening a substantial part of the plugged pore space. The heavier brine thus generated sank gravitationally into the Lockport and flowed "downstream" within it. As more salts were dissolved the water in the Lockport further away from the basin's rim became more concentrated. The dissolution potential of the aquifer was gradually decreasing basinward until, eventually, a zone was reached beyond which waters were too concentrated to affect any further salt solution within the reefs. It is quite possible that this zone actually retreated upstream with time. When this critical concentration was reached the situation in the reefs was frozen. Along the middle arcuate belt, the reefs remained partly plugged (probably, and this is subject to confirmation, in their upper parts) whereas further inward, the reefs remained totally plugged.

The question now arises whether it can be shown that such a hydrodynamic system could have been maintained for a long enough time period to be effective. This question can be rephrased as follows: When, following the A-2 Evaporite, was the Lockport subaerially exposed on the tectonic arches rimming the basin along its southeastern end? Apparently, the only time interval during which the arches might have not been exposed was in the early Middle Devonian during the deposition of the Lucas Formation of the Detroit River Group (Briggs, written communication, July 28, 1971). Thus, for about 30 million years following the Niagaran and another 350 million years following the Devonian, the Lockport on the arches could have served as an intake area for fresh water. It is, therefore, conceivable that the reopening of the reef void space, where it did occur, was accomplished already prior to the Middle Devonian and, in any case, not later than about late Mississippian. Each of these can serve as an upper time limit prior to which entrapment of hydrocarbons could have occurred.

The fresh water circulating within the reefs could have been responsible for the dissolution of the A-2 Salt in the immediate proximity of the reefs. Subsequent differential compaction induced local closures in higher strata directly above the reefs. Post-depositional salt solution might have enhanced the draping of the higher strata over the reef flanks. If the absence of salt near the reefs is due entirely to post-depositional solution (and not, at least in part, to synsedimentary dilution, as argued earlier), and provided that the dissolution was dependent only on the influx of fresh water from the reefs (and not, in some unspecified manner, on the compactional processes themselves), then the "anhydrite halos" should not be found in the salt plugged reefs.

The present isotopic composition of formation waters in Michigan, which indicates that practically all formations were flushed by pre-Pleistocene fresh water (Clayton *et al.*, 1966; Graff *et al.*, 1965a, b) lend further support to the hydrodynamic model proposed in this study.

10. Maturation of hydrocarbons in the A-1 Carbonate and their migration into the reef - The A-1 Carbonate is rich in organic matter of algal origin and its authigenic pyrite indicates the prevalence of reducing conditions in the formation soon after its deposition. Its organic carbon and hydrocarbon content is significantly higher than the average for non-reservoir carbonate (see page 184) . This, together with additional circumstantial stratigraphic considerations, leads to the conclusion that the A-1 Carbonate is the most conceivable source rock for the oil and gas now contained in the Guelph reefs and that ancient sabkha deposits in general are potential source beds for hydrocarbons.

The overburden pressure to which the A-1 Carbonate was already subjected at the time of the deposition of the Middle Devonian Detroit River Group was about 1500 feet in the BRM area and at least twice as much in the basin's center. This overburden, the resultant temperature and the elapsed time were probably more than adequate as far as the maturation and migration of hydrocarbons in the A-1 Carbonate source beds is concerned. In the case of the Niagaran reefs, the limiting factor to the entrapment of hydrocarbons within them was most probably the timing of their reopening and not the availability of hydrocarbons. Therefore, lateral migration of hydrocarbons from

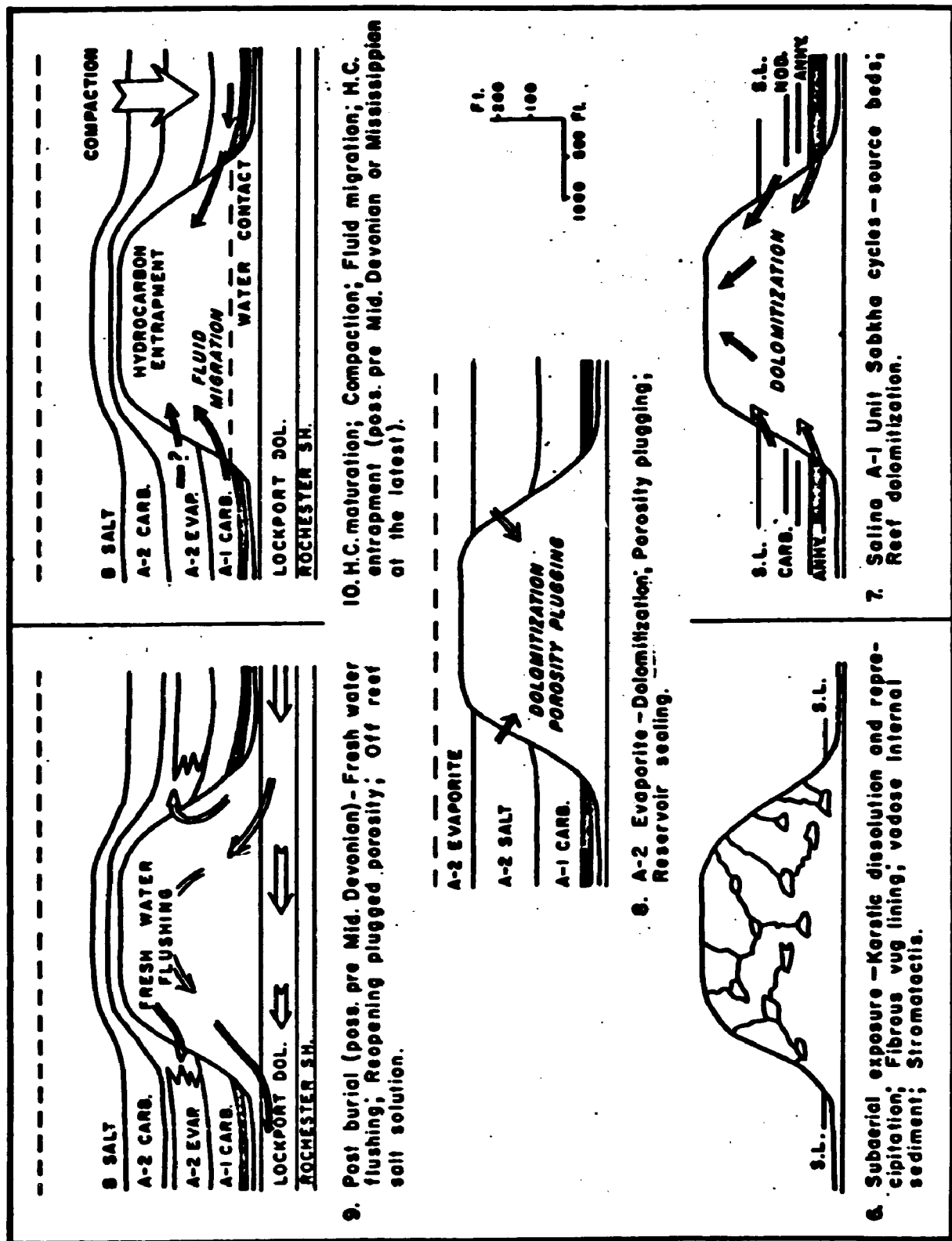


Fig. 6-2: Sedimentation and diagenetic alterations during lower Salina Gr., post burial diagenesis and H.C. entrapment.

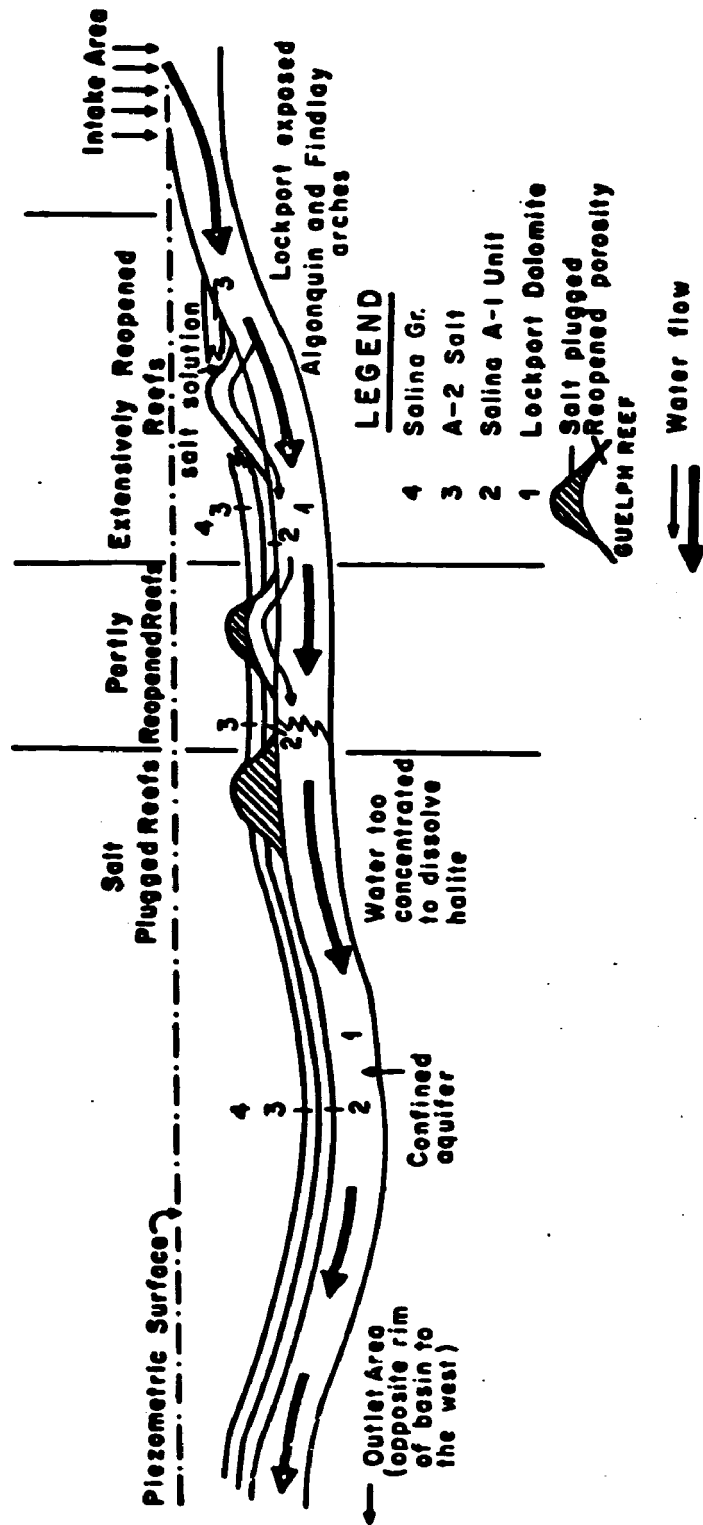


Fig. 6-3: Fresh water flushing and reef porosity reopening during Upper Silurian—Lower and Middle Devonian.
(Schematic hydrodynamic model)

the A-1 Carbonate into the reefs could have started as soon as the reefs were ready to accept them. That the A-1 Carbonate underwent severe compaction during which most of its contained fluids must have been expelled, is indicated by the ubiquitous presence of stylolites in it. In fact, due to its compaction, the A-1 Carbonate became impervious and thereby an effective seal in itself.

Thus, the Belle River Mills Reef, as well as the rest of the productive Niagaran Guelph reefs, constitute classic examples of stratigraphic trap oil and gas fields, resulting from an ideal temporal and spatial source-reservoir-seal relationships to form a commercial accumulation of hydrocarbons.

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APPENDIX

PLATES

(1 - 16)

All carbonate rock specimens are dolomite

Scale on rock slabs is 2 cm long

(32/2499) designates location: well no. 32 at depth 2499 feet

Transition from Reef substrate to biohermal stage

1. Dark gray argillaceous mudstone with abundant stylolites. Rare crinoid fragments, lower part of bioherm, transition zone from the underlying Lockport Dolomite (32/2499).
2. Sedimentary boudinage in lower part of bioherm in highly argillaceous crinoidal wackestone arenite (4/2521).

Biohermal stage - BRM Wackestone Member

Lithofacies 1 - Biomicrite

3. Dark gray Crinoid wackestone arenite. Well sorted mud supported crinoid fragments, 1-2 mm in size, constitute up to about 40% of the rock (42/2475).
4. Light (left slab; 19/2547) to dark (right slab, 19/2488) gray crinoid wackestone rudite. Poorly sorted crinoid fragments, ranging in size from 0.5 to 3 cm., constitute about 30% of the rock. The skeletal grains do not show any preferential stratigraphic orientation and are scattered randomly in a massive, dense carbonate mud. The darker areas on the right slab (greenish dark gray in the original sample) represent higher concentrations of disseminated argillaceous material.
5. Gray crinoid-bryozoa wackestone arenite and rudite. Elongated well preserved delicate feather-like forms of bryozoa, which disintegrate and form small rounded grains, and crinoid fragments are the main skeletal constituents. Small Halysites corals are present in subordinate amounts (right center, 19/2535).
6. Same as no. 3. Rudimentary bedding planes, marked by concentrations of argillaceous material can be discerned in the lower half of the sample. Grain supported crinoid packstone arenite is locally present in irregular patches (upper right) and along "bedding planes" (center, 42/2475).
7. Same as no. 5. Note Halysites coral (at lower right center, 19/2476).
8. Framebuilders in Biomicrite lithofacies. Favosites Sp. (tabular colonial coral) and small rugose cup coral (lower left) in crinoid-bryozoa wackestone (19/2521).
9. Geopetal infill of brachiopod shell in crinoid-bryozoa wackestone. The flat topped dark lower half is formed by internal sedimentation and entrapment of mud and a crinoid fragment present at the site and time of deposition. The void space left at the top half of the shell was infilled by fibrous cement at a late diagenetic stage. The round grains to the right of the brachiopod shell are basal sections in bryozoa fragments (19/2546).

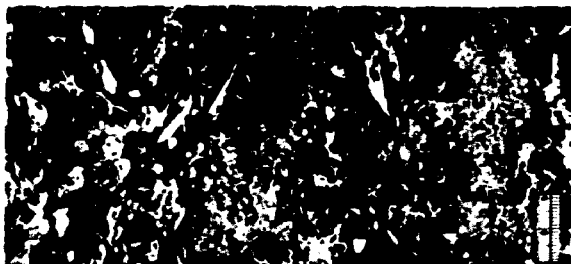
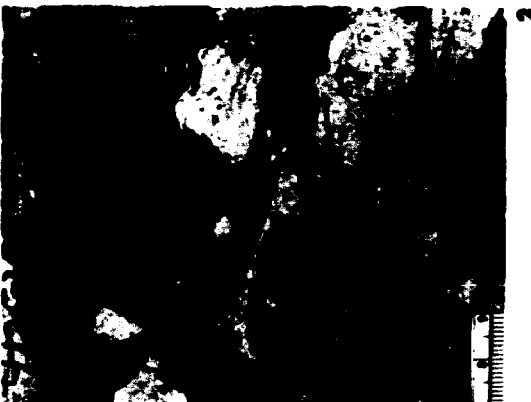


PLATE 2

Biohermal stage - BRM Skeletal Wackestone (continued)

Lithofacies 1 (continued) - Biomicrite with framebuilders

1. Large tabular colonial coral (*Arachnophyllum* Sp. ?) in orinoid wackestone (15/12489).
2. Tabular colonial coral (*Heliolites* Sp. ?, upper right) and platy, tabular stromatoporoids (thin white streaks at upper left and center) in orinoid-bryozoa wackestone (19/2507).

Lithofacies 2 - Bioherm Core Facies

3. Tabular stromatoporoid showing some remnants of internal structure - horizontal laminations with small vertical pillars between laminae (19/2466).
4. Tabular stromatoporoid Bioherm core facies. Very abundant, very thin (1-2 mm) platy tabular stromatoporoids in orinoid - bryozoa wackestone. Micritic mud and argillaceous material is entrapped and stabilized between plates (dark streak at center, 26/2480).
5. Tabular stromatoporoid bioherm core facies, stromatoporoid plates, ranging from a few millimeters up to about 3 cm in thickness and tabulate colonial corals (lower left) in orinoid-bryozoa wackestone (25/2496).
6. Same as no. 5 with large encrusting tabulate colonial coral. Late vug-filling calcite at center (19/2463).
7. Branching Bryozoa (bioherm core) Facies. Whole and broken bryozoa fragments, locally grain supported, constitute about 40% of the rock. The matrix is composed of a tan micritic mud, recrystallized into a very fine unbedded dolomite mosaic (4/2483).
8. Same as no. 7; mud supported (22/2453).

Lithofacies 3 - Skeletal-Lithoclast lithofacies

9. Skeletal lithoclast packstone rudite facies. Skeletal material of orinoid, bryozoa, brachiopod, and rare coral fragments and poorly sorted, mostly angular lithoclasts of a micritic rock (darker grains) constitute about 60% of the rock. The fragments are grain supported. Intergranular cement is a very fine unbedded dolomite mosaic with irregular patches of original (dolomitized) micrite (42/2425 at left, 42/2426 at right).
10. Enlarged portion of left slab in no. 9. Note the micritic envelopes, coating skeletal grains (orinoid at upper center and others, 42/2425).

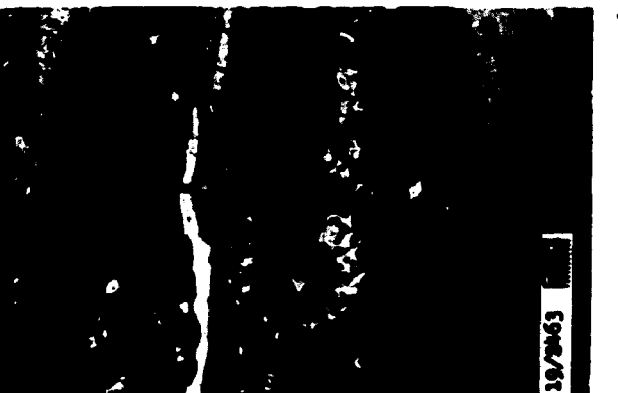
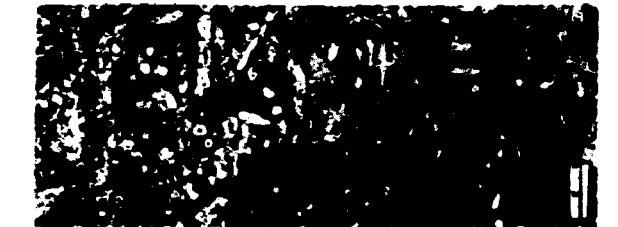
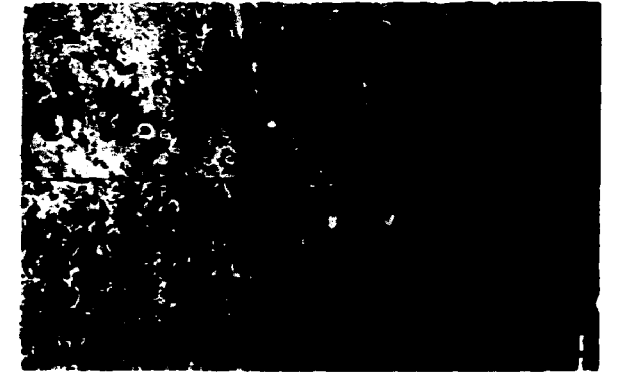
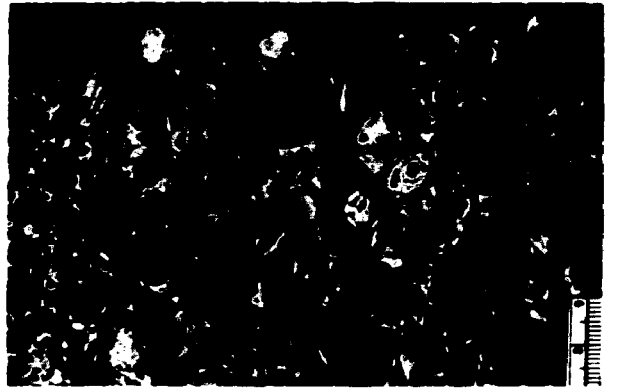


PLATE 3

Organic reef stage - BRM Boundstone MemberLithofacies 4 - Reef core faciesMassive stromatoporoids

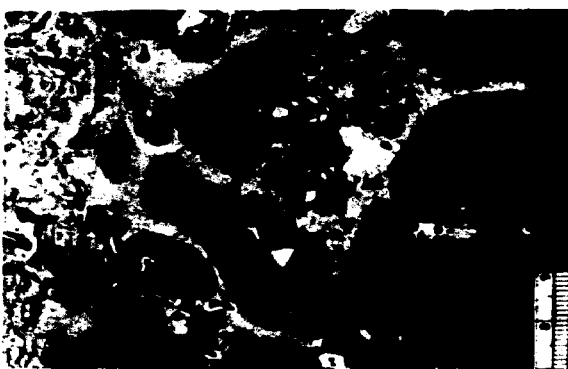
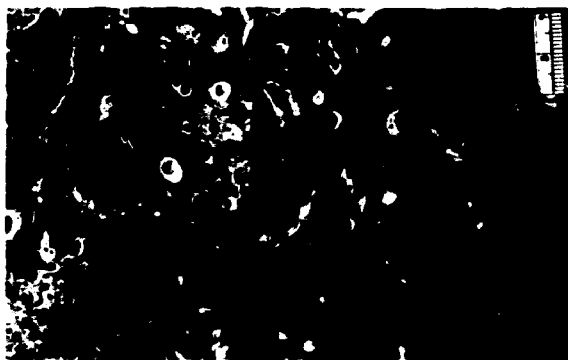
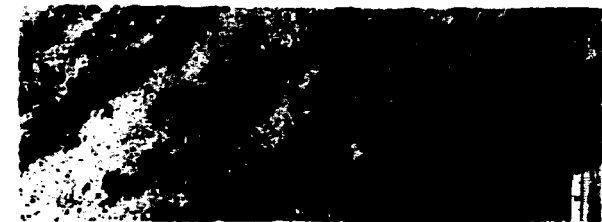
1. Typical texture of recrystallized massive stromatoporoid. Note horizontal growth lines (Photomicrograph, plane light, 25/2465).
2. Massive stromatoporoid. Part of a 2 feet reef-derived boulder embedded in the off-reef Saline a-1 Carbonate Unit (1/2498).
3. Massive stromatoporoid, probably part of a large hemispherical "head". Each laminae represents several organic latilaminae. Vugular porosity due to selective leaching of pillars along laminae. Some of the pinpoint micropores probably represent original organic chambers and galleries (22/2332).
4. Massive stromatoporoid, completely recrystallized into a brown homogeneous dolomite mass, showing only barely discernable traces of internal lamination (25/2269).
5. Part of a massive hemispherical stromatoporoid which is continuous vertically for 2 feet. Organic chambers, enlarged by preferential leaching along laminae, are saturated with heavy tar (22/2339).
6. Massive hemispherical stromatoporoid, surrounded by a matrix of skeletal debris of bryozoans, corals and stromatoporoids (18/2316).

Digitate stromatoporoids

7. Digitate stromatoporoid in growth position. Latilaminae and pillars discernable in portions of the specimen. Highly irregular base. Two finger-like vertical outgrowths, encrusted by bryozoa, protrude into the overlying skeletal debris (32/2363).
8. Horizontal section through a digitate stromatoporoid overturned and now lying in a vertical position (25/2315).

Encrusting stromatoporoids

9. Encrusting stromatoporoid (dark highly irregular patches throughout sample) binding and engulfing skeletal material of bryozoan, brachiopods and branching corals. Digitate stromatoporoid fragment at top of slab (11/2433).
10. Two colonies of encrusting stromatoporoids (bottom and center) in a matrix of mixed skeletal debris of bryozoans, branching and tabulate corals and fragmented digitate stromatoporoids (31/2262).



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PLATE 4

Organic reef stage - BRM Boundstone Member (continued)Lithofacies 4 (continued) - Reef Core faciesCoral framebuilders

1. Favositid coral in reef-core facies. Digitate stromatoporoid at top of slab and at center, beneath coral; encrusting tabulate coral at bottom of slab (31/2278).
2. Favosites colony, probably in growth position, in reef-core facies. Digitate stromatoporoid at bottom of slab. Matrix of broken skeletal material of stromatoporoids and bryozoans (42/2306)
3. Encrusting colonial coral in reef-core facies (31/2285).
4. Reef-core facies. Encrusting colonial coral (white) in association with encrusting stromatoporoids (dark irregular patches) binding and cementing coarse stromatoporoid debris (31/2333).

Algal (?) Boundstone

5. Small scale "stromatactis" in algal boundstone (19/2310).
6. Algal boundstone (?). Minute interlaced filamentous threads of algal (?) origin form continuous undulating laminae (31/2270).
7. Algal framebuilders in the organic reef stage. Laterally linked hemispheroid stromatolite at top. Undulating clusters of closely spaced very thin algal laminae binding and stabilizing a muddy sediment at center (39/2353).
8. Mottled (clotted) mudstone interpreted as representing algal boundstone (cryptalgal biolithite or thrombolite of Aitken, 1967). The clots consist of dense micrite and are darker in color. A fine grain-growth mosaic together with a coarser drusy infill of primary constructional interstices comprise the lighter colored matrix. The highly irregular clots seem to interlock and form a continuous spatial framework (38/2371).
9. "Thrombolite", as above. More regularly shaped clots, occasionally pelletal, with better defined boundaries. Some scattered mostly brachiopod, shell material (39/2423).
10. Algal boundstone (?). Framework consisting of small pillar-like grains, interwoven with minute horizontal filaments (31/2266.5).

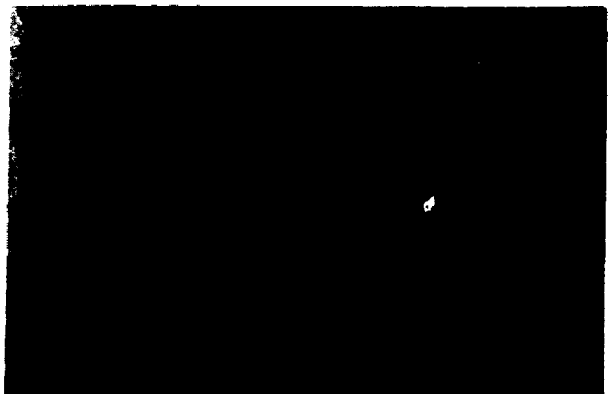
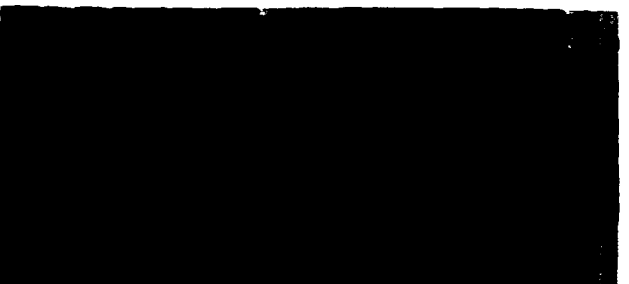
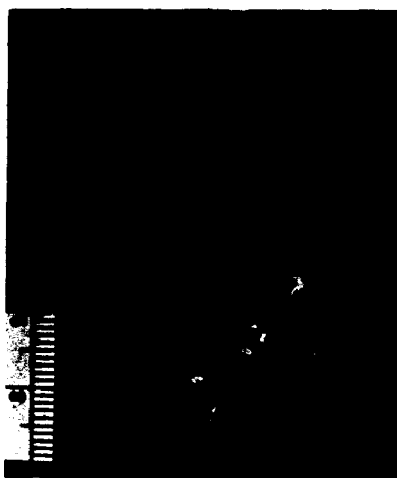
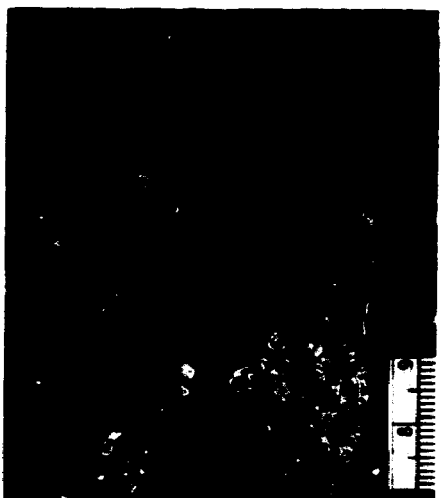


PLATE 5

Organic reef stage - BRM Boundstone Member (continued)

1. Algal boundstone (?). Thin laminae are probably algal encrustations. Upper left - an "algal-stromatoporoid consortium" (?), consisting of alternating algal and encrusting stromatoporoid laminae (22/2317).

Lithofacies 5 - Coarse skeletal wackestone (reef detritus) facies

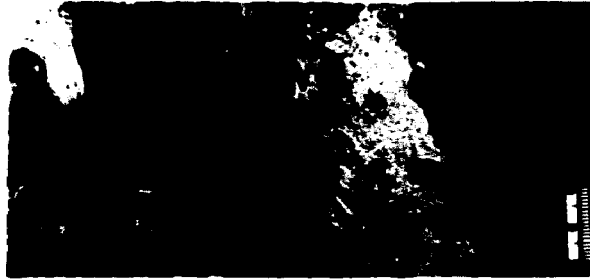
2. Coarse skeletal wackestone associated with reef-core facies. Large skeletal fragments of stromatoporoids (upper and lower right), corals (upper left and center) and bryozoa (center) scattered in a matrix consisting of fine skeletal debris (mostly broken stromatoporoids) and carbonate mud. Digitate stromatoporoid in growth position encrusted by bryozoa at lower left (31/2311).
- 3:4. Coarse skeletal wackestone. Very coarse (center) and fine stromatoporoid debris in a carbonate mud matrix. Some of the smaller irregular lighter colored specks are small scale stromatolites (3:31/2310; 4:31/2310).
5. Coarse skeletal wackestone, large fragments of favosites colonies in a carbonate mud matrix (42/2356).
6. Same as above. Note cross cutting calcite (now dolomite) vein at top (25/2244).
7. Coarse skeletal wackestone of digitate stromatoporoids, corals and bryozoa (31/2283).

Lithofacies 6 - Fine skeletal wackestone (Reef dwellers) facies

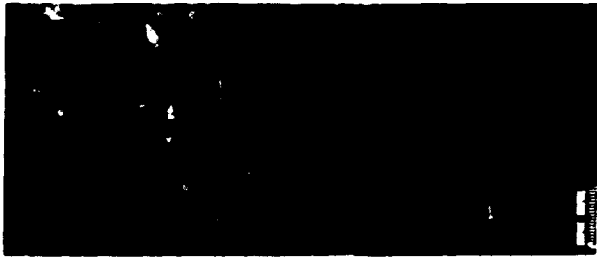
8. Fine skeletal wackestone, representing an assemblage of reef dwelling organisms, consisting of solitary rugose corals and bryozoans (branching and encrusting - thin white threads; 26/2362).
9. Fine skeletal wackestone, bryozoa, rugose and tabulate corals and crinoids. Locally grain supported (18/2269).
10. Fine skeletal-lithoclasts packstone arenite and fine rudite consisting of fragments of crinoids, bryozoans, brachiopods and small lithoclasts (11/2350).
11. Brachiopod packstone, grading into a wackestone in lower part, below stylolite (36/2400).



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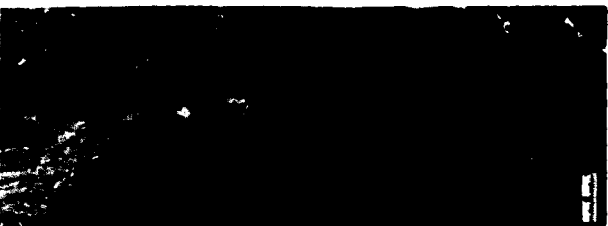
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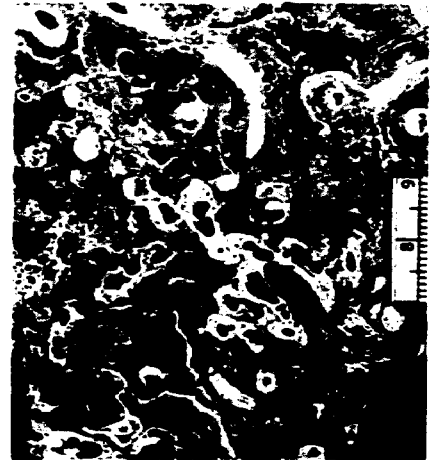
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PLATE 6

Organic reef stage - BRM Boundstone Member (continued)Lithofacies 7 - Lagoonal facies

1. Lagoonal facies. Laminated pelletal mud with ostracods. Birdseye (31/2268).
2. Same as above with mud-filled burrow (15/2287).
3. Lagoonal facies. Very finely laminated pelletal. Mud with fenestral (birdseye) fabric. Thin algal laminae at center (31/2244).
4. Lagoonal facies. Laminated pelletal mud with birdseye. Algal laminated structure (31/2245).
5. Lagoonal facies. Massive, mottled, burrowed pelletal mudstone with birdseye overlaid by finely laminated mudstone (15/2281).

Lithofacies 8 - Subaerial and vadose deposits

6. Finely laminated caliche, cross cut by calcite (now dolomite) vein (38/2277).
7. Vadose pisolite. Top view of closely fitted pisoliths. Anhydrite infilling vugs (white at top left, 31/2247).
8. Finely laminated, entrolithic caliche (38/2277).
9. Vadose pisoliths. Photomicrography, crossed nicols (19/2271D).
10. Large vadose pisolith "sandwiched" in between two laminar caliche horizons. A fragment of laminated caliche crust serves as a nucleus. It is truncated by an outer encircling suit of concentric laminae (31/2234).

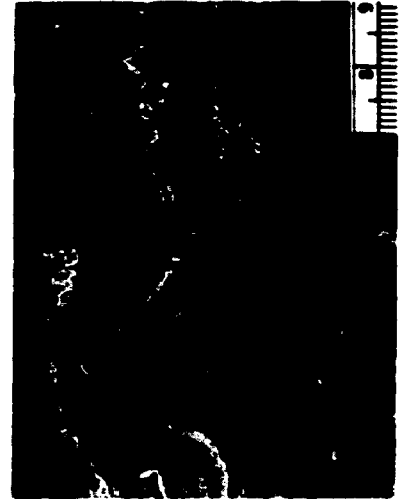
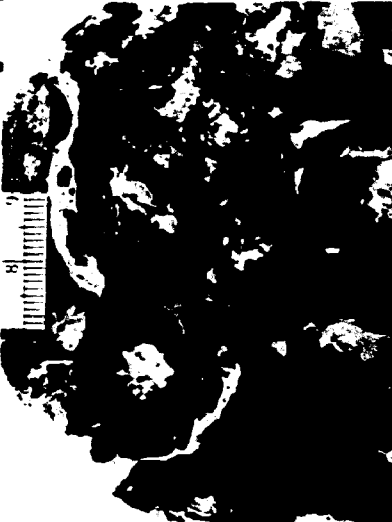
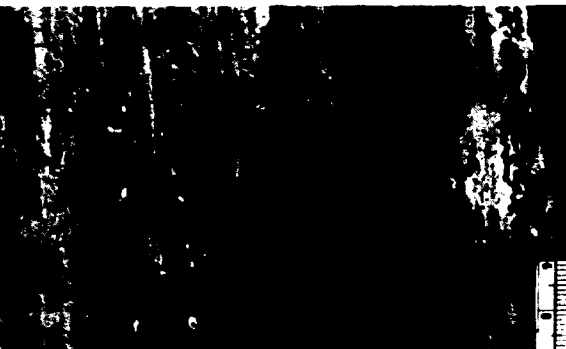


PLATE 7

Organic reef stage - BRM Boundstone Member (continued)Lithofacies 8 - Subaerial and vadose deposits (continued)

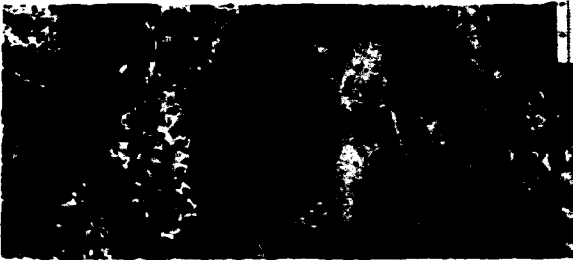
1. **Pisolithic caliche (32/2269).**
2. **Pisolithic caliche, coating wall of an open crack. Broken chunks of laminated caliche form part of the debris infilling the crack (31/2236).**
3. **Sinuuous solution crack infilled with lithoclasts and sparry cement. Caliche layers coat the irregular protrusion at center (31/2233).**
4. **Carbonate vein cross cutting fenestral laminated pelletal mud of the lagoonal facies (31/2240).**
5. **Pisolithic caliche. Detail of part (upper center) of no. 11. Photomicrograph, plane light (26/2349D).**
6. **Infilled crack cross cutting algal boundstone. Infilling consists of unsorted debris of lithoclasts and pebble size fragments of caliche crusts (39/2290).**
- 7-11. **Pisolithic caliche. Negative prints of thin sections (7:26/2349E; 8:26/2349D; 9:31/2236; 10:31/2236A; 11:26/2349D).**
12. **Thin section of botryoidal cave wall lining with incipient stalactites, sub-recent cave, Wadi Ara, Israel. Compare with "pisolithic caliche" (Plane light).**



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PLATE 8

Supratidal Island stage - BRM Stromatolite MemberLithofacies 9 - Algal stromatolite

1. Closely spaced, laterally linked small hemispheroid algal stromatolite (15/2252).
2. Same as above. Note the delicateness and the high degree of conformity in laminae (31/2230).
3. Undulating, small LLH stromatolite at bottom; flat pebble conglomerate horizon at center; two stromatolite heads at top (18/2228).
4. LLH stromatolite interbedded with laminated, fenestral, pelletal packstone arenite (18/2211).
5. Laterally linked hemispheroid structure, as viewed in a section parallel to the bedding (31/2231).
6. Anhydrite laths in algal stromatolite (22/2286).
7. Part ("flank") of large hemispheroid stromatolite "head" (18/2227).
8. Stromatolite, photomicrograph, plane light (15/2250).
9. Blocky anhydrite in algal stromatolite (15/2207).

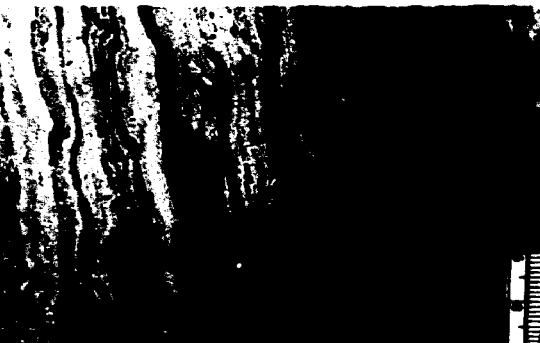
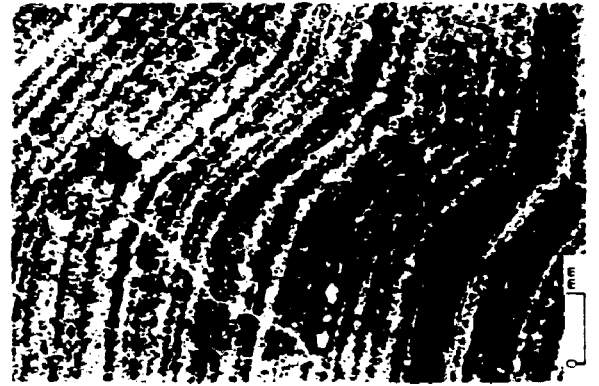
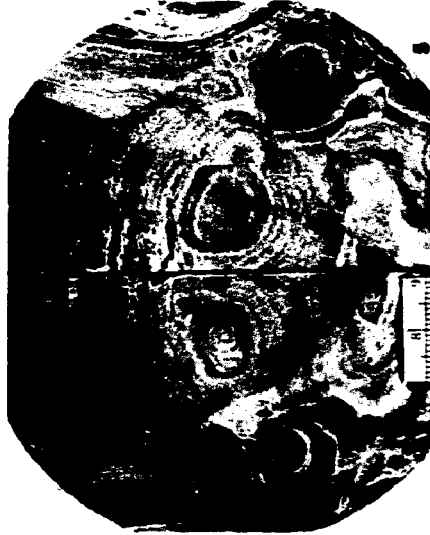


PLATE 9

Supratidal Island stage - BRM Stromatolite Member (continued)Lithofacies 10 - Flat pebble conglomerate

1. 2. Flat pebble conglomerate composed of algal stromatolite fragments (1:39/2285; 2:39/2287).
3. 4. Flat pebble conglomerate, interbedded within the flat laminated algal stromatolite of lithofacies 9 from which it was derived (3:25/2199; 4:19/2255).

Lithofacies 11 - Burrowed mudstone

5. Burrowed mudstone. Light colored mottles are infilled burrows (38/2260).
6. Burrowed mudstone. Well preserved burrow (38/2272).

Lithofacies 12 - Pelletal wackestone

7. Pelletal wackestone (31/2189).

Reef Rubble - BRM Conglomerate Member

- 8-10. BRM Conglomerate Member, upper part, consisting of pebbles of algal stromatolite debris (8:4/2417; 9:4/2431; 10:4/2432).



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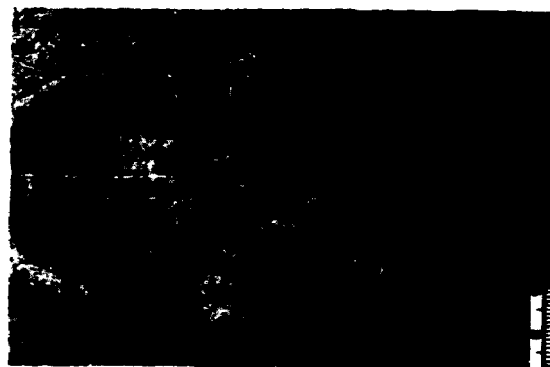
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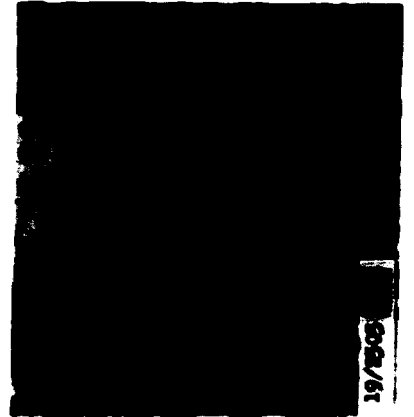
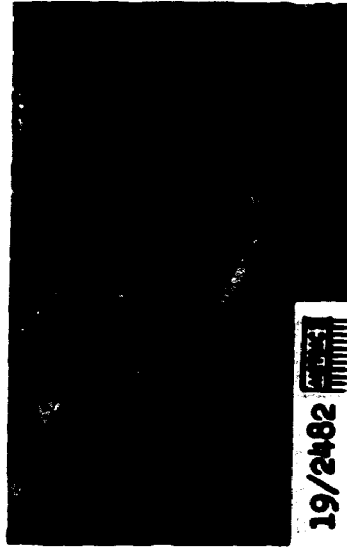
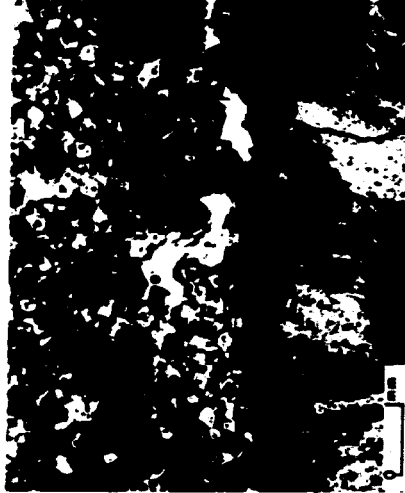
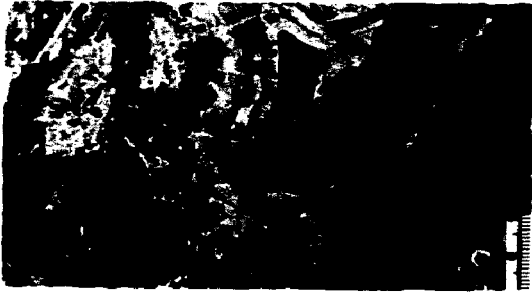
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Diagenetic alterations

1. Interconnected solution vugs formed by non-fabric-selective ("n. f. s.") leaching of skeletal material (crinoids) and interparticle matrix in crinoid biomicrite (lithofacies 2). The vugs in the lower part and at upper right are infilled with coarse, transparent halite crystals (31/2515).
2. Large non-fabric-selective solution cavities in fine skeletal facies (left slab 11/2360) and reef-core facies (algal boundstones, right slab 22/2325). Scale in inches.
3. Same as above in Crinoid wackestone arenite of lithofacies 1. Very coarse, idiomorphic "dog tooth" calcite crystals inside cavity (42/2450).
4. N. f. s. solution cavity in bioherm core facies (lithofacies 2), infilled by several, concentrically arranged successive generations of fibrous calcite. Central part of void plugged by halite. This fabric qualifies as a large stromatolite (25/2442).
5. Same as above. Note stromatolite at upper right (25/2510).
6. Large n. f. s. solution cavity infilled by several generations of vug-lining fibrous cement. Complete filling in upper part; central reduced "residual" void in lower part (25/2464).
7. Small solution cavities, many of them flat bottomed, stromatolite-like, infilled by vug-lining fibrous carbonate. Note secondary preferential leaching of vug infillings (42/2366).
8. Stromatolite in lithofacies 1. All the stages of the diagenetic history of the reef are documented in this slab: n. f. s. karstic solution; vug lining by an even layer of fibrous cement (multiple generations thereof in upper left); infill by dark brown second generation cement; secondary leaching at cavity center and final plugging by blocky calcite (19/2482).
9. Intricate maze of several generations of vug-lining and particle-enveloping fibrous cement. Internal sediment (greenish in original) fills residual vugs and interconnecting channels and passages (19/2505).
10. From bottom to top: Fibrous cement, thin layer of internal sediment; infill by idiomorphic zoned dolomite rhombs. Photomicrography, plane light (42/2514C).
11. Fibrous structure of vug-lining layer. Vug is infilled by felted acicular anhydrite laths. Photomicrograph, plane light (39/2506 B).



Diagenetic alterations (continued)

1. Large solution cavity lined with several generations of fibrous carbonate cement. Central part infilled by transparent halite (in biohermal crinoid-bryozoa biomicrite; 25/2509).
2. Intensively diagenetically altered crinoid-bryozoa wackestone. Original unaltered rock (dark gray patched) constitutes less than 50% of slab. White is for the most part fibrous vug filling cement and in part recrystallized matrix. Vugs are lined with two generations of cement - an outer white and an inner brown. Secondary leaching and dissolution of brown infillings to form new vugs. Note geopetal infilling (by original marine sediment) of fossil at upper center. To the right of it - a stromatolite-like fabric (42/2501).
3. Same as above. Brown fibrous cement occludes most of solution "channels porosity" of interconnected vugs. Secondary leaching. Salt plugging at lower right (42/2495).
4. Molds after coral (preferential solution) and intensive non-preferential dissolution. Recrystallization in matrix (white) and abundant rimmed stromatolite vugs. Large stromatolite at top, completely infilled by brown internal sediment (42/2519).
5. Very large solution cavity in algal boundstone, lined by a very thin layer of fibrous carbonate (darker) and infilled by felted coarse anhydrite laths (32/2419).
6. Thin section of white dolomite infill. Note euhedral rhombs, dark rhombohedral frames and cores (probably ferroan dolomite or hematite). Photomicrograph, plane light (42/2513B).
7. Central residual part of vug infilled with snowy white idiomorphic zoned dolomite (42/2513).
8. Very coarse crystalline anhydrite infilling unrimmed vug. Photomicrograph, plane light (4/2511B).
9. Laminated internal sediment (vadose silt and micrite, greenish on slab) inside a large solution cavity (which is lined by fibrous cement along only part of its roof, 19/2495).
10. Large solution cavity infilled with anhydrite. Brecciated roof. Prior to roof collapse the vug was lined by brown fibrous cement. The detached lining now occur as angular pebbles within the cavity, floating in the anhydrite infill (Fracture within anhydrite infill due to sample damaging; 10:22/2536; 11:11/2436).

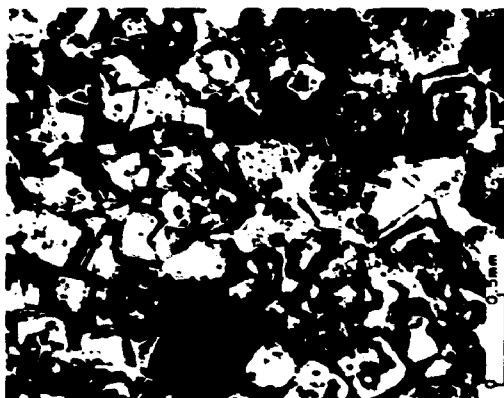
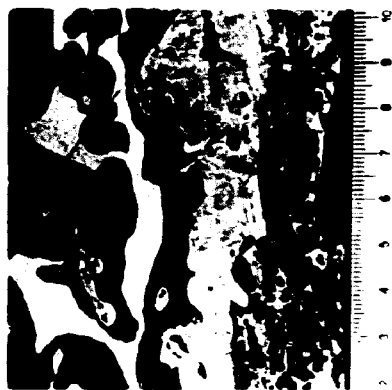
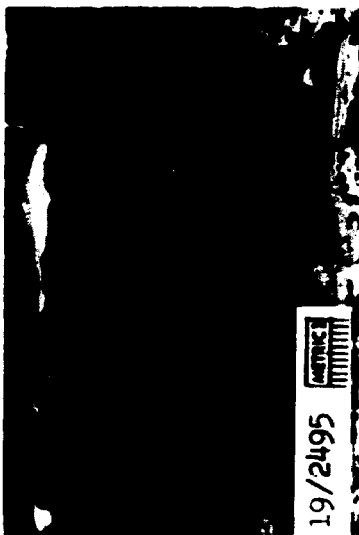
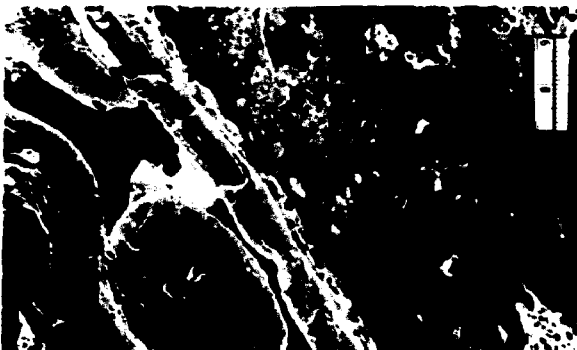
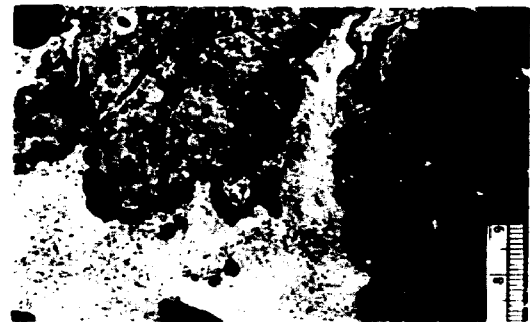


PLATE 12

A-1 Anhydrite

1. Slightly distorted mosaic of flattened coalescing nodules (center) bounded by distorted laminite. Note small diapiric structure at top (3/2525).
2. A sequence of anhydrite fabrics typical of A-1 Anhydrite. From bottom to top: "laminated massive" composed of alternating laminae of dolomierite, carbonaceous matter and anhydrite (the anhydrite laminae consist of closely packed coalescing nodules), two horizons of "enterolithic" anhydrite separated by a "distorted mosaic" fabric, dolomieritic laminae alternating with organic laminae (center), bedded distorted mosaic in upper half (3/2528).
3. "Distorted mosaic" overlaid by "laminated massive". "Enterolithic" fabric at center (3/2524).
4. Slightly distorted micro-enterolithic, undulating laminated fabric, consisting of laminae of dolomierite, very rich with organic matter, alternating with anhydritic laminae of massive microcrystalline anhydrite and anhydritic laminae consisting of coalescing nodules (10/2557).
5. Same as above, transmitted light (10/2557).
6. "Distorted nodular" anhydrite emplaced and interbedded with very finely laminated dolomierite. Nodules flattened parallel to bedding (17/2528).
7. "Nodular mosaic" fabric - nodules, slightly distorted, partly separated by carbonaceous dolomieritic matrix (transmitted light; 41/2579).
8. Highly contorted, convoluted fabric (41/2570).
9. Highly contorted (compactional flowage) fabric (transmitted light, 27/2502).
10. A laminated dolomierite horizon within the A-1 Anhydrite. Note desiccation cracks in top lamina (41/2575, 5).
11. Fenestral fabric ("birdseye") infilled with anhydrite in dolomieritic laminite within the A-1 Anhydrite. Laminite intracasts embedded in anhydrite in lower part (41/2575).

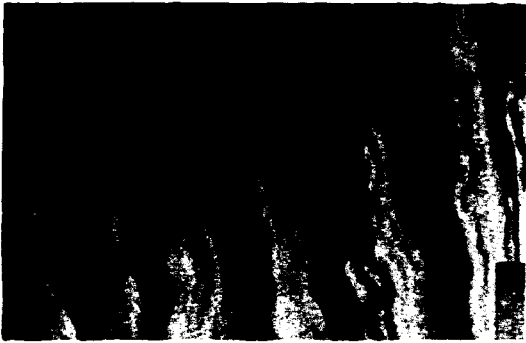


PLATE 13

A-1 Carbonate

Lithofacies 1 - Faintly microlaminated mudstone

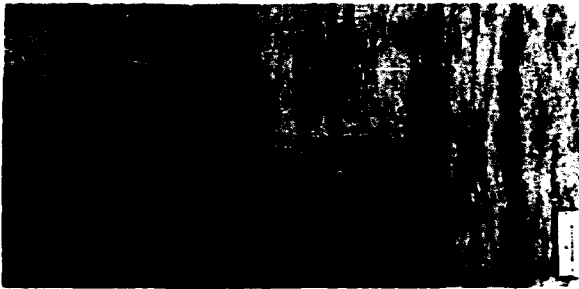
- 1, 2. Faintly microlaminated mudstone. Even, discontinuous, parallel to subparallel laminations. Thin carbonaceous streaks are intricately interlaced in "horse tail" seams pattern (1:40/2434; 2:48/2460).
3. Faintly microlaminated mudstone. Wavy discontinuous parallel and subparallel laminations (40/2465).
4. Well laminated mudstone, even, parallel continuous laminations (41/2535).
5. Photomicrograph of faintly laminated mudstone. Minute filamentous carbonaceous threads are the main source of lamination (plane light, 40/2450).
6. "Mat chips" (short, black carbonaceous flakes) in faintly microlaminated mudstone (41/2502).
7. Photomicrograph of "mat chips" in microlaminated, partly recrystallized, mudstone (plane light, 23/2520).
8. Small anhydrite nodules in microlaminated lithofacies (5/2467).
9. Photomicrograph of anhydrite laths in microlaminated mudstone (plane light, 4/2393).
10. Post-lithification vertical fissure, infilled with very coarse crystalline anhydrite. Photomicrograph, plane light (26/2379).



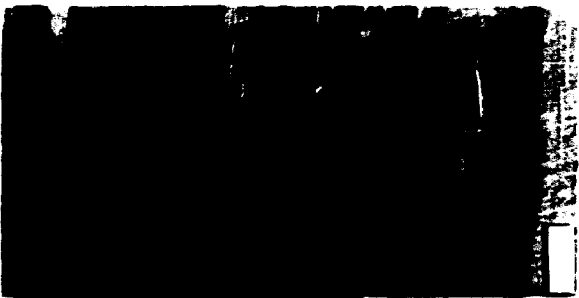
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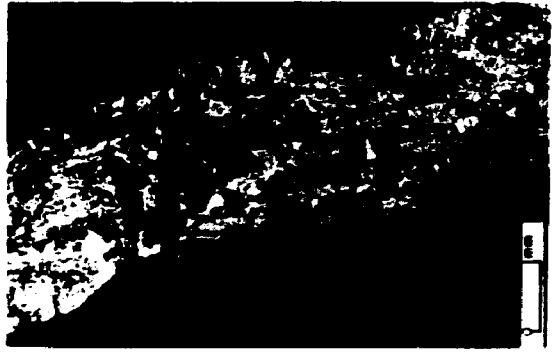
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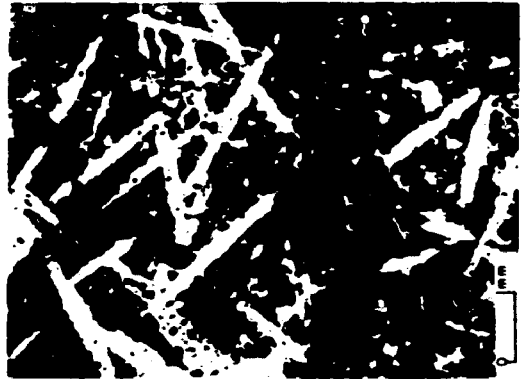
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PLATE 14

A-1 Carbonate (continued)Lithofacies 1 (continued)

1. Irregular contact between algal laminated sediment (lithofacies 2) and overlying laminated mudstone of lithofacies 1. The algal laminated sediment is penetrated by burrows, generated by organisms which inhabit lithofacies 1 (28/2437).
2. Disseminated framboidal pyrite in lithofacies 1 (48/2512).

Lithofacies 2 - Flat algal laminated sediment (Planar stromatolite).

3. Very densely packed flat algal laminated (40/2524).
4. Very densely packed algal laminated section. Organogenic laminae constitute about 50% of the rock. Vertical fissure along which some "faulting" has occurred is infilled with very coarse anhydrite crystals (41/2565).
5. Photomicrograph of very densely packed algal laminated sediment. Dark streaks are carbonaceous films, about 0.01 mm thick, representing remains of algal mat material (plane light, 5/2510).
6. Planar stromatolite and undulating algal mat horizons. Abundant disseminated pyrite (3/2514).
7. Flat algal laminated, with a relatively large proportion of intermat mud layers (28/2460).
- 8;9. Fenestral fabric (white voids) in intermat mud laminations. Many of the voids are infilled with clear blocky anhydrite crystals. Photomicrographs, plane light (8:4/2399B; 9:4/2399B).
10. Algal laminated, with anhydrite nodules in intermat layers (10/2628).
11. Substrate and intermat surface irregularities perpetuated by succeeding laminae. Abundant acicular anhydrite (4/2393).

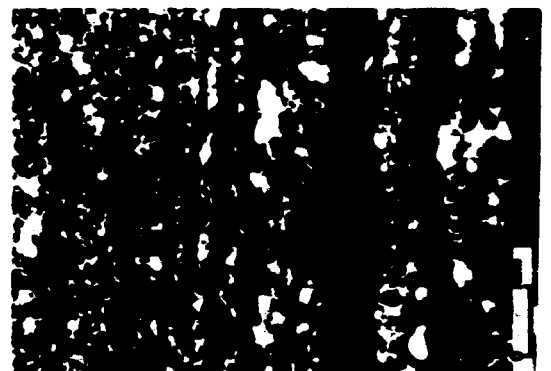
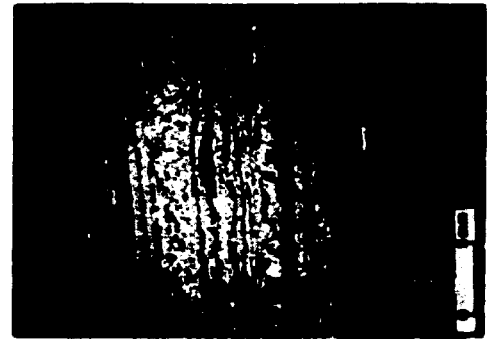
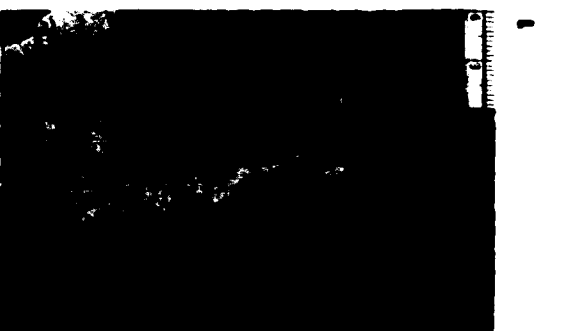
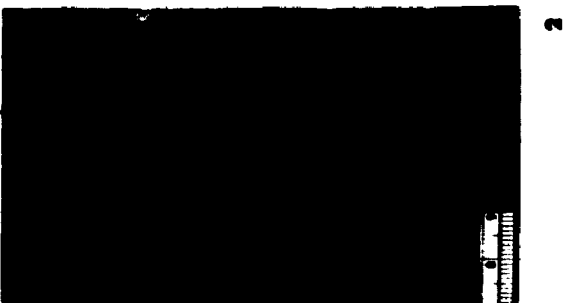
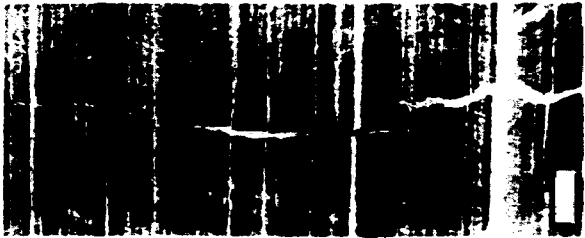


PLATE 15

A-1 Carbonate (continued)

1. Pyrite replacing anhydrite nodules in lithofacies 1 (16/2490).

Lithofacies 2 - Planar stromatolite (continued)

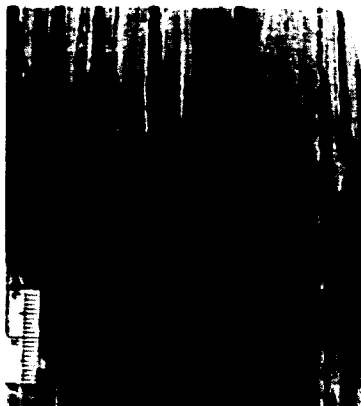
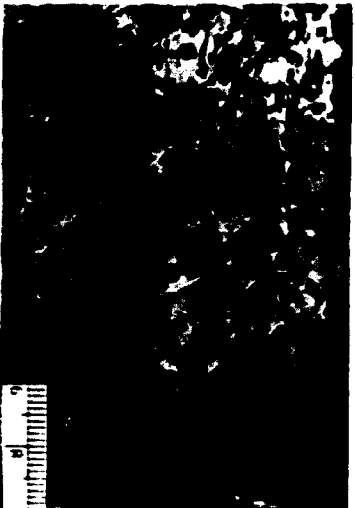
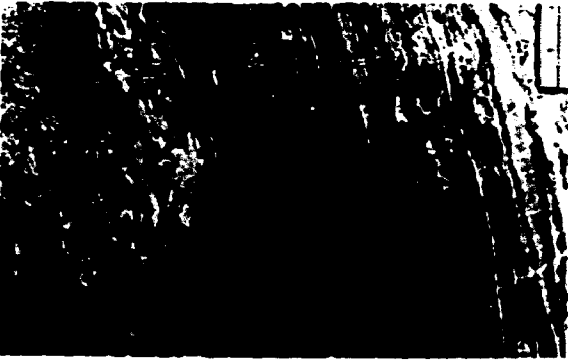
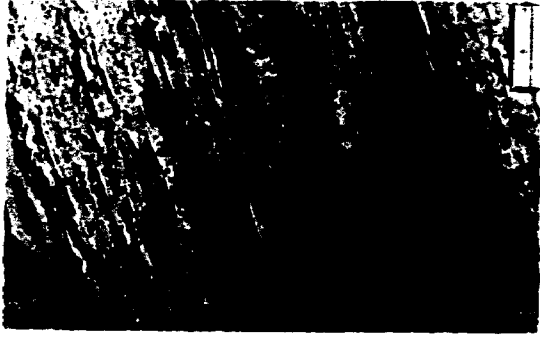
2. Microunconformity between algal laminated sediments of lithofacies 2 and overlying laminated mudstone with mat chips of lithofacies 1. Desiccation cracks in the upper part of the algal laminated sediment, enlarged during exposure by subaerial erosion, are infilled by the overlying sediments (40/2454).
3. Flat algal laminated sediment. In upper part-disintegration products of desiccated algal mat in the form of curled concave saucerlike flakes and short, flat mat chips (4/2358).
4. Intralaminar desiccation cracks, confined to single intermat mud layers (center). Mat chips and "flat pebble" fragments of indurated crust in upper part (4/2359).
5. "Poker chips" lithology. Flat algal laminated sediment with parting developed along algal mat horizons (10/2545).
6. Overturned mat, in a mud supported microbreccia of mat chips and fragments of indurated crust material (34/2519).
7. Elongated, well rounded pellets, concentrated along lamina partings in algal laminated, "Poker chips" lithology (Top view, 5/2505).
8. "Poker chips" lithology - alternations of algal mats and pelletal wackestone laminations (34/2520).

Lithofacies 3 - Pelleted wackestone

9. Pelletal wackestone. Faint, poorly developed laminations in upper part (34/2525).
10. Well laminated pelletal wackestones, packstones and mud layers. Desiccation cracks, infilled with anhydrite, confined to the mudstone laminae in lower part of slab. Note 30 degrees dip (28/2421).

Lithofacies 4 - Indurated crusts

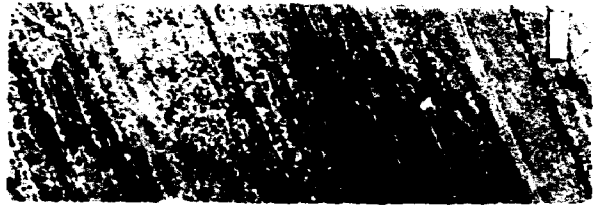
11. Very coarse, cubic, transparent halite crystals within indurated crust horizon (40/2437).



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11



10



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PLATE 16

A-1 Carbonate (continued)Lithofacies 4 - Indurated crusts (continued)Lithofacies 5 - Intraformational breccia and flat pebble conglomerate

1. Desiccated, indurated dark brown crusts, interbedded with microlaminated mudstone. Salt plugged elliptic vug in lower right (46/2447).
2. From bottom to top: Intraformational breccia, composed of flat and angular fragments of indurated crusts and algal laminated sediment overlaid by alternations of desiccated crust horizons and layers of microlaminated mudstone (47/2455).
3. Two layers of intraformational breccia consisting of indurated crust fragments, separated by a dark brown crust layer which is draped over the irregular surface formed by the lower breccia (37/2429).
4. Intraformational breccia, consisting of small angular fragments of indurated brown crusts. Interparticle porosity in lower part (3/2412)
5. Desiccated and jointed crust layer, with fragments still in place (center), separating two layers of intraformational breccia. Salt plugged vugs in lower left, upper left and at center (40/2442).

Lithofacies 6 - Nodular Anhydrite

6. Alternations of flat algal laminated and faintly microlaminated mudstone, both rich in small anhydrite nodules (1/2468).
7. Felted texture of anhydrite nodules. Photomicrograph, plane light (4/2391A).
8. A succession of different anhydrite fabrics typical of the "Rabbit Ears" anhydrite layers. The different fabrics are a result of variations in the nodule to matrix ratio, bedding and degree of distortion. Using Maiklem's terminology (Maiklem et al., 1969) the following fabrics can be recognized from bottom to top: "nodular", "bedded nodular mosaic" (in the algal laminated section at center), "distorted nodular mosaic", "nodular" and "bedded nodular mosaic" (1/2470).
9. "Distorted nodular" fabric. Most nodules are flattened parallel to the bedding. Lateral transition from "distorted mosaic" to "distorted nodular" in lower part (1/2471).
10. "Distorted mosaic" anhydrite overlying a storm deposit layer of debris of algal laminated sediments. The storm deposit layer is impregnated with small crystals of pyrite. The pyrite mineralization occurs along algal streaks, as irregular clusters in the carbonate matrix and as replacement of small anhydrite nodules (28/2433).

