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Petroleum Geology of the Mississippian Mission Canyon Formation, Waskada Field, Southwestern Manitoba

By Murray Rodgers

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ABSTRACT

Mississippian oil production in the Waskada area of southwestern Manitoba was first achieved in 1952. Subsequent exploration efforts led to the discovery of five small pools during the period from 1952 to 1980. A resurgence of interest in the Waskada area followed the discovery of oil in the Jurassic Lower Amaranth Formation in June 1980 and, since that time, interest in the potential of the Mississippian Mission Canyon Formation has resumed as well.

The Mission Canyon Formation is a carbonate-evaporite unit correlative with the Alida Beds and Tilston Beds of Saskatchewan. In Manitoba the Mission Canyon is subdivided into three members, MC-1, MC-2 and MC-3. The MC-1 and MC-3 are productive in the study area, with the bulk of Mississippian production occurring in the two porous units of the MC-3, known locally as MC-3a and MC-3b, in ascending order.

This report reviews available well data from a four-township area that includes the entire Waskada Field. The lithology consists of complex interbedded grainstones, packstones, wackestones and mudstones which are representative of cyclic deposition in a shallow water, moderate energy setting. Periodic episodes of restrictive conditions resulted in the formation of dense evaporites which constitute the MC-2 member.

The structure of the Waskada Field is a complex of local anticlinal features and associated 'relict lows'. This is thought to have resulted from multiple stage solution and collapse of the underlying Devonian Prairie Evaporite Formation.

The information and conclusions in this report are based on data available to July 1, 1984.

June, 1985,
Winnipeg.

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INTRODUCTION

PURPOSE OF STUDY

The purpose of this study is to assess the petroleum geology of the MC-3 and MC-1 pools of the Waskada Field, and to assess the hydrocarbon potential of adjoining exploration acreage. Specifically, this study will attempt to:

1) Describe regional stratigraphic relationships of the Mission Canyon Formation in southwest Manitoba and adjacent regions;
2) Present a synopsis of exploration activity in the study area;
3) Describe the lithofacies in the study area by means of core descriptions, core analyses, thin sections, stratigraphic sections, and log responses;
4) Present relevant data in the form of various structure maps;
5) Synthesize the above data into a stratigraphic-structural model which may be applied in regional and field exploration studies; and
6) Speculate upon exploration potential of the Mission Canyon Formation outside of the study area.

The intent of this report is to provide an overview of relevant data concerning hydrocarbon accumulation in the Mississippian which will provide a basis for future work of a more detailed nature from both an exploration and an academic perspective.

AREA OF STUDY

The producing beds of the Mission Canyon Formation (MC-1, MC-3a, MC-3b) are present over the extreme southwestern part of Manitoba, covering an area of approximately 30 townships (2 800 km^2) (Fig. 1).

The Waskada Field area defined for the purposes of this study as Townships 1 and 2, Ranges 25 and 26 WPM, has been chosen for several reasons. Significant oil production is obtained from three stratigraphic intervals in the Mission Canyon Formation (MC-1, MC-3a, MC-3b) at Waskada, and limits of many of these pools have not yet been defined. The Mississippian strata underlie the entire area of basal Jurassic Lower Amaranth Formation production.

Hydrocarbon accumulation is controlled by a complex interplay of structural and stratigraphic factors, and although limitations are imposed by the lack of deep well data in the area, sufficient well control exists upon which to base a preliminary study.

ACKNOWLEDGEMENTS

This report was prepared while active drilling continued in the Waskada Field area. As information becomes available, it becomes apparent that the Mississippian geology of the Waskada Field and surrounding area presents an extremely complex problem.

The author's attempts to highlight some of these problems have been aided in particular by the input and assistance of Dr. H. R. McCabe of the Geological Services Branch, Manitoba Energy and Mines. Critical reviewing of the text was also provided by Dr. H. R. Young of the Department of Geology, Brandon University.

The author would also like to express his appreciation to Barry Bannatyne of Geological Services Branch for his assistance in editing this report and to Mike Fedak and Clayton Sandy for their excellent drafting work.

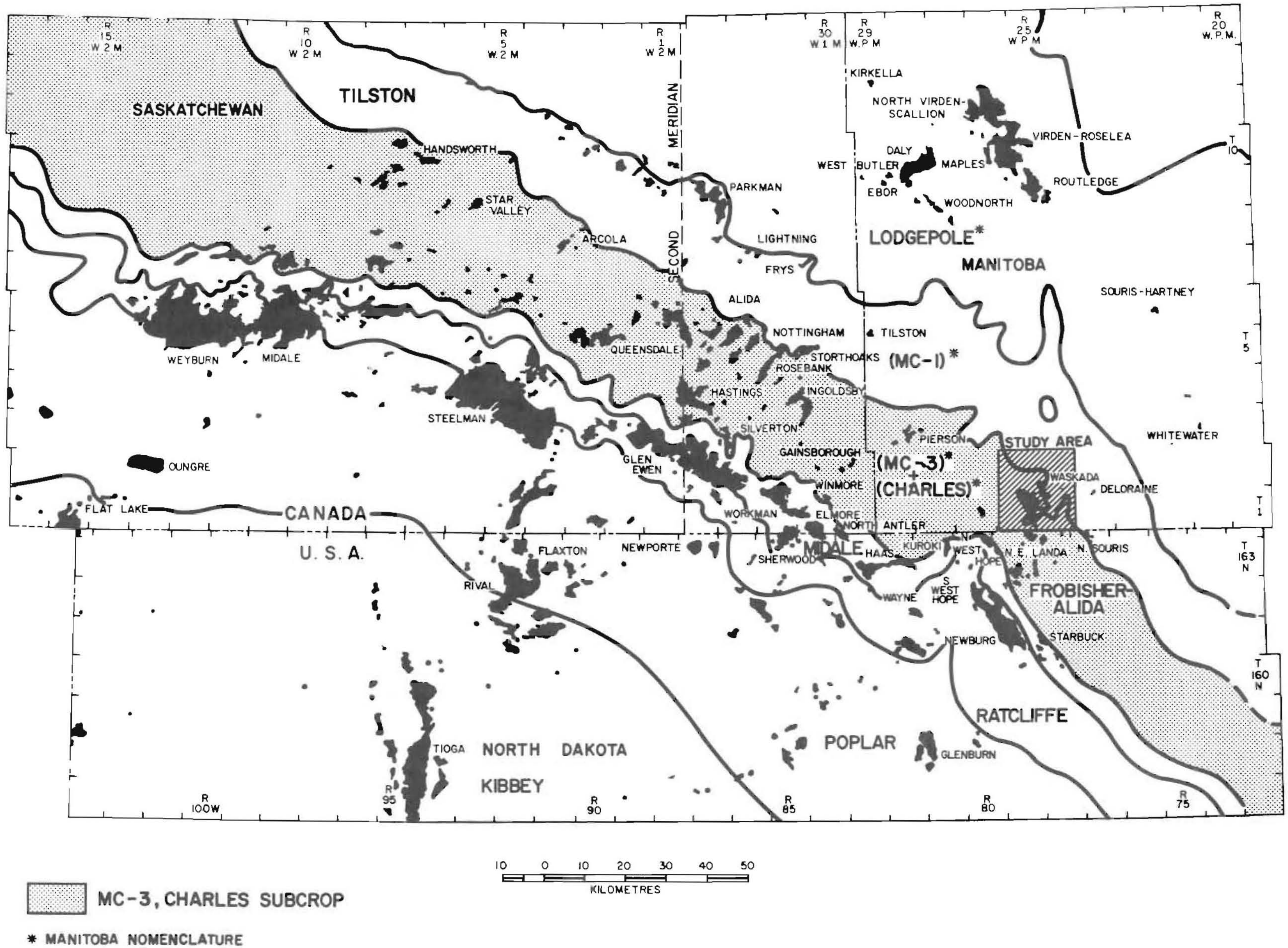

FIGURE 1: Regional Setting:
Location of study area along Regional Mississippian Subcrop Belt

REGIONAL STRATIGRAPHIC SETTING

The strata discussed in this report are part of the lower Mississippian Madison Group (late Kinderhookian-early Osagean). Identification of Mississippian rocks in the subsurface of Manitoba was originally made by Kerr (1949) and subsequent subdivisions were based on terminology used in the central portion of the Williston Basin (McCabe, 1959) (Fig. 2).

The Mississippian sequence was thus divided into, in ascending

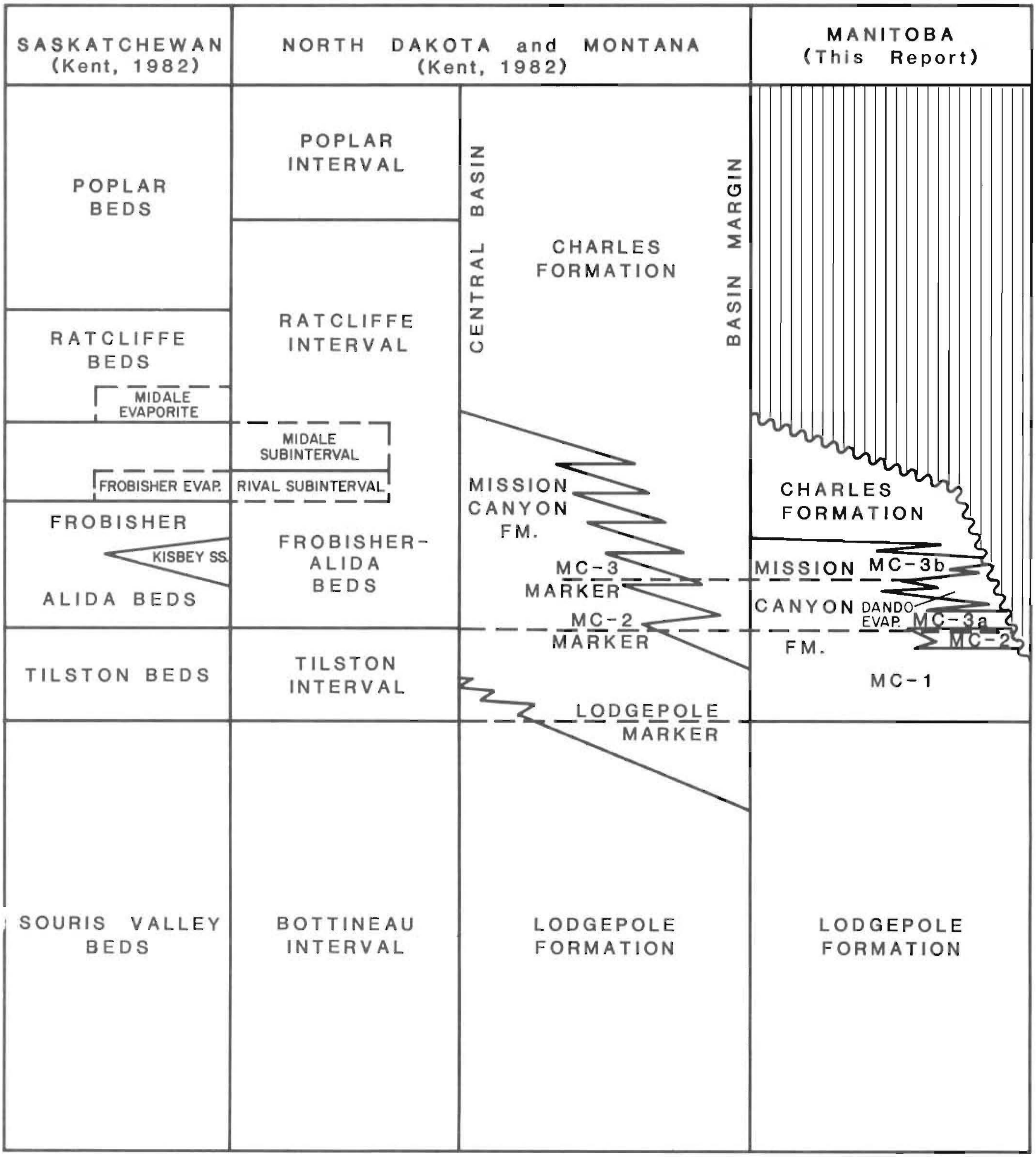

FIGURE 2: Regional Mississippian Stratigraphy

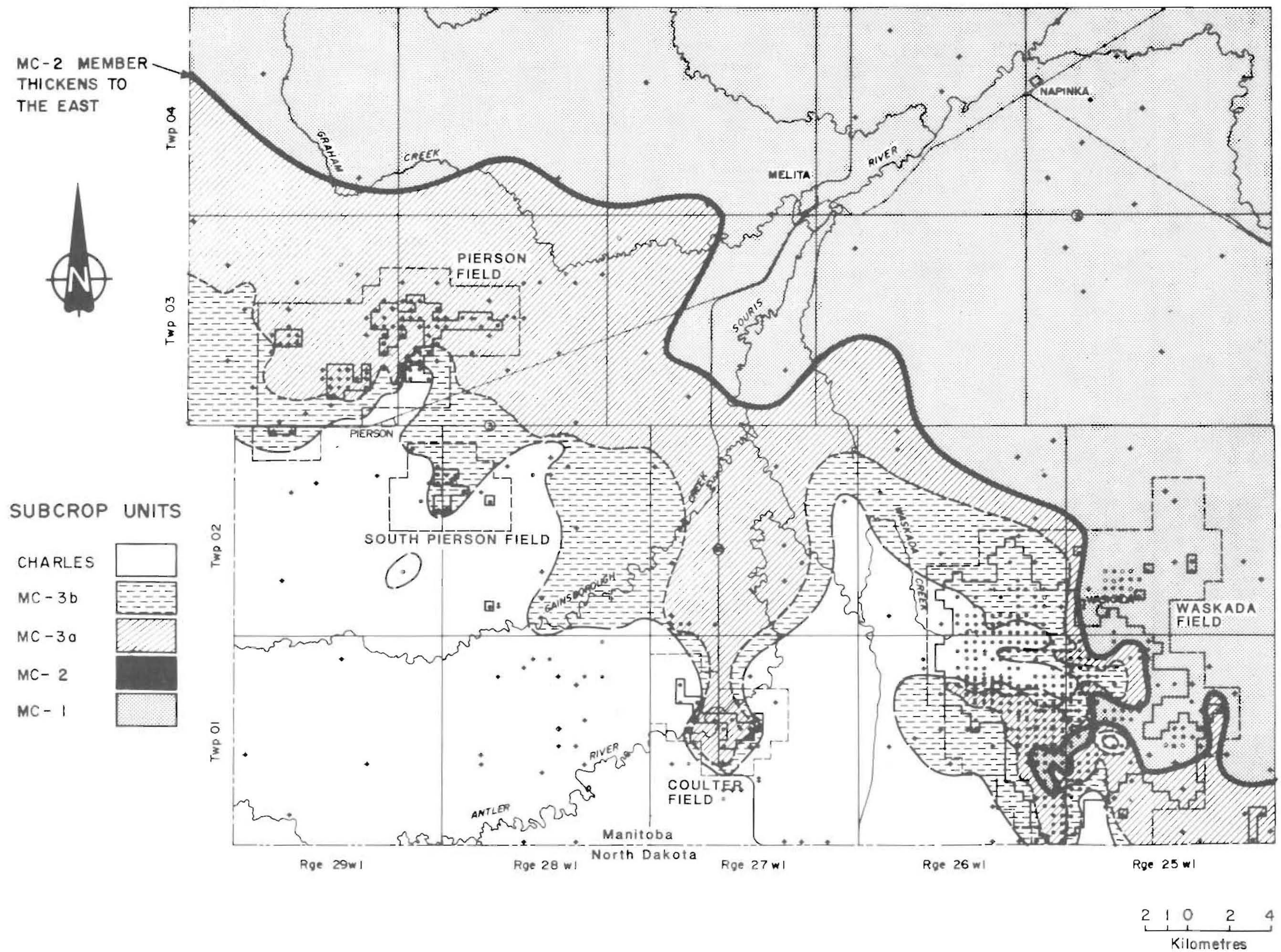

FIGURE 3: Mission Canyon Subcrop — Southwest Manitoba

order, the Bakken, Lodgepole, Mission Canyon and Charles Formations. The Mississippian strata in the study area are unconformably overlain by the 'Red Beds' of the Jurassic Lower Amaranth Formation (Watrous of Saskatchewan) which are also productive in the study area.

Mississippian strata in the northeastern portion of the Williston Basin are truncated progressively northeastward by the pre-Jurassic unconformity and form a series of generally northwest trending subcrop belts (Fig. 3). The bulk of Mississippian oil production in southeast Saskatchewan and Manitoba occurs where porous reservoir rocks are truncated at the unconformity surface. The three productive units of the Mission Canyon Formation (MC-1, MC-3a, MC-3b) subcrop in the study area.

STRATIGRAPHIC SUBDIVISIONS USED IN THIS REPORT

Detailed stratigraphic subdivisions of the Mission Canyon Formation in southwest Manitoba are shown in Figure 4.

Stratigraphic subdivisions based on formations are commonly employed in Manitoba. This contrasts with the marker-defined or 'bed' system used in Saskatchewan and North Dakota. It was noted by McCabe (1959) that classifications based on formations are of limited use in regional stratigraphic studies because of the diachronous nature of the units, and that a system of nomenclature based on both formations and beds or formats would be most effective.

While this report adheres to the 'formation' system of nomenclature, it is important to note that the units of the Mission Canyon can be subdivided on the basis of argillaceous 'marker' beds in the study area. It is suggested that because changes in gross lithology are accompanied by argillaceous 'marker' beds on gamma-ray logs, the formation/member system is interchangeable with the marker-defined system in the study area.

The Mission Canyon Formation has been subdivided into three members: the MC-1, MC-2 and MC-3, all of which exhibit characteristic log responses in the study area. These are illustrated in Figure 5.

The lowermost MC-1 member consists of limestones and dolomitic limestones which overlie the argillaceous marker at the top of the Lodgepole Formation and underlie the carbonate/evaporite sequence of the MC-2 member. The MC-1 and lower MC-2 are equivalent to the Tilston Beds of Saskatchewan.

The MC-2 member includes shaly carbonates and evaporites found above and below the MC-2 marker. This marker is an excellent mappable marker bed as an indicator of true Mississippian structure. The MC-2 marker forms the top of the Tilston Beds and displays a very characteristic response on both gamma-ray and SP logs. The MC-2 member varies considerably in thickness throughout southwest Manitoba due to facies change rather than differential subsidence (McCabe, 1959).

The MC-3 member consists of limestones, dolomite and locally, evaporites, which overlie the MC-2 marker and underlie the Charles evaporites. The MC-3 is further subdivided into two porous zones known as the MC-3a and MC-3b. These units are separated by an argillaceous marker bed which has been designated the 'MC-3 marker'. This marker undergoes an east-northeast facies change into a primary evaporitic unit known locally as the Dando Evaporite. Evaporites of the MC-2 and Dando are thought to represent the basinward edge of a series of basin margin evaporite pans.

The MC-3a and MC-3b carbonates display log responses which are characteristic of cyclic patterns of deposition. Local operators commonly refer to these zones as the Lower Alida (MC-3a) and Upper Alida (MC-3b); this report, however, employs exclusively Manitoba terminology.

The uppermost Mississippian strata found in the study area are the evaporites of the Charles Formation. These rocks subcrop regionally in the extreme southwest corner of Manitoba, and locally in the study area where they have been preserved from erosion in 'relict lows'.

Charles Formation rocks overlie the clean carbonates of the Mission Canyon and unconformably underlie the terrigenous clastics of the Jurassic Lower Amaranth Formation. The preserved portion of Charles strata of Manitoba is equivalent to the middle part of the Frobisher-Alida beds of Saskatchewan (McCabe, 1959).

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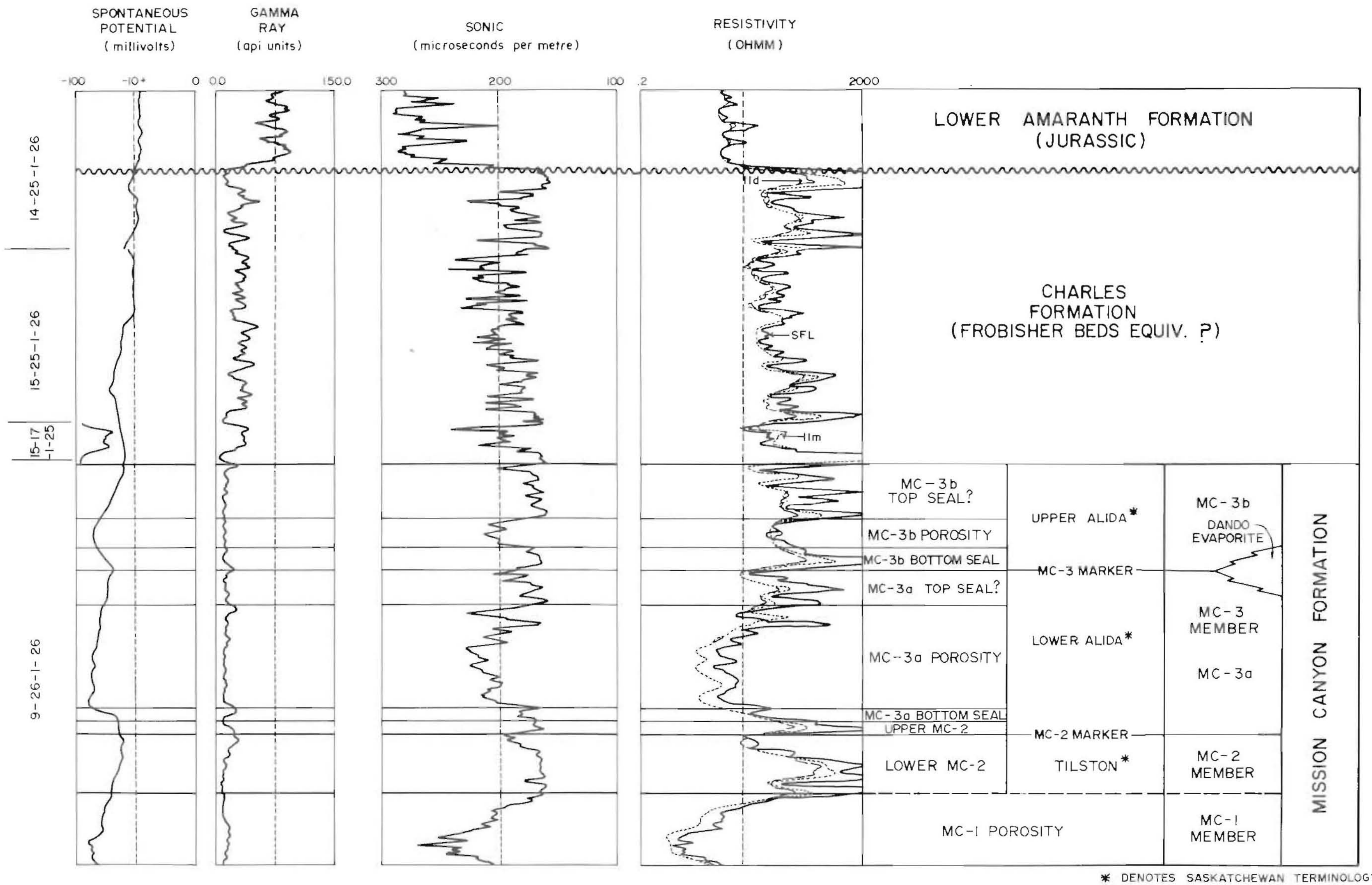


FIGURE 5: Composite Type Log/Detail Stratigraphic Subdivisions

INTRODUCTION

Oil production in the study area prior to 1980 was limited to five small pools which totalled seventeen wells (Fig. 6). The pools represented isolated accumulations of limited areal extent which did not reflect the extreme complexity in the Mississippian which is evident today. Production varied considerably and economic factors at the time made many wells only marginally profitable. The Waskada area was thus largely ignored until June of 1980 when Omega Hydrocarbons recompleted 11-30-1-25 WPM in the Lower Amaranth Formation. The discovery of oil in these 'Red Beds' led to a period of development drilling which continues today. As of June 30, 1984 a total of 16 Mississippian pools (Fig. 7) have been discovered in the study area, and there is every indication that further Mississippian discoveries will result.

The following discussion documents the discovery of the various Mississippian pools in the study area.

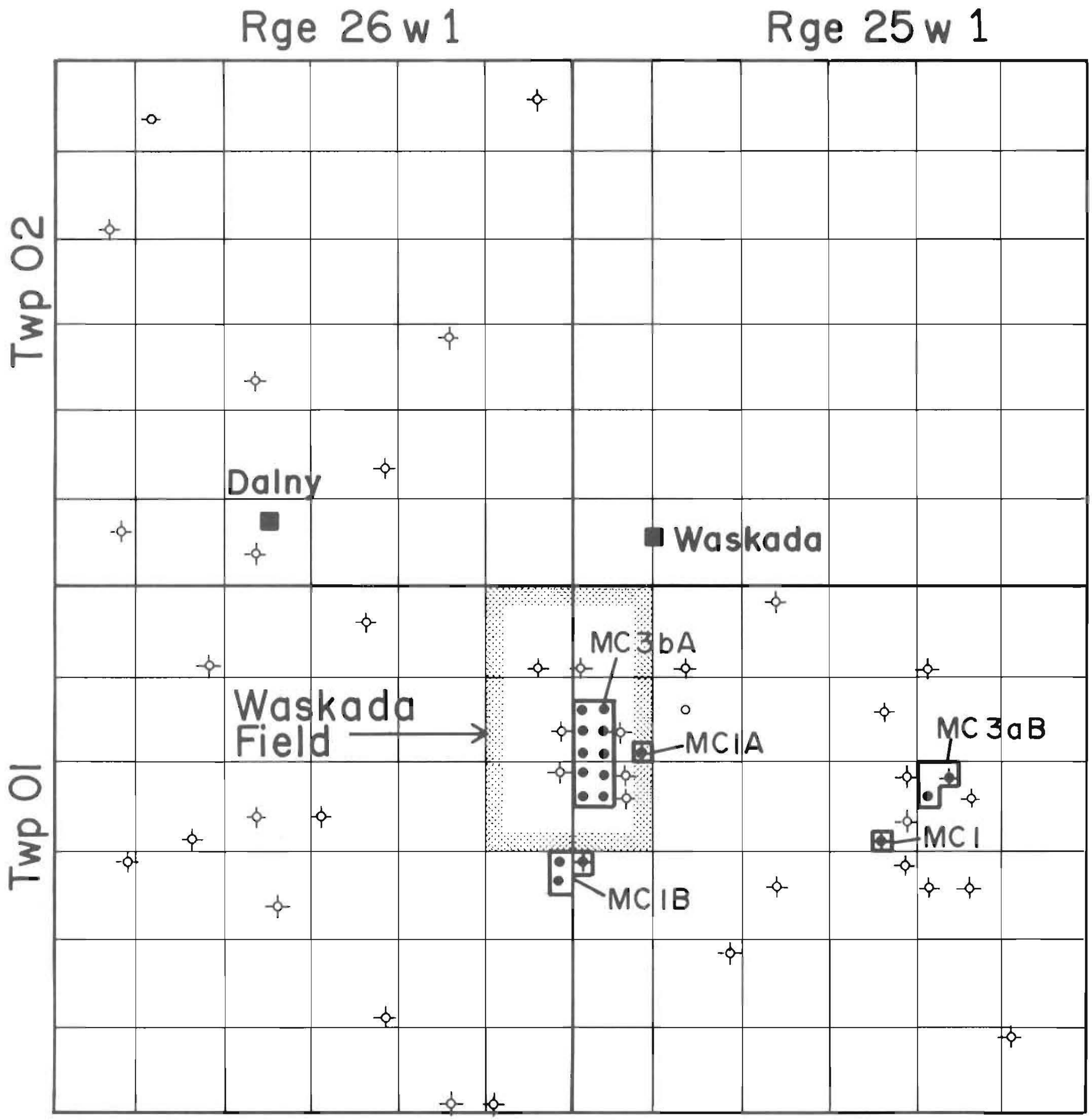


FIGURE 6: Pool Map: pre-1980

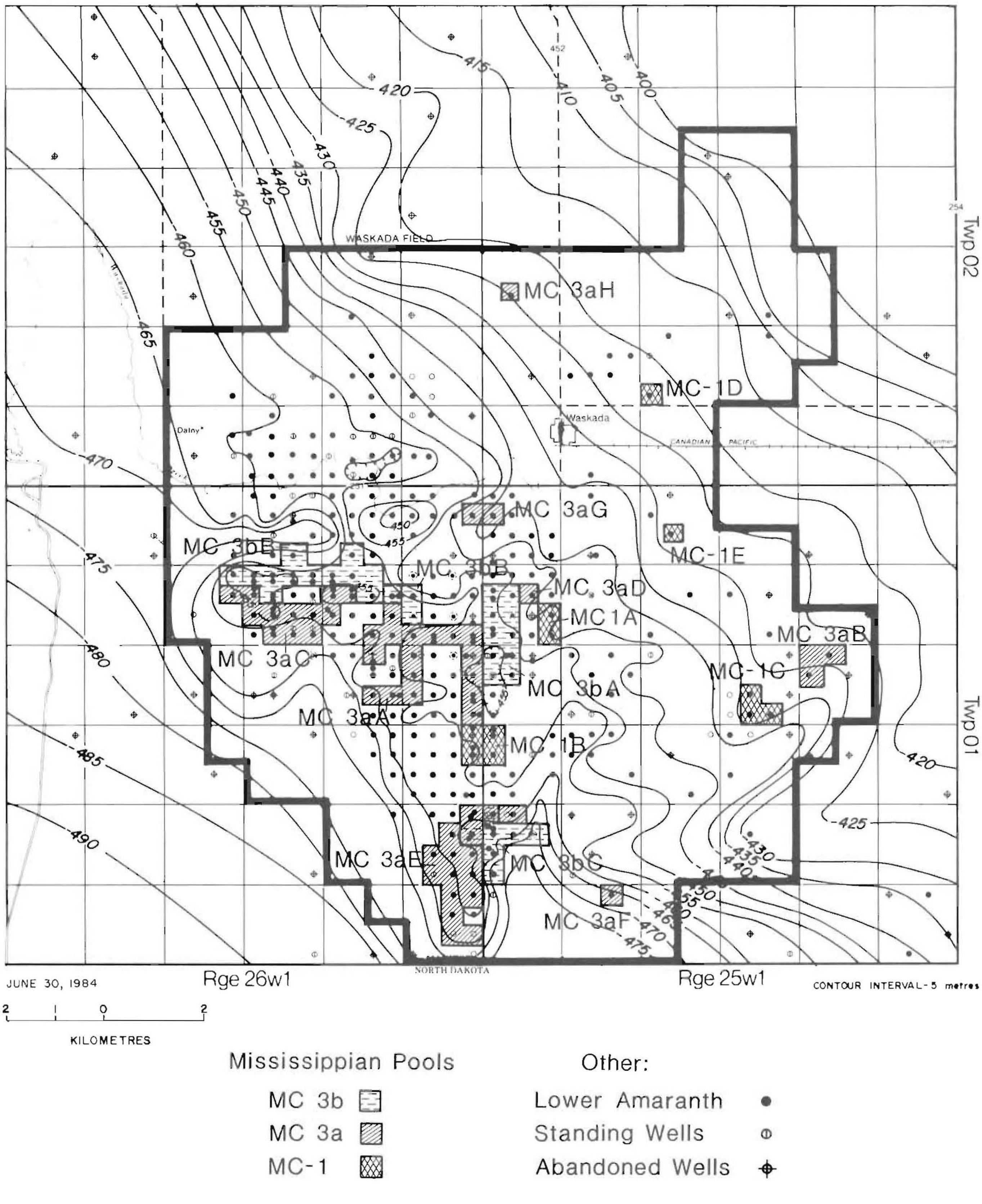


FIGURE 7: Mississippian Pools-Mississippian Erosional Structure (as of June 30, 1984)

PRE-1980 DISCOVERIES

(a) MC-1 B Pool

Oil was first discovered at Waskada in 1952 by the California Standard Company (9-13-1-26 WPM). The well was drilled on a seismically defined high and was completed in the MC-1 beds with 7.5 metres (24 feet) of pay. Initial production tests yielded 32 BOPD. California Standard drilled an unsuccessful development well in 1953 at 16-13-1-26 WPM. A successful development well was drilled at 13-18-1-25 by Lyle Lee and Associates in 1955. The A13-18-1-25 WPM location was successfully redrilled in 1979 by Copperhead Oil Company and remains active. The locations at A9-13 and A16-13 were redrilled in 1980 by Omega Hydrocarbons and are still active. In 1982, KLM Ventures drilled the 12-18-1-25 WPM location which was later recompleted in the Lower Amaranth Formation.

(b) MC-1 A Pool

In August of 1956 Imperial-Cal Standard Hernfield 1-30-1-25 WPM was drilled on a separate Mississippian structural high and was completed in the MC-1 beds. The well penetrated 3.7 m (12 feet) of pay and yielded 35° API oil. Production results were not encouraging and the well was suspended in the fall of that year after having produced 352 m^3 (2,218 barrels) of oil and 357 m^3 (2,244 barrels) of salt water. One development well (8-30) was drilled by Omega Hydrocarbons in 1982 which produced 363 m^3 (2,283 barrels) of oil and 918 m^3 (5,773 barrels) of water before being recompleted as a Lower Amaranth well in September of 1983.

(c) MC-3b A Pool

The MC-3b A Pool was discovered in January of 1967 by Omega Hydrocarbons. The discovery well, Omega Waskada 11-30-1-25 WPM was drilled downdip from the MC-1 A Pool in 1-30-1-25, confirming the presence of porous MC-3b beds which were preserved from the effects of erosion. The pool was subsequently expanded to include ten wells.

After having produced 22 399 m^3 of oil, the six wells in Section 30 were placed under waterflood in 1976. Unit wells have produced 64 248 m^3 to July of 1984.

Cumulative production for the pool to July of 1984 is 125 081 m^3 oil and 64 975 m^3 water.

(d) MC-1 C Pool

This period of renewed activity in 1967/1968 led to the discovery of a third MC-1 pool at Waskada. DeKalb Petroleum drilled 2-22-1-25 WPM west of a southwest-trending structural nose which appeared to be separate from the main Waskada structure. This wildcat attempt penetrated MC-1 porous beds which produced at an initial rate of 40 BOPD. The well ultimately produced 235 m^3 (1,478 barrels) of oil and 120 m^3 (755 barrels) of water before being abandoned.

No further attempts were made to enlarge the pool until 1983 when Sasko Oil and Gas and partners drilled 6-22-1-25 WPM as an offset to 2-22. This recent well produced 25 m^3 (157 barrels) of oil and 3 m^3 (19 barrels) of water over an initial five-day production period. To July, 1984, the well has produced 499 m^3 (3,138 barrels) of oil and 466 m^3 (2,931 barrels) of water.

(e) MC-3a B Pool

The first MC-3a (Lower Alida) production was discovered by DeKalb Petroleum at 14-23-1-25 WPM in May of 1968. This was followed by DeKalb et al Waskada 12-23-1-25 WPM in September of the same year. Both wells were drilled on the flank of the same structure on which the previously mentioned wells of the MC-1 C pool were drilled. However, by moving downdip from these MC-1 producers, a preserved section of MC-3a porosity was encountered. These MC-3a wells averaged 25 BOPD over initial five-day production tests and to July, 1984 have produced 6 708 m^3 (42,188 barrels) of oil and 300 m^3 (1,886 barrels) of water. The 14-23 well has since been abandoned.

1980 — PRESENT

Since 1980, 11 new pools have been discovered in the Mississippian at Waskada, totalling 79 wells, 46 of which were producing as of June 30, 1984. Most current Mississippian producing wells are potential Lower Amaranth producers as well.

(a) MC-3b B and C Pools

As exploration and development progressed subsequent to the first Lower Amaranth discovery at 11-30-1-25 WPM, it became increasingly apparent that Mississippian potential was far greater than the early drilling had indicated.

Two MC-3b pools were discovered during this period, the MC-3b B Pool in 1981 and the MC-3b C pool in 1982. The B pool is located on the western edge of the Waskada structural complex where reservoir beds are preserved in a downdip position along the flank of the structure.

The pool was developed to 10 wells with 9 currently producing. The pool has produced 20 436 m^3 (128,528 barrels) of oil and 14 760 m^3 (92,836 barrels) of water as of July 1, 1984.

The MC-3b C pool is located on the south end of the Waskada structure and currently contains 5 producing wells. Total production for the pool as of July 1, 1984 is 10 604 m^3 (66,691 barrels) of oil and 15 527 m^3 (97,654 barrels) of water.

(b) MC-3a Pools

Since the discovery of the MC-3a A pool in 1981, six separate oil accumulations have been discovered in MC-3a reservoir beds.

The MC-3a A pool was discovered by Omega Hydrocarbons in 1-25-1-26 WPM. The well recovered 14 m^3 (88 barrels) of oil and 3 m^3 (19 barrels) of water over a five-day test, and a further 8 wells have been completed in the pool by Omega. As of July 1, 1984, the pool has produced 18 224 m^3 (114,620 barrels) of oil and 18 997 m^3 (119,477 barrels) of water.

The remaining MC-3a pools, designated C through H have been discovered since 1982 and range in size from eight wells (MC-3a E) to one well (MC-3a D, F and H). All are characterized by subcropping reservoir beds located on the flanks of the structural complex. As Figure 7 illustrates, the locations of these pools reflect the complex local variations in structure which will be dealt with in greater detail in the part on Structural Aspects.

(c) MC-1 D and E Pools

Two separate one-well locations drilled in 1982 resulted in the discovery of isolated oil pools in the MC-1 beds.

The pool designated MC-1 D was discovered by Roxy Petroleum at 4-9-2-25 WPM in October 1982 and has produced 201 m^3 (1,264 barrels) of oil and 5 967 m^3 (37,528 barrels) of water as of July 1, 1984.

The MC-1 E Pool was discovered by Petro-Canada in 6-33-1-25 WPM and has produced 401 m^3 (2,522 barrels) of oil and 4 200 m^3 (26,425 barrels) of water as of July, 1984.

Both wells are located along the regional subcrop edge of the MC-1 and, as is the case with all MC-1 production at Waskada, the wells produce prolific amounts of water and show a rapid decline in oil production (50% year).

From this overview of the history of exploration for Mississippian oil at Waskada, it can be seen that development has been sporadic over the past thirty years. As more pools were discovered, the complexity of the structure and Mississippian lithostratigraphy has been highlighted by the varied configurations and widespread locations of the pools.

The remainder of this report will deal with the lithology and structure of the Waskada Field and its significance to oil exploration.

DESCRIPTIVE LITHOLOGY

GENERAL

The determination of lithology, sedimentary structure and texture was done by examination of slabbed cores with a low power binocular microscope. Cores from 34 wells were examined, totalling 570 m.

Many of the Mississippian wells in the field have not been cored, and among those that have, most do not cover a complete productive interval. This is due partly to the drastic structural variations and truncation of reservoir beds in the field, and partly to common operator practice. As a result, this core study can only be viewed as preliminary until further data become available.

Petrographic thin sections from selected intervals (50 total) were examined. Lithologic descriptions are based on Dunham's (1962) classification of carbonate rocks which is based on depositional texture. Porosity has been described according to Choquette and Pray (1970).

Rocks of the Mission Canyon Formation in the study area form a complex mosaic of carbonates and evaporites. The carbonates, which consist primarily of limestones and dolomitic limestones, are indicative of deposition in a shallow marine carbonate shelf environment. The occurrence of primary anhydrite and laminated carbonates indicates periodic restrictive conditions accompanied by low energy and high salinity.

These rocks reflect an overall regressive depositional history. They are characterized by rapid lateral and vertical changes and show depositional cyclicity common to Mississippian carbonate reservoirs in other parts of the Williston Basin. Excellent examples of cyclicity are found in the Haas Field of North Dakota which was discussed by Elliot (1978), and the Little Knife Field of North Dakota (Lindsay and Roth, 1982).

Reservoir beds have been truncated by post-Mississippian erosion, and subsequent anhydritization has in-filled upper porous zones as well as most fracture networks near the unconformity. Lateral facies variations occur in the north portion of Township 1, Range 25 WPM and form a purely stratigraphic trap.

LITHOLOGY

Core study has led to the identification of six gross lithology types, which will be discussed separately. This is not a comprehensive study of all diagenetic processes but it is hoped this will lead to further studies of a more specific and academic nature. Typical lithology/log correlations for each of the three porous units are shown in Figure 8.

(a) Coated Grain Packstone to Grainstone

This rock type is characterized by an abundance of coated grains. Types of grains include ooids, pisoids and compound pisoids (Fig. 9(a),(b)) which form interbedded vertical sequences of packstones and grainstones.

Pisoids represent the dominant component of these rocks and generally exhibit a non-skeletal nucleus. The nucleus consists of peloids, pisolite intraclasts or microspar bodies. These grains range in size from a few millimetres to 1.5 cm. They typically display a range of shapes from rounded and symmetrical to elongate and polygonal.

Groups of laminae are distinguished by alternating layers of light (microspar ?) and dark (micrite ?) laminae. Outer laminae commonly form accretionary layers around the grain and may link other pisoids in forming a 'compound' pisoid (Fig. 9(c)).

Many of the pisoids of this facies are micrite-rich and exhibit indistinct laminae. Irregular micritic laminae have been described as being of algal origin (Dunham, 1962). Local operators commonly refer to this rock type as an 'algal lump limestone'; however, the origin of the grains can only be determined through further study.

Ooids are associated with and are gradational into pisolitic limestones; however, the original texture of many ooids has been altered by recrystallization. Some grains exhibit poorly developed concentric laminations or radial fibrous structure (Fig. 9(d)) but the general absence or modification of internal structure suggests that these grains could be more accurately termed 'pseudo-ooids'.

Alternatively, these grains may represent introduced non-oolitic clasts which have undergone periodic agitation in a predominantly low energy environment.

Porosity occurs in two forms. Primary interparticle porosity has been preserved where in-filling by clear, subhedral to anhedral anhydrite and sparry calcite has not been pervasive. In general, the presence of secondary pore-filling material severely limits the permeability throughout much of these reservoirs (Fig. 9(e)).

Secondary porosity caused by dissolution is the predominant porosity type in the coated grain facies. Voids formed are of irregular shape and size and may or may not be interconnected. Fracture porosity occurs throughout much of the reservoir, although many of the fractures have been infilled with anhydrite. Where in-filling has not occurred, it is thought that these fractures greatly enhance permeability. In general, porosity ranges from 5 to 20 per cent in these rocks.

Secondary cements greatly reduce permeability in the coated grain facies. Both calcite and anhydrite occur in varying amounts. Two types of sparry calcite cement have been observed: 1) blocky or equant cement and 2) drusy or fringing cement. Grains are commonly cemented with both forms.

A first generation fringe of drusy calcite cement surrounds the grains and a later generation of blocky calcite fills a portion of the remaining pore space (Fig. 9 (e)).

Anhydrite emplacement postdates calcite cementation and acts as a pervasive inhibitor of permeability. Anhydrite infills much of existing pore space in addition to much of the aforementioned fractures (Fig. 9(f)).

(b) Non-Coated Grain Wackestone to Packstone

These rocks are characterized by an abundance of non-coated grains such as peloids, intraclasts and agglomerated micrite lumps (Fig. 10(a)). An important distinguishing feature is an abundance of micrite, some of which has been partially dolomitized. Dolomitization acts selectively on the finer grained matrix material whereas the coarser grains remain unaltered. Such preferential dolomitization of finer grained material has been noted in studies by Powers (1962) and Murray and Lucia (1967).

Peloids in this facies are structureless micrite grains ranging in size from 1 to 3 mm (Fig. 10(b)). Grains are oval to spherical in shape and occur in thin beds between coated grain beds. Lithology types are commonly mixed, thus making the characterization of separate rock types difficult.

Intraclasts range in size from 0.2 to 0.8 mm. The grains are generally poorly sorted and angular, but in places are found as thin, flat and horizontally aligned fragments. These grains occur in thin bands and are thought to represent soft-sediment deformation due to compaction.

Three types of porosity have been observed. Primary intergranular porosity occurs sporadically where secondary in-filling by anhydrite is incomplete. Secondary microcrystalline matrix porosity results from dolomitization of finer micritic material. There is some doubt regarding the importance of this type of porosity in view of the small size of the pore throats.

Dissolution of grains and matrix has occurred in varying degrees and constitutes a large portion of the effective porosity in this facies.

Porosity is reduced by both anhydrite and calcite in-fill. Anhydrite commonly occurs as bladed crystals (Fig. 10(c)).

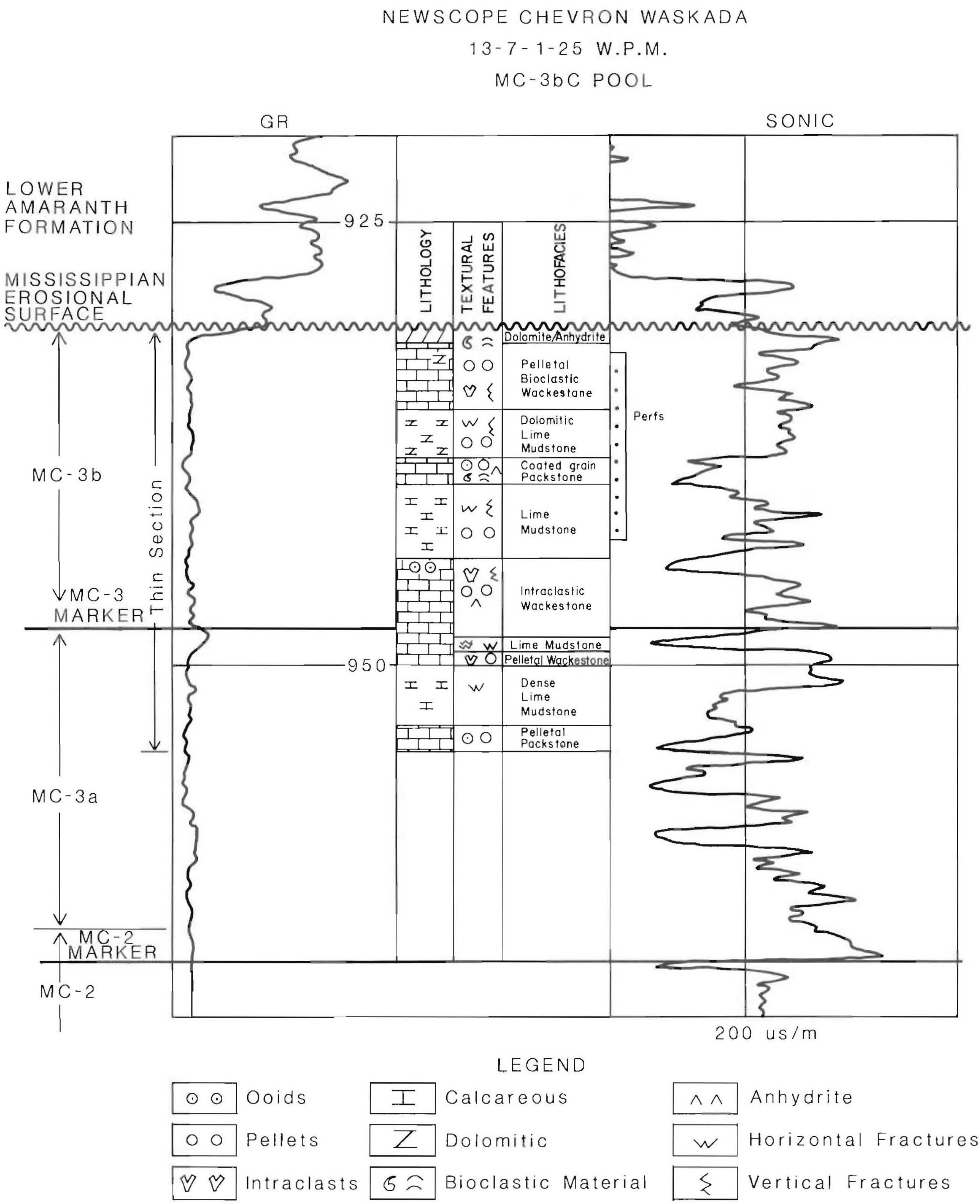


FIGURE 8: Lithology/Log correlations (a) MC-3b

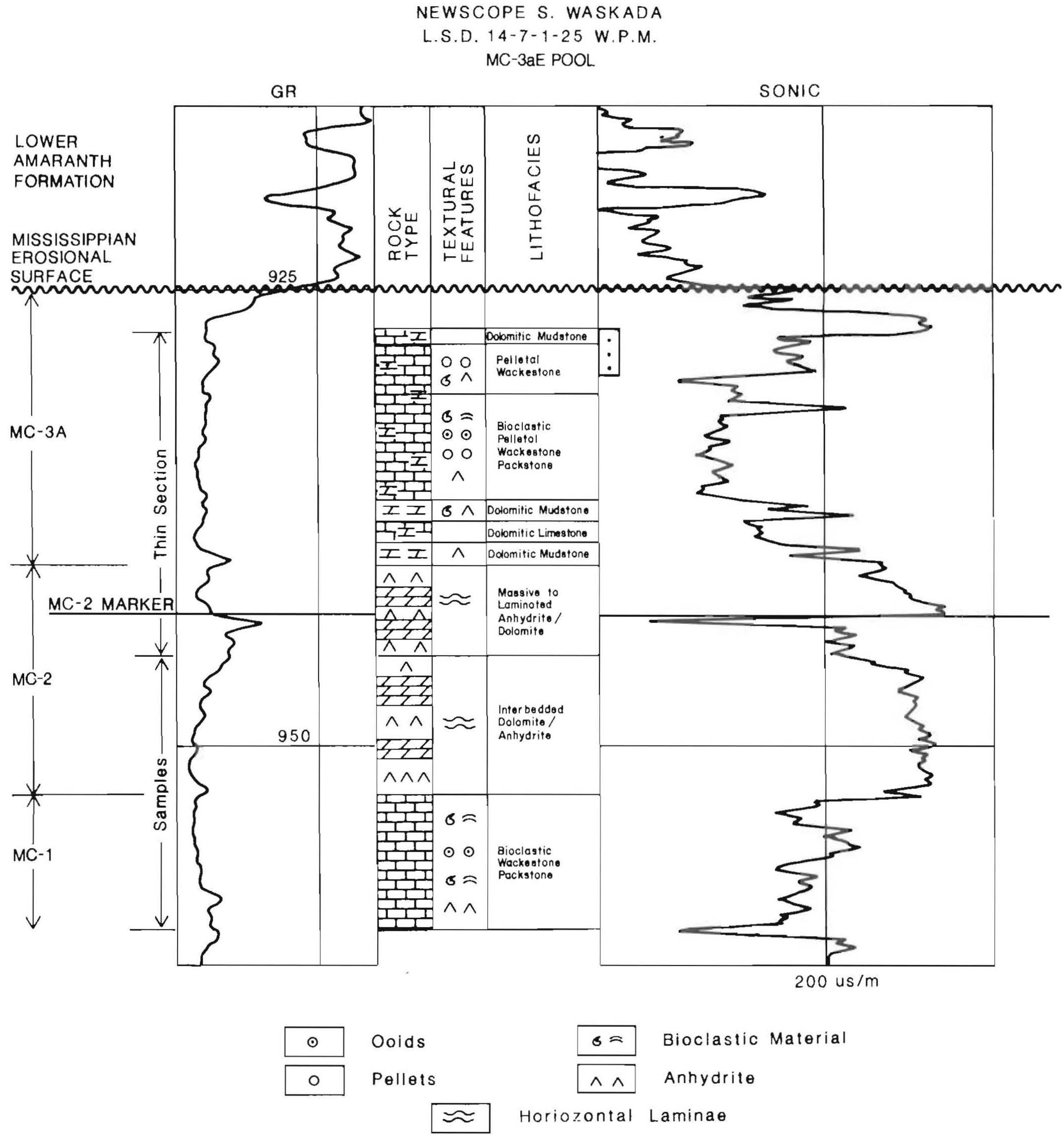


FIGURE 8: (Cont.) Lithology/Log correlations (b) MC-3a

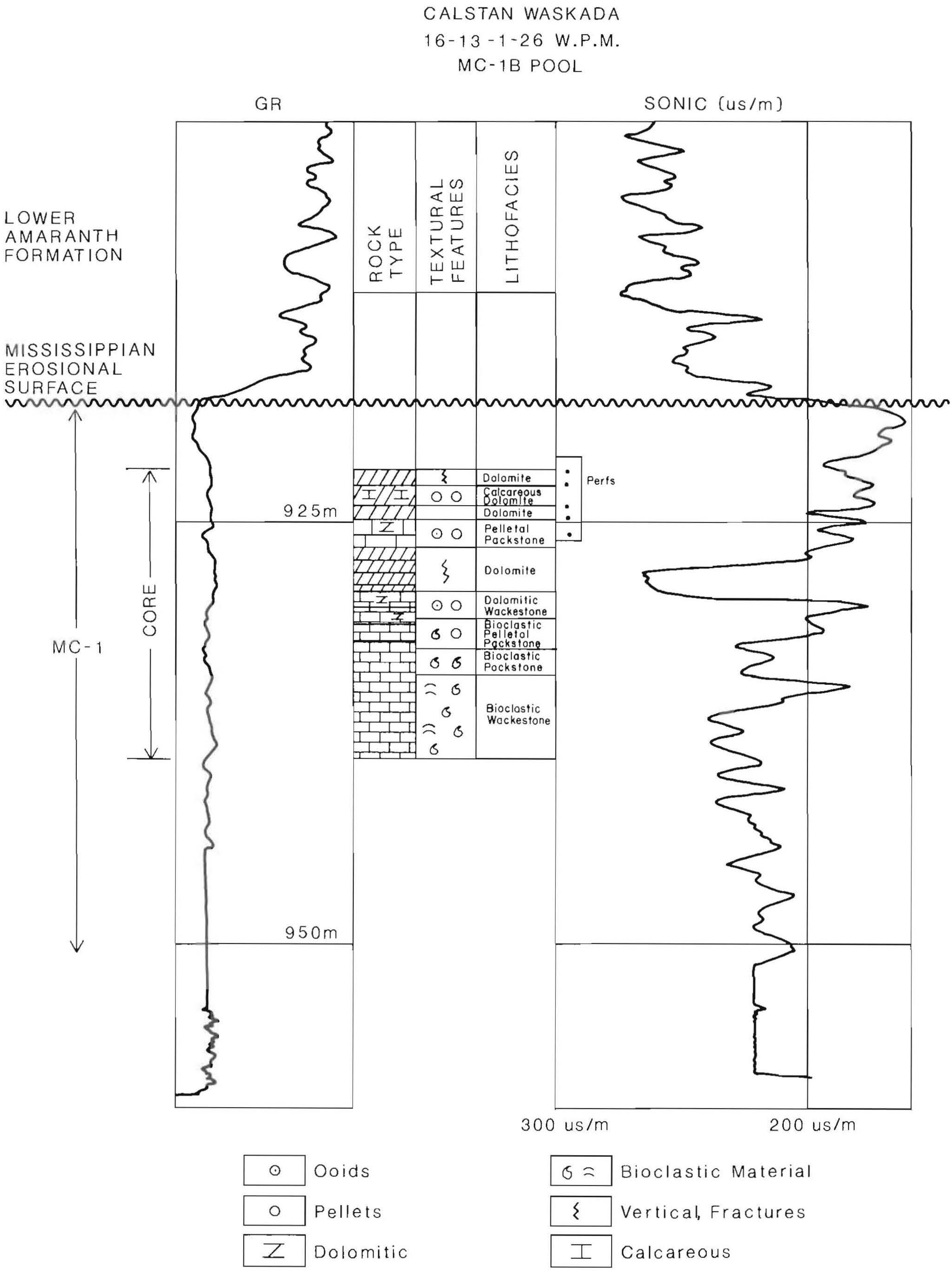
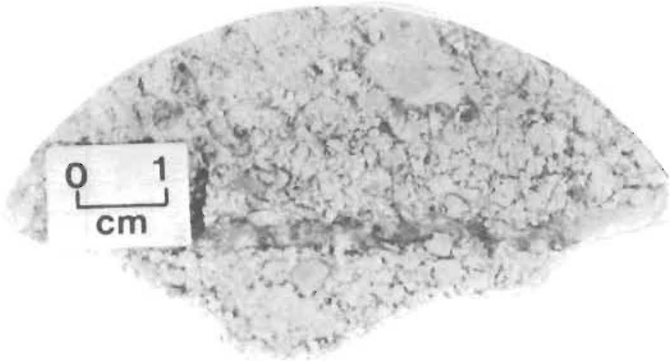
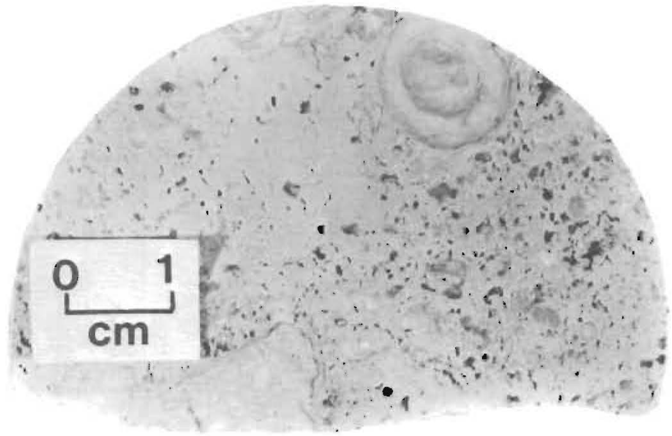


FIGURE 8: (Cont.) Lithology/Log correlations (c) MC-1



a



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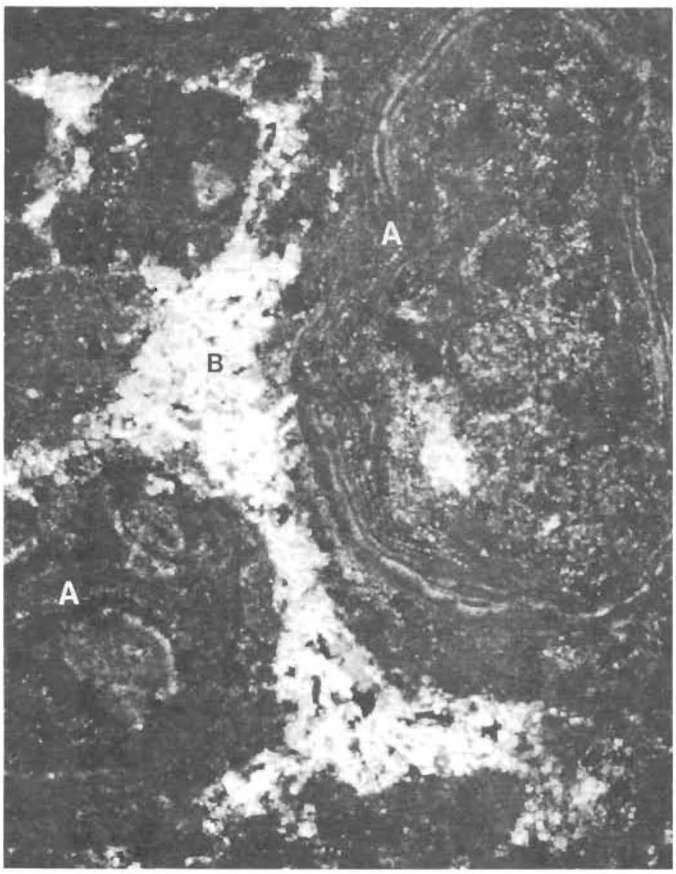


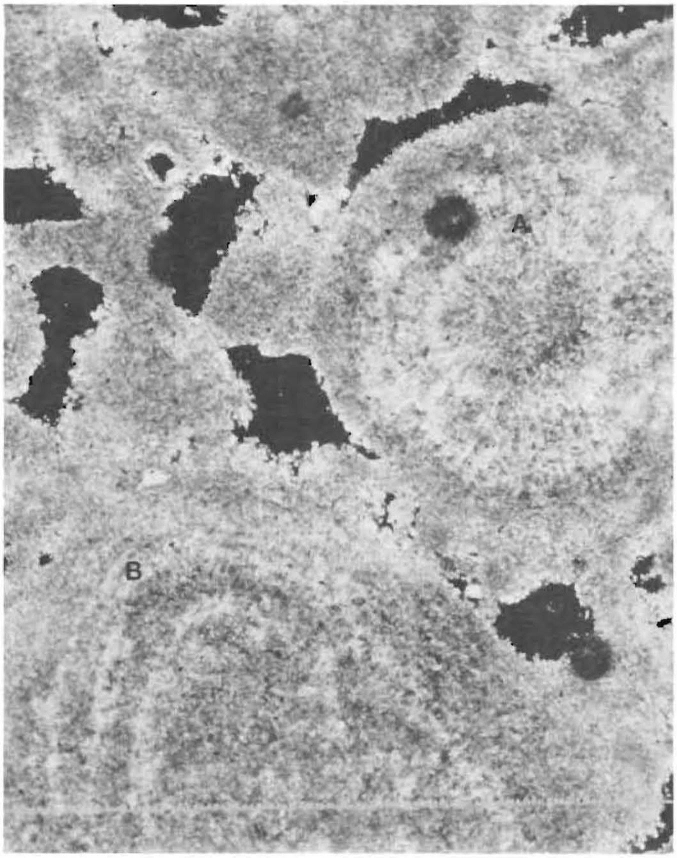
c

(a) Newscope S. Waskada 14-7-1-25 WPM; core slab-MC-3a

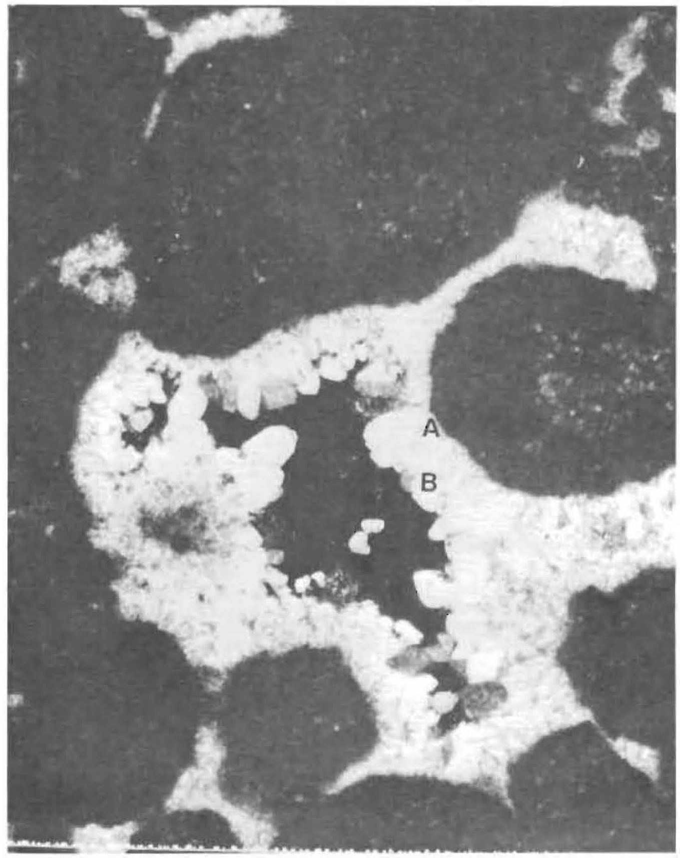
(b) Newscope S. Waskada 13-7-1-25 WPM; core slab-MC-3b
(note: compound grain (A)

(c) Algal grains (A). Micritic material within grains has been partly dolomitized. Anhydrite (B) in-fills porosity.
(MC-3b; Omega Waskada 13-27-1-25 WPM; Depth-929.9 m;
Thin section X 2.5)

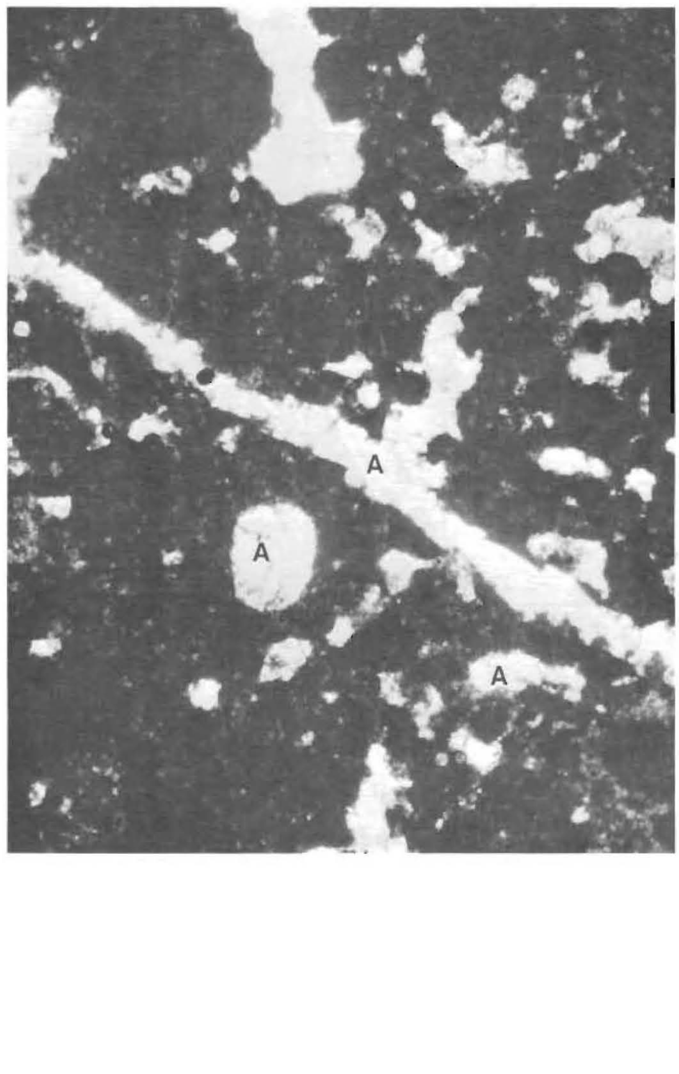
FIGURE 9: Coated grain facies



d



e



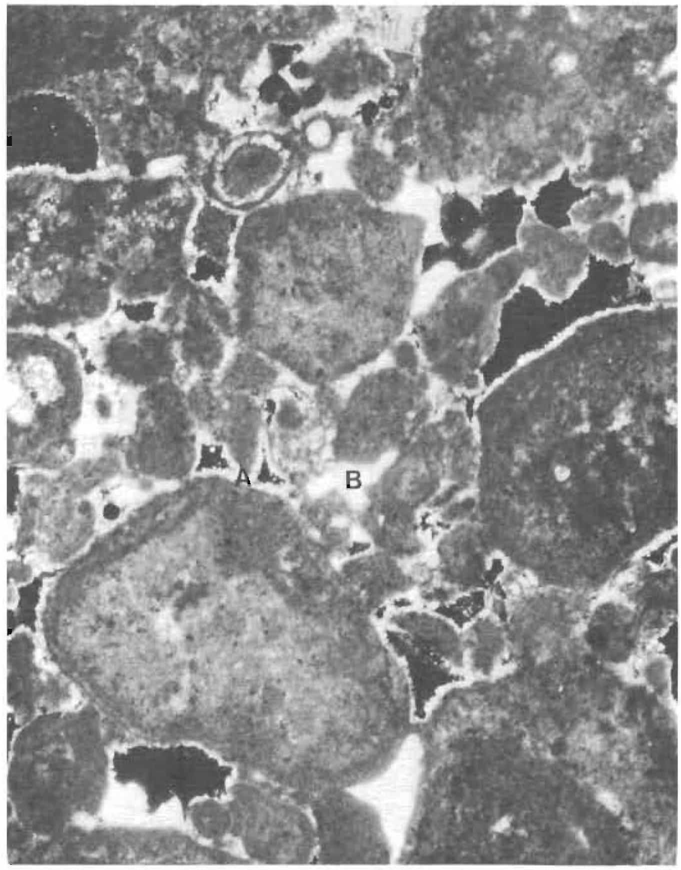
(d) Ooids display radial (A) and concentric (B) structure. (Newscope S. Waskada 14-7-1-25 WPM; Depth 930.5 m; Thin Section x 10)

(e) Grainstone: grains are cemented by a thin fringe of drusy calcite (A) and blocky calcite (B). Intergranular porosity is well developed. (Newscope S. Waskada 13-7-1-25 WPM; Depth 939.5 m; Thin Section X 2.5)

(f) Anhydrite (A) infills fracture and pore space. (Newscope S. Waskada 13-7-1-25 WPM; Depth 934.7 m; Thin Section x 2.5)

FIGURE 9: (Cont.) Coated grain facies

a



b

c

(a) Newscope S. Waskada 13-7-1-25 WPM; core slab

(b) Poorly sorted peloidal grainstone. Structureless grains are partly cemented by drusy calcite (A); anhydrite infills pore space (B).
(Omega Waskada 13-27-1-25 WPM; Depth 926.7 m; Thin Section X 2.5)

(c) Anhydrite crystal (A) infilling pore space and replacing grain.
(Newscope S. Waskada 14-7-1-25 WPM; Depth 928.2 m; Thin Section X 10)

FIGURE 10: Non-Coated Grain Facies

(c) Bioclastic Mudstone to Wackestone

Rocks of this category are characterized by abundant micrite, with grains comprising only 2 to 10 per cent of the rock (Fig. 11 (a)). Grains consist of shell fragments, intraclasts and scattered peloidal grains. In many cases the species and genera of the fossil fragments cannot be determined; however, those that have been identified include brachiopods, crinoid ossicles, ostracods and rare solitary rugose corals. Bioclasts are often filled with micrite.

Intraclasts and peloids occur as thin 'beds' up to 2 cm in thickness. Micrite intraclasts range in size from a few millimetres to 1 cm and are commonly irregular and broken in appearance.

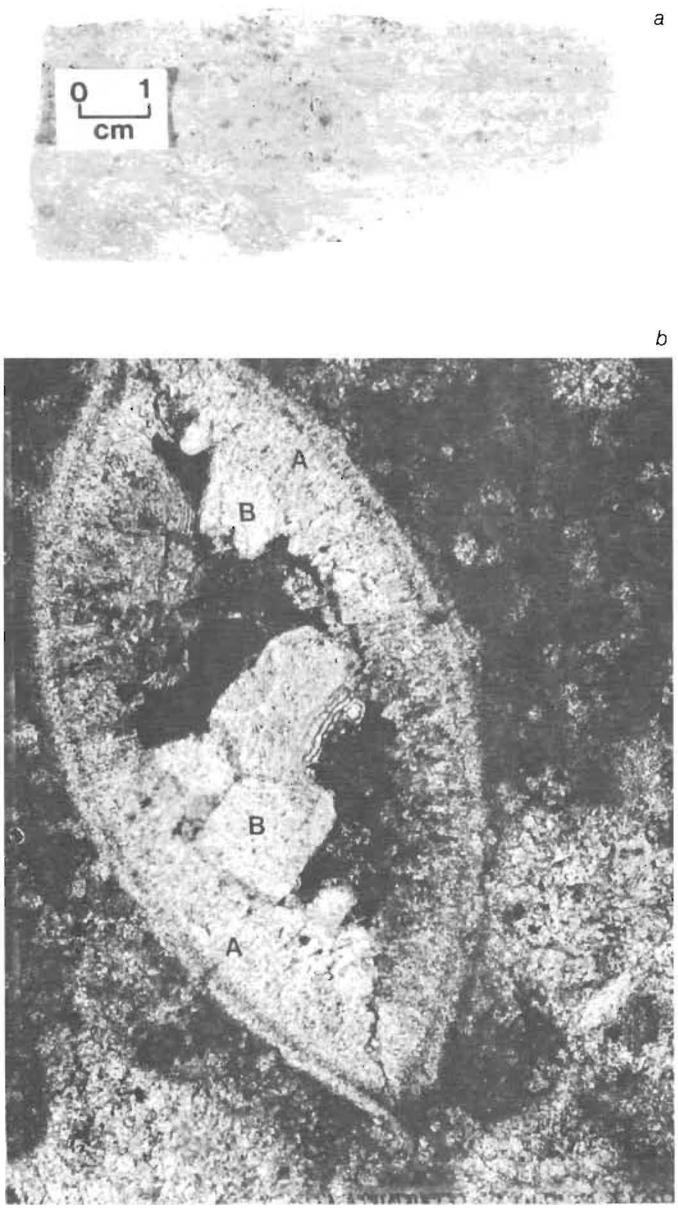


FIGURE 11: Bioclastic-Intraclastic Wackestone-Packstone Facies
(a) Chevron Waskada 16-13-1-26 WPM; core slab
(b) Ostracod: primary void space partly in-filled with two generations of calcite cement: (A) drusy; (B) blocky (Newscope S. Waskada 13-7-1-25 WPM; Depth 939.8 m; Thin Section X 2.5)

The presence of microstylolites provides evidence of post-depositional compaction. The microstylolites are generally horizontal and consist of a contorted pattern of dark organic and argillaceous-rich film.

The rocks of this facies are generally dense; porosity, where developed, occurs either as moldic resulting from dissolution of fossil grains (Fig. 11 (b)), or intraparticle within the grains. Porosity is commonly occluded by dark brown metasomatic anhydrite.

(d) Laminated Lime Mudstone

This rock type is completely micritic and is characterized by thin, horizontal laminae. In some instances nodular bedding is developed and is contorted into ovoid, irregular masses which are either separated into discrete masses or are at best poorly linked.

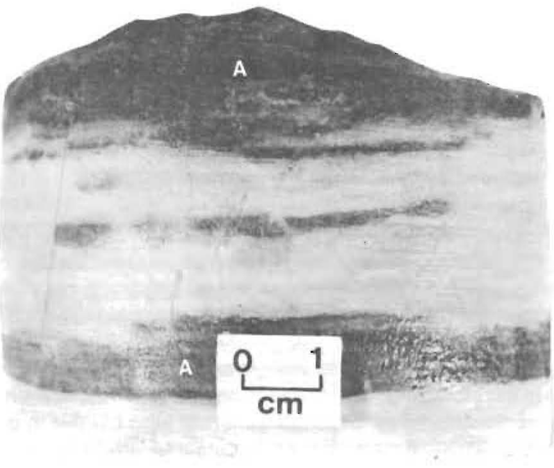
Thin (5 mm) convoluted algal laminations are a distinguishing feature of this facies (Fig. 12). Microstylolites are common, as are horizontal and vertical fractures. Stylolites generally form parallel to bedding and contain insoluble material such as hematite, argillaceous material and pyrite. These dense mudstones generally form effective top and bottom seals and act as barriers to vertical fluid migration where they have not been extensively fractured.

FIGURE 12: Laminated Lime Mudstone Facies
Roxy et al Waskada 9-26-1-26 WPM; core slab (note: stylolites (A)).

(e) Dolomite

Dolomite is present in both primary and secondary forms. Primary dolomite appears as dense microcrystalline thin beds which are interbedded with nodular and dense microcrystalline to cryptocrystalline anhydrite. Figure 13(a) illustrates that some dolomite found within Charles Formation caprock is heavily oil stained. This is an isolated occurrence as Charles Formation rocks occur to a very limited degree in the study area. Secondary (microsucrosic) dolomite is the result of both early (Mississippian) and late (Jurassic) diagenetic processes. These two types of secondary dolomite are indicative of a complex diagenetic history in the study area.

a



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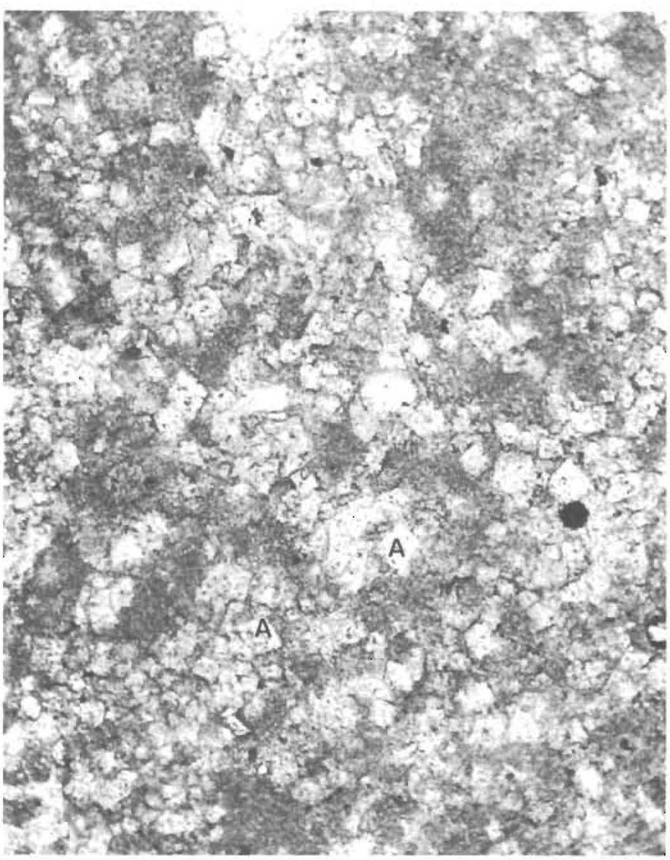


FIGURE 13: Dolomite Facies
(a) Roxy et al Waskada 9-26-1-26 WPM; core slab (note: oil staining (A))
(b) Dolomite replacing micritic material (Newscope S. Waskada 14-7-1-25 WPM; Depth 932.0 m; Thin Section X 10)

Microsucrosic dolomites are best developed near the pre-Jurassic unconformity within the anhydritized zone. Dolomitization is generally restricted to zones of lagoonal wackestones and lime mudstones (Fig. 13 (b)) although bedding contacts are transected where dolomitization is pervasive. Intercrystalline matrix porosity is generally well developed in finer grained rocks where anhydritization has not in-filled pore space.

Microsucrosic dolomite also occurs in thin zones between beds of undolomitized carbonate. These zones of dolomite are thought to represent an earlier diagenetic event which preceded dolomitization of carbonates within the overlying anhydritized zone.

The origin of microsucrosic dolomites has been the topic of considerable discussion. Fuzesy (1973) proposed that these dolomites formed by refluxing magnesium-rich, hypersaline water from supratidal flats. Authors such as Badiozamani (1973) and Folk and Land (1975) have demonstrated that dolomitization can take place in the mixing zone between phreatic fresh water and sea water.

The author believes that at least two major dolomitization events occurred. The first occurred during the Mississippian by either refluxing magnesium-rich brines from Charles Evaporite supratidal flats or within a mixing zone of phreatic fresh water and sea water during an emergent event at a time of maximum regression.

The second dolomitization event is associated with formation of the anhydritized zone. Authors such as Young and Greggs (1975) and McCabe (1959) proposed that dolomitization of Mississippian strata took place by seepage refluxion of evaporitic brine during deposition of Middle Jurassic Upper Amaranth anhydrite and this view is supported by the author.

(f) Anhydrite

The presence of both primary depositional anhydrite and secondary anhydrite associated with an anhydritized zone near the pre-Jurassic unconformity has a significant impact on reservoir quality.

The following forms have been observed in core within the study area:

i) Primary Mississippian Anhydrite

This form of anhydrite occurs in two district forms: nodular mosaic and massive bedded.

Nodular mosaic or 'chickenwire' anhydrite occurs in association with primary dolomite (Fig. 14 (a)). This type of anhydrite is thought to be indicative of a supratidal sabkha depositional setting (Maiklem et al. 1969). Nodular anhydrite occurs as in the dense caprock in the northern part of the field and is known locally as the Dando Evaporite.

Massive bedded anhydrite is characterized by subhedral texture with some mottling and interfingering.

Both massive bedded and nodular anhydrite are closely associated with dense primary dolomite.

ii) Replacement Anhydrite

Metasomatic (bladed) anhydrite occurs as brown (oil coated) elongate crystals up to 1.5 cm in length which replace calcite (Fig. 14(b)). This form of anhydrite occurs beneath the zone of anhydritization and is believed to be associated with a Mississippian diagenetic event.

iii) Secondary Anhydrite Associated with the Pre-Jurassic Unconformity

The anhydritized zone beneath the unconformity is composed mainly of dolomitic limestone with up to 60% secondary anhydrite. Anhydrite replaces carbonate, fills in voids and in places occurs as sheet-like bodies (Kendall, 1975).

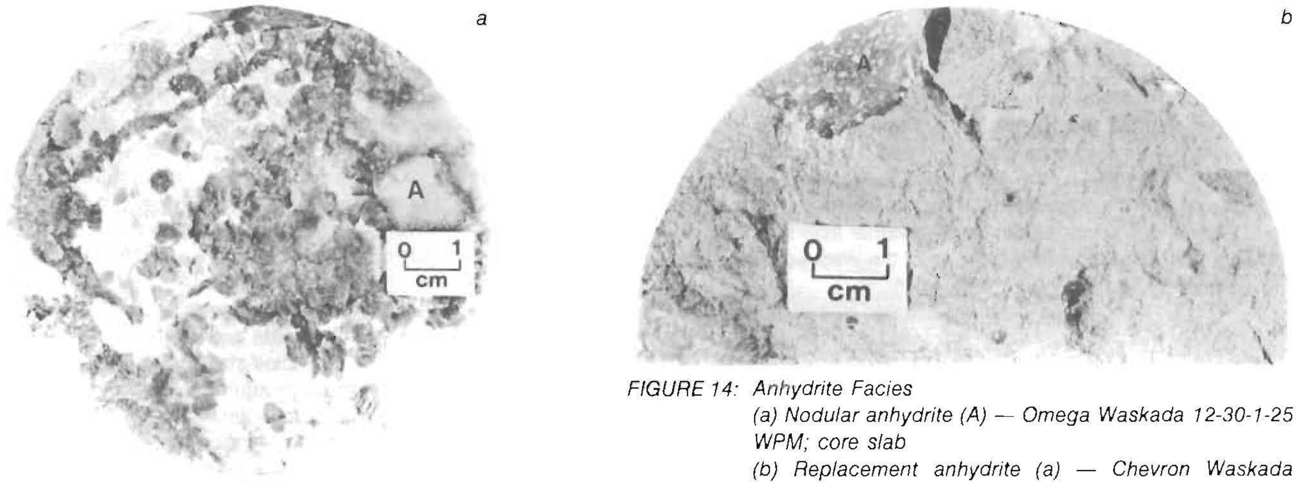


FIGURE 14: Anhydrite Facies
(a) Nodular anhydrite (A) — Omega Waskada 12-30-1-25 WPM; core slab
(b) Replacement anhydrite (a) — Chevron Waskada 16-13-1-26 WPM

In Manitoba, authors such as Young and Greggs (1975) and McCabe (1959) have noted a relationship between the thickness of the Lower Amaranth red beds and the degree of development of an underlying anhydritized zone. This is suggested as evidence to support their proposition that downward percolation of hypersaline brines during deposition of the Upper Amaranth evaporites is the likely mode of origin of the anhydritized zone.

At Waskada, the Lower Amaranth isopach thins over the structurally high Mississippian erosional surface. The Lower Amaranth red beds are sufficiently permeable to act as an oil reservoir, and Barchyn (1982) noted the presence of anhydrite cements in the red beds.

Anhydrite in the upper portion of the zone of alteration completely occludes intercrystalline, vuggy, moldic and fracture porosity and in places forms the caprock for Mississippian reservoirs. At greater depth, reservoir quality is not as adversely affected by anhydrite.

STRUCTURAL ASPECTS

GENERAL

Many structural anomalies found throughout the northern Williston Basin region have been formed by solution of salt beds of the Middle Devonian Prairie Evaporite Formation and collapse of overlying beds (Parker, 1967; Smith and Pullen, 1967; Anderson and Hunt, 1959). It is believed that the edge of the Devonian Prairie Evaporite Formation in Manitoba represents a solution edge rather than a limit of evaporite deposition. The approximate location of the Waskada Field relative to this solution edge is shown in Figure 15.

An in-depth discussion of salt solution and collapse is not within the scope of this paper; however, some ideas will be presented to lend support to the idea that multi-stage salt collapse formed the Waskada structure. Deep well control in the study area is insufficient to establish whether any basement movement has occurred; therefore, this discussion will focus on Upper Devonian and Mississippian structural styles.

Previous work by McCabe (1959, 1963, 1978) has shown the likelihood that salt solution and collapse were the mechanisms which formed structures at Virden, Daly and Waskada. Major geophysical anomaly patterns occur along the north-south trending 'Birdtail-Waskada Axis' which is thought to coincide with the postulated Churchill-Superior crustal boundary. Because the solution edge of salt in the Elk Point Group occurs along this trend, it is thought to have tectonic significance.

Comparatively few wells have been drilled below the Upper Devonian Nisku Formation in the study area; however, there is evidence of at least one major solution event during early Mississippian time (McCabe, 1959), whereas late Mississippian and possibly Jurassic and Cretaceous events are inferred.

McCabe (1959) illustrated that anomalous thickening occurs in the Bakken Formation in the few deep tests drilled in structurally high areas. This is thought to represent thickening due to solution and removal of Devonian Prairie Evaporite salt during Bakken deposition. This so-called 'anomalous thick' trends north-south through the centre of the field and is illustrated in Figure 15. Thus, it is possible that a major salt solution event occurred during early Mississippian time.

The structure on the Mississippian MC-2 marker (Fig. 16) suggests that a solution event occurred during post-Mississippian pre-erosion time. This was followed by a period of erosion which led to the partial truncation of the structure. 'Relict lows' allowed for the preservation of MC-3b and Charles beds, while the structurally high areas were eroded down to the MC-3a or MC-1 beds.

WASKADA FIELD STRUCTURE

The Waskada Field comprises a series of discrete anticlinal structures that form a very irregular 'structural complex'. The structures are either closed (as in Section 35-1-26 WPM) or open to the northeast (as in Section 30-1-25 WPM). These are illustrated in Figure 16. Although an overall structural 'trend' cannot be readily defined, the structural complex displays a generally northwest-trending aspect with reservoir beds dipping regionally in a southwesterly direction. The Waskada Field area encompasses approximately 180 km^2.

A regional structure cross-section was constructed using available deep well data and is shown in Figure 17. This section indicates that truncation of Mississippian structure occurred during the pre-Jurassic erosional event. Mississippian structure is not expressed at the erosional surface along this line of section; however, detailed structure contours on the Mississippian erosional surface (Fig. 18) and on the Mississippian MC-2 marker (Fig. 16) reveal greater complexity than is shown by the cross-section. Several local Mississippian structures are, in fact, expressed on the Paleozoic erosion surface.

Examination of the detailed structure contour maps reveals the highly variable nature of the structural complex. The areas which appear structurally low (Sections 34,35,36-1-26 WPM, Sections 6,7-1-25 WPM, Section 20-1-25 WPM) are thought to represent 'relict lows' as defined by the surrounding anticlinal structures. These lows do not appear to be low relative to regional dip (McCabe, pers. comm.).

Five separate structural highs have been defined and are designated A through E in Figure 16. These structures are more or less linear in nature but display no particular orientation. The author speculates that the structures were formed during periods of salt solution and collapse ranging from Mississippian to possibly Cretaceous time.

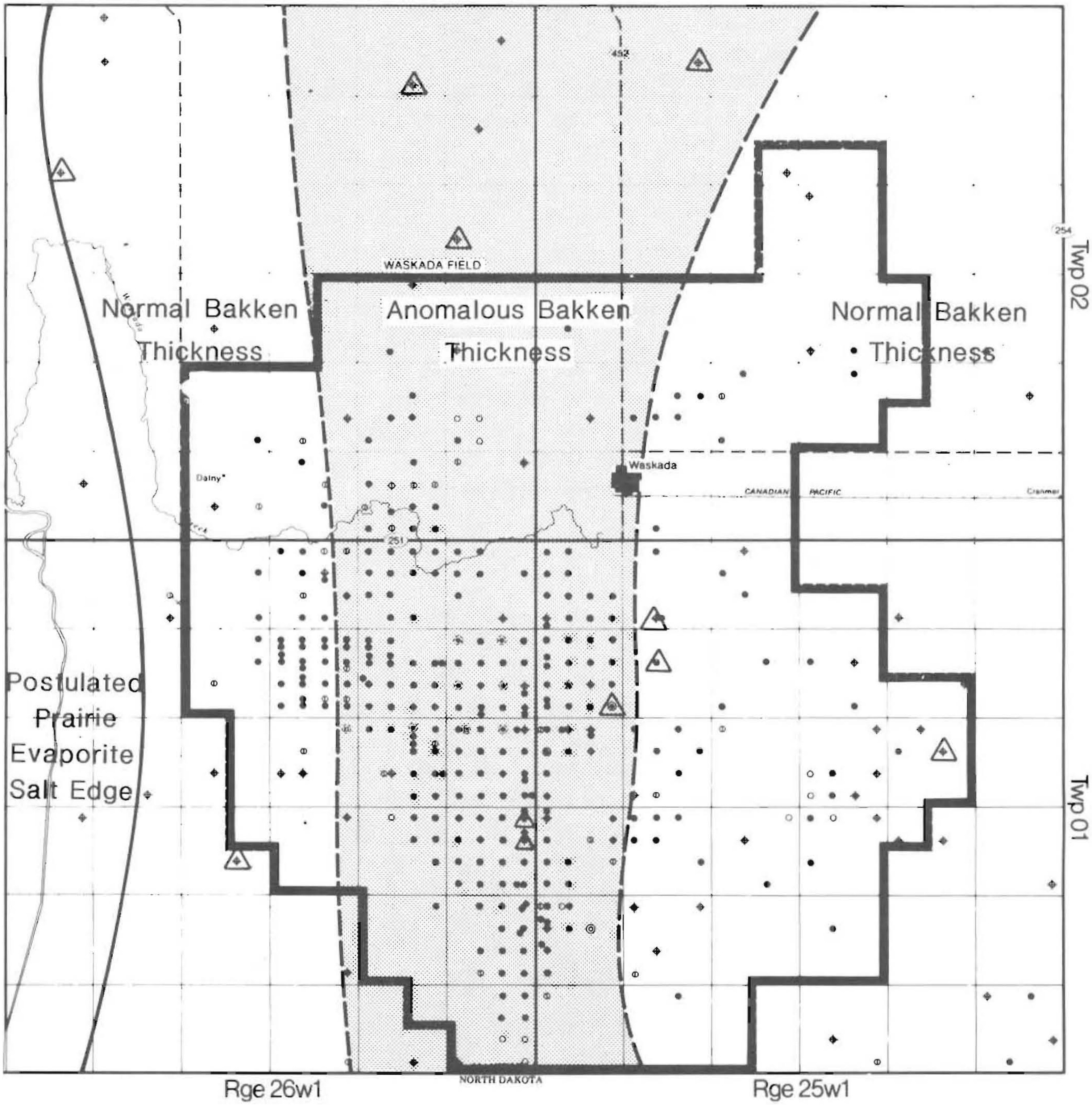
Although a detailed study of the timing of the various collapse events is not within the scope of this report it is suggested that the structures in the eastern part of the field (D,E) formed earlier than those to the west (A,B,C). The westerly structures show structural expression on the unconformity and are at least in part post-erosional and pre-Amaranth in origin. Structures D and E in the eastern part of the field are expressed only vaguely on the erosion surface. This may be due in part to differential erosion but it is likely that the easternmost structures formed either prior to or during the early stages of erosion.

Structure contours on top of the Lower Amaranth Formation (Fig. 19) show subdued expression of underlying Mississippian structure. The isopach map of the Lower Amaranth (Fig. 20) appears very regular and indicates that Lower Amaranth deposition was generally not influenced by topography.

An exception to this is in Sections 6 and 7-1-25 WPM where anomalous thickening of the red beds occurs over a structural low on the Mississippian erosion surface. A subsequent structural low on the top of the red beds in this area may be due, in part, to differential compaction.

The general absence of effects of differential compaction in the field area as shown by the red bed isopach indicates a post-Lower Amaranth structural component.

The discordance between the regional subcrop pattern and that of subcropping units in the study area is a reflection of the complex structural history noted above. The subcrop pattern in the study area (Fig. 18) illustrates the unpredictability of occurrence of truncated reservoir facies which creates a higher element of risk in development drilling than would normally be expected in simple truncation-trap settings.



Note: Wells in Shaded Area Show Anomalous Bakken Thickness

Deep Well Control

FIGURE 15: Deep Well Anomalies

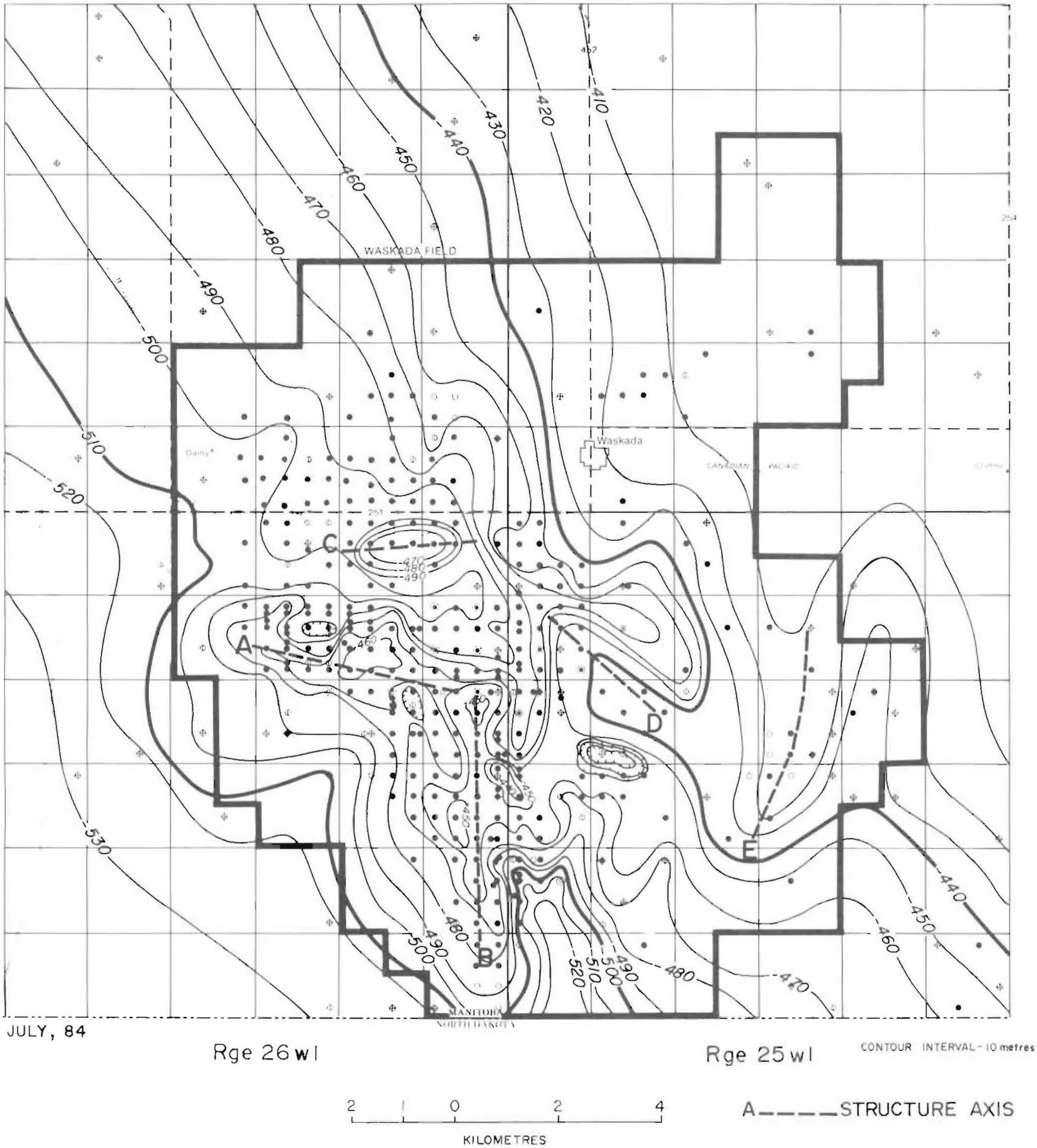


FIGURE 16: Structure on Mississippian MC-2 Marker

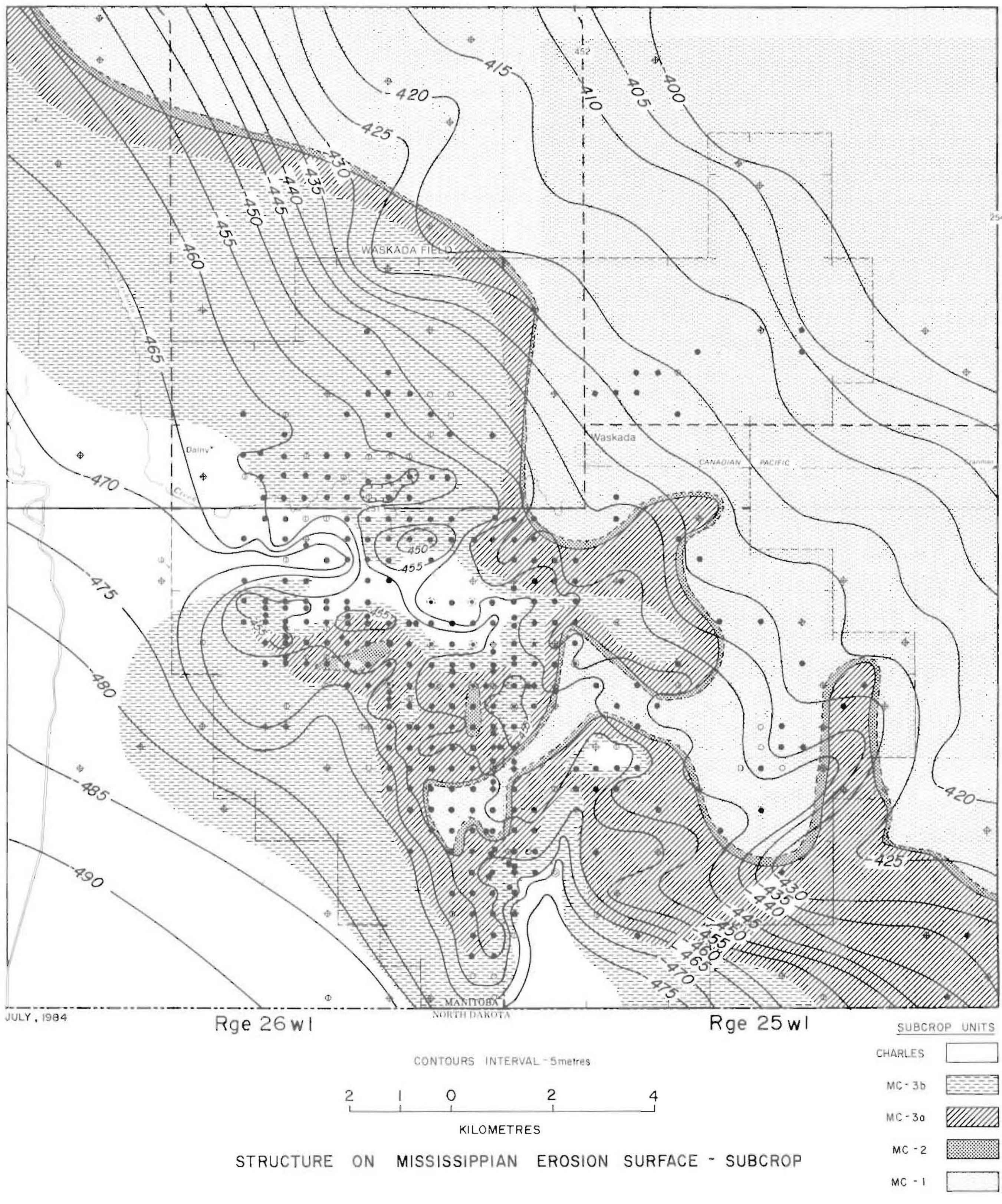


FIGURE 18: Structure on Mississippian Erosional Surface and Subcrop Map

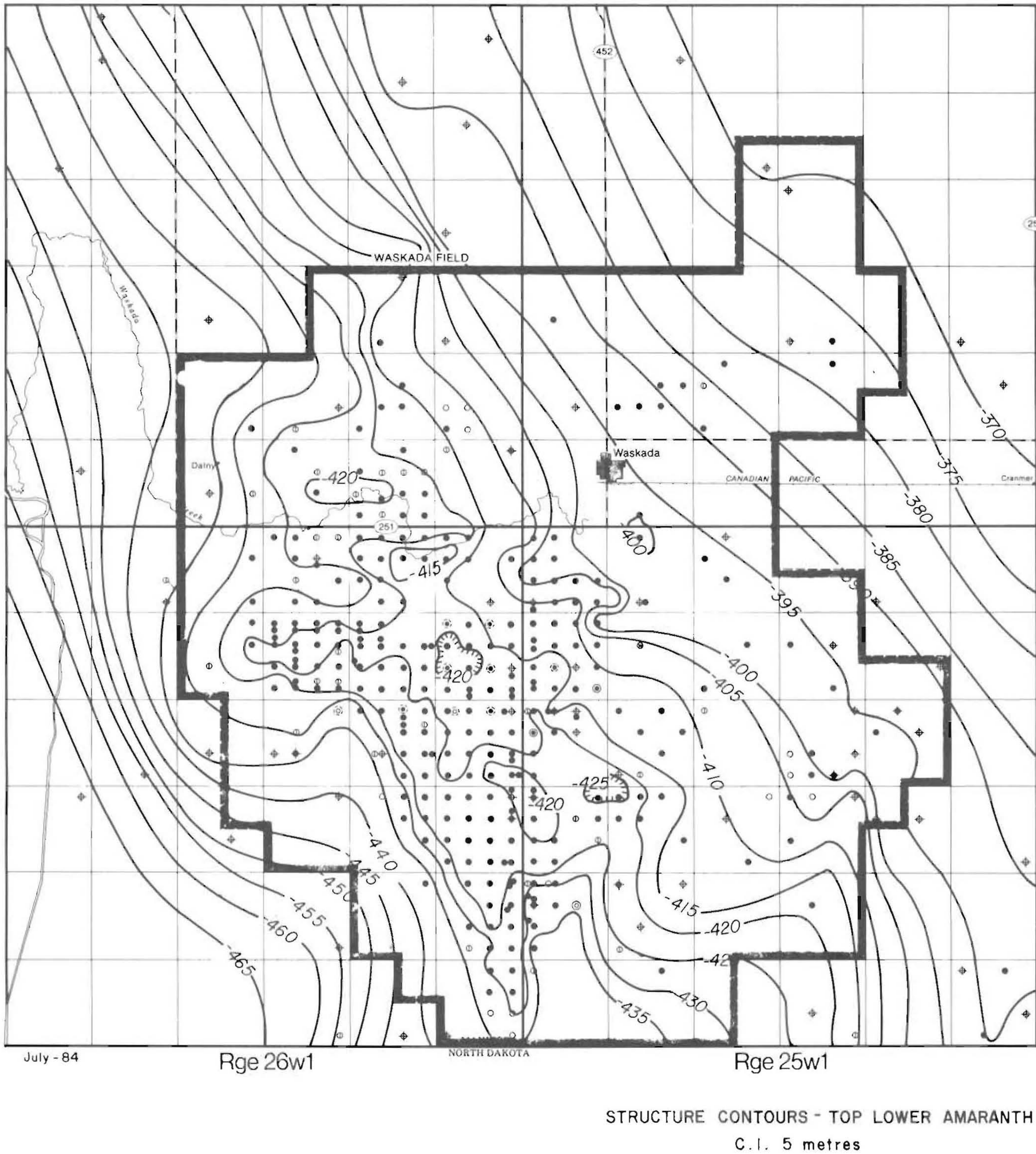


FIGURE 19: Structure Contours — Top Lower Amaranth

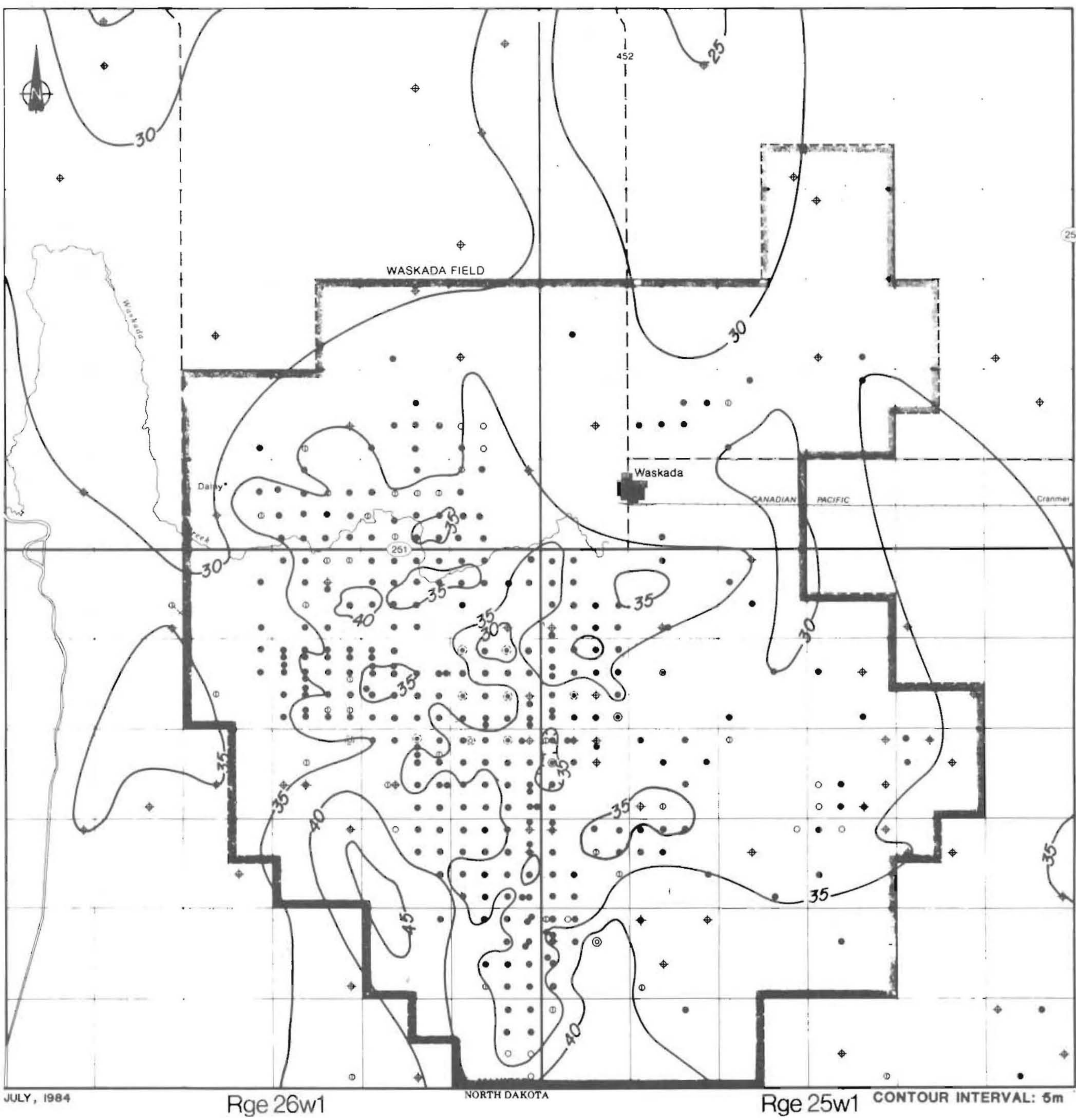


FIGURE 20: Isopach-Lower Amaranth

TRAPPING MECHANISMS

Trapping occurs regionally where subcropping porous reservoir rock is truncated at the Mississippian erosional surface. The location of the structural complex is coincident with the subcrop edge of the porous MC-1 and MC-3 members. Localization of oil accumulation in the study area is controlled partly by the position of the subcropping units.

Stratigraphically controlled variation in porosity and permeability are also extremely important in the localization of oil accumulation within the structural complex. Diagenetic factors such as dolomitization, anhydritization and leaching control reservoir quality and these secondary effects vary considerably over the entire productive area.

These stratigraphic factors combine with local structural variations in providing the limits to oil accumulation. Oil production occurs in the following trapping configurations which occur locally in the study area and are illustrated in Figure 21.

(a) Mississippian Structural High

This trap type is characterized by truncation of Mississippian structural highs. Oil accumulation of this type occurs on the crest of structures (MC-1 A,B and C Pools) which are of limited areal extent, or in truncated beds on the flanks of a structure (MC-3a A, C and E Pools). This latter type tends to encompass slightly larger areas.

(b) Structural Lows

Preserved remnants of porous MC-3b beds occur in local Mississippian lows and are productive on the steep flanks. These traps tend to be situated along the periphery of the structural complex and are expressed as structural lows on both the MC-2 marker and the Mississippian erosional surface. Preserved MC-3b beds in this setting form the MC-3b A, B, and C Pools.

These structures are believed to be early (pre-erosional) salt solution features.

(c) Primary Lithofacies Traps

Lateral facies variation from porous carbonate to anhydrite occurs at the northward extension of the MC-3b A Pool which is thought to represent the limit of deposition of MC-3b porous beds.

(d) Secondary-Diagenetic Facies Traps

The influence of various diagenetic factors has been discussed previously but warrants mention in this context. Diagenetic processes have affected reservoir quality to varying degrees in all Mississippian pools in the Waskada Field. Whereas none of these accumulations can be termed strictly 'diagenetic traps', this diagenetic component nevertheless has had or has been a major influence in localizing oil accumulation.

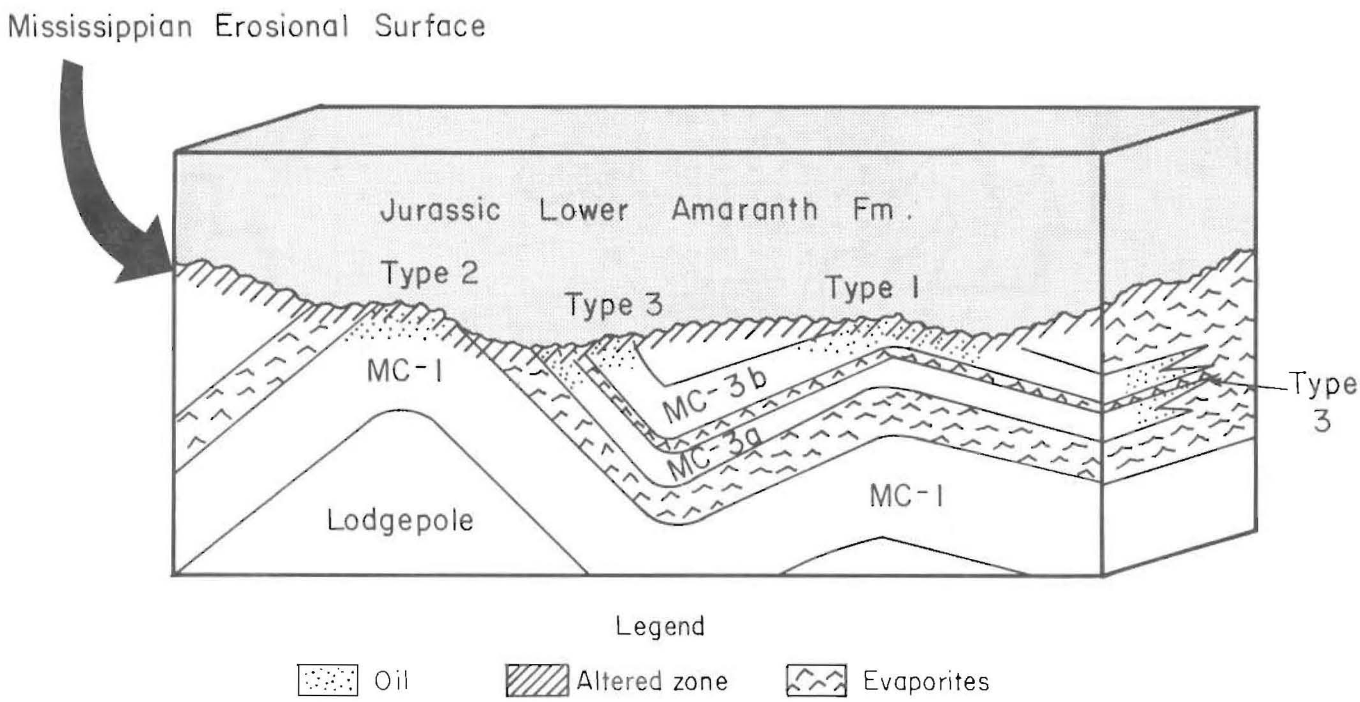


FIGURE 21: Schematic of Trap Types

RESERVOIR CHARACTERISTICS

As of June 30, 1984, there were 261 producing oil wells at Waskada, 46 of which were producing from the Mississippian. Of the remaining wells, 21 are former Mississippian wells which have been recompleted in the Lower Amaranth Formation. Reservoir parameters have been obtained from core analyses and core descriptions as well as electric logs and are shown in Table 1. Each productive interval (MC-1, MC-3a, MC-3b) is discussed separately.

MC-1

Production from the MC-1 is currently restricted to five separate pools of limited areal extent (1 to 4 wells). These wells are situated on Mississippian structural highs that have been truncated at the Paleozoic erosion surface. This type of trap is illustrated in Figure 22. The section illustrates the pronounced structural deformation which occurs in the Mississippian over very short distances. The Mississippian structural high in this example is coincident with a subtle paleotopographic high. The oil column exceeds paleotopographic closure and, as Barchyn (1982) suggested, a migration pathway exists for the passage of oil from the Mississippian to the Lower Amaranth in this type of setting. As a result of the limited areal extent of these structural anomalies, wells drilled in the MC-1 drain very limited acreage and are not prolific producers. Some typical initial production values are shown in Table 2.

The productive lithology of the MC-1 is a bioclastic packstone-wackestone with porosity as high as 18% and permeability averaging 20 md. Porosity occurs as primary intergranular and secondary solution-enlarged vugs.

Daily oil production ranges as high as 8.0 m³/day although water encroachment presents a severe problem. Water to oil ratios range from 0.2 to 25.0 and oil production declines at rates as high as 50% per year.

The top of the producing interval ranges from 1 m to 3 m below the Mississippian erosion surface and it is apparent that water encroachment increases in the absence of an effective bottom seal.

MC-3a

Oil production is obtained from the MC-3a interval in eight pools which range in size from one well (MC-3a D Pool) to twelve wells (MC-3a A Pool).

The productive reservoir facies is the bioclastic-peloidal packstone to wackestone which exhibits both intergranular porosity and micro-vuggy solution porosity. In many cases the reservoir rock found beneath the Paleozoic erosion surface has been dolomitized and subjected to anhydritization. The extent to which these rocks have been altered is variable and no distinct pattern is apparent from the limited data available. The thickness of the altered zone ranges from zero to 8 m.

TABLE 1

CHARACTERISTIC RESERVOIR DATA[1]

Parameter	MC-3b	MC-3a	MC-1
Average Porosity	13.5%	14.4%	14.0%
Average Permeability (from core analysis)	40 md	20 md	28 md
Average Net Pay Thickness (m)	3.0 m	2.5 m	2.0 m
Shrinkage[2]	0.83	0.83	0.83
Well Spacing	16 ha (40 acres)		
Recovery Mechanism	Fluid Expansion/Water Drive		
Production Decline Rate/yr			
Primary	17% (A Pool)	6% (B Pool)	48% (B Pool)
Waterflood	15% (A Pool)	—	—
Recovery Factors[3]			
Primary	25%		
Waterflood	35%		

Crude Characteristics:

(average for all 3 members)

Colour:	Brown
Density:	834 — 849 kg/m³ (35-38° API gravity)
Sulphur:	6.5 g/kg (0.65%)
Bubble Point:	6 129 KPa @ 46.7°C (889 psi @ 116°F)

[1] based on limited data
[2] Stock Tank cubic metres/Reservoir cubic metres
[3] reference: Waskada MC-3b A Pool

TABLE 2

SELECTED INITIAL PRODUCTION RATES
(5-day test)

	Well	Oil Production (m³/d)	WOR* (m³/m³)
MC-3b			
	5-7-1-25 WPM	37.0	0
	13-7-1-25 WPM	9.6	0
	11-30-1-25 WPM	5.0	0.76
	11-27-1-26 WPM	4.4	0.67
MC-3a			
	14-7-1-25 WPM	8.2	0.27
	8-12-1-26 WPM	11.0	0.31
	16-12-1-26 WPM	11.3	0.10
	8-23-1-26 WPM	13.7	0.46
	12-24-1-26 WPM	3.3	1.4
MC-1			
	1-30-1-25 WPM	7.5	0.80
	8-30-1-25 WPM	4.4	0.87

*Water/Oil Ratio

Although it is thought that dolomitization generally increases porosity, all the pores may not be effective. Studies by Davies (1979) have shown that dolomitization of limestones commonly enhances porosity and permeability to varying degrees depending on the extent of dolomitization. It has also been shown that dolomite content from 10—80% tends to decrease permeability. Dolomite contents of 80—90% show an increase in permeability, but beyond this point (90%), porosities and permeabilities tend to decrease (Powers, 1962). Thus the degree of dolomitization would determine whether or not porosity has been increased.

Porosity in the MC-3a averages 14.4% using a 1 md cut-off. Permeability is variable, ranging from 0.5 to 78 md with an average from all pools of 20 md. Anhydrite and calcite occur as pore-filling cements which cause the extreme variations in permeability both vertically and horizontally.

Vertical fractures are common throughout the MC-3a and tend to increase permeability where they are not healed with anhydrite. The lack of a definite oil/water contact is thought to be partly due to the presence of an extensive fracture network.

Wells are completed from 0.3 to 10 metres below the Paleozoic unconformity surface over perforated intervals ranging from 1—3m.

The largest and most prolific pools (MC-3a A and C Pools) are situated where MC-3a reservoir rocks subcrop on the broad flat crest of the structure in Sections 23,24,25,26 and 27 of Township 1, Range 26 WPM. Production figures are shown in Table 2 for purposes of comparison. The wells in these pools have the potential to drain 30 to 40 acres of reservoir per 40-acre spacing unit whereas wells situated along steep flanks of the structure have the potential to drain approximately 10 or 20 acres per 40-acre spacing unit. The cross-section in Figure 23 illustrates the truncation of porous MC-3a beds at the unconformity on the broad crest of the structure (10-23, 12-24, 1-25). The well in 10-30-1-25 WPM has been included to show that pools of limited areal extent (i.e., one well) are found where thin porous beds subcrop and are bounded by Mississippian structural anomalies created by the effects of salt removal and collapse.

MC-3b

Oil production is obtained from the MC-3b interval in three pools which range in size from five wells (MC-3b C) to thirteen wells (MC-3b B).

Reservoir rock consists of bioclastic-pelletal packstones and, to a lesser extent, coated grain packstones where they are sufficiently well developed.

Porosity averages 13.5% using a 1 md cut-off and may range as high as 22%. Both intergranular porosity and micro-vuggy solution porosity occur although diagenetic processes have reduced the effectiveness to varying degrees. Anhydrite and calcite occur as pore-filling cements which in places completely destroy porosity. Permeability can range as high as several hundred millidarcies and averages between 30—40 md.

Dolomitization has occurred to varying degrees in these beds but no consistent pattern has been observed from the data available. Vertical fractures are abundant and are often in-filled with anhydrite. No definite oil/water contact has been established in the various pools, partly due to the discontinuous nature of the porosity and partly due to the extensive fracture networks.

Reservoir beds in the MC-3b are situated on the downdip flanks of Mississippian structural highs where porous beds have been preserved from the effects of erosion. These anomalous highs occur as linear features which trend either north-south (Sec. 7-1-25; Sec. 30-1-25) or east-west (Sec. 27-1-26) and are bounded laterally by updip truncation at the Paleozoic erosion surface. This trapping configuration is illustrated by the cross-section in Figure 24.

Porous beds in the MC-3b A Pool in Sections 19 and 30 of Township 1, Range 25, are shown to undergo a northward facies change to anhydrite, which is unrelated to structure. Figure 25 shows the progressive thinning and eventual transition of the MC-3b porous beds to dense Dando evaporite. Thus it can be seen that oil accumulation in the MC-3b beds is controlled by the combined effects of Mississippian structure, paleotopography and lithofacies change.

Productive beds in the MC-3b underlie the Mississippian erosional surface by as little as 0.5 m to as much as 5.0 m. Wells are completed over perforated intervals ranging from 1 to 5 m.

PRODUCTION

Cumulative production figures for Mississippian pools as of July 1, 1984 are shown in Table 3.

TABLE 3

CUMULATIVE PRODUCTION TO JULY 1, 1984

POOL	OIL (m^3)	WATER (m^3)
MC-3b A	124 775.0	63 544.2
MC-3b B	20 437.1	10 132.2
MC-3b C	10 605.0	15 527.0
MC-3a A	18 225.0	18 997.3
MC-3a B	6 709.0	300.2
MC-3a C	6 762.2	9 981.7
MC-3a D	594.3	178.0
MC-3a E	7 495.0	4 779.0
MC-3a F	415.0	76.9
MC-3a G	1 557.3	2 670.0
MC-3a H	6.0	30.8
MC-1 A	1 860.7	10 780.4
MC-1 B	7 708.1	39 933.0
MC-1 C	729.0	704.1
MC-1 D	201.1	5 968.0
MC-1 E	401.4	4 201.0

CONCLUSIONS

The development of the Waskada Field from discovery to present day has revealed that complex stratigraphic and structural controls combine to localize oil accumulation. The drilling hiatus experienced in the '60s and '70s is significant in that it illustrates the tendency on the part of many geologists to underestimate the complexity, and hence the true potential, of a given area. The potential of the Mississippian Mission Canyon has not yet been fully realized within the study area or beyond.

Reservoir rock in the study area consists primarily of limestones and dolomitic limestones. These grainstones, packstones and wackestones are indicative of cyclic deposition in a shallow water low-energy environment. Diagenesis is thought to have occurred during both the Mississippian and Jurassic. The effects of dolomitization, anhydritization and leaching have altered the original character of the reservoir rock considerably. The prediction of the occurrence of favourable reservoir rock thus becomes an arduous task.

The structural complexity of the Waskada Field is thought to result from multi-stage solution and collapse of the Middle Devonian Prairie Evaporite Formation. A major single solution event is thought to have occurred during early Mississippian (i.e. Bakken) time. An anomalously thick Bakken Formation through the centre of the study area lends support to this contention. Subsequent local salt collapse events occurred both prior to and following the pre-Jurassic erosional event. Further study is warranted to determine the precise timing of events. Salt solution and collapse may have occurred on a local scale through to the Cretaceous time; however, this is unsubstantiated at this time.

Oil is trapped in Mississippian reservoir rock that has been truncated at the pre-Jurassic erosional surface. The complex structural component cited above in combination with the effects of erosion has resulted in the formation of a highly contorted pattern of subcropping units.

Virtually all Mississippian oil accumulations in the Waskada Field occur in truncation-type traps with an underlying Mississippian structure. One purely stratigraphic trap created by depositional facies change has been identified.

All reservoir rock in the study area has been subjected to secondary diagenetic processes which ultimately control porosity and permeability.

Oil accumulations originating through complex multiple-stage salt solution events, although not predictable, can be found through careful mapping of Mississippian Bakken—generated structure. Subtle structural expression on the Mississippian erosional surface may, in some cases, provide an indication of underlying Mississippian structure.

Detailed mapping of subcropping reservoir facies must be integrated with both internal Mississippian structure and Mississippian erosional structure in order to identify possible trapping configurations.

Development of these types of reservoirs must also include an understanding of the various diagenetic factors which influence reservoir quality and act as a control in oil accumulation.

Reservoir evaluation would be enhanced if greater emphasis were placed on testing and coring programs.

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APPENDIX: SELECTED CORE DESCRIPTIONS

Of the 46 wells which are producing from the Mississippian Mission Canyon (as of June 30, 1984), 40 wells were cored. Wells in which complete sections were recovered are few. Reasons for this include:

a) common operator practice of only coring the overlying Lower Amaranth red beds and penetrating approximately 15 m into the Mississippian;
b) combined effects of Mississippian structure and erosion often result in partial truncation of reservoir facies;
c) incomplete sequences of core from various older wells are due to mishandling and poor storage facilities in the 1950s and 1960s.

Five core descriptions are included which were described according to the following terminology:

a) Porosity Grade

poor porosity	0- 6%
fair porosity	6-12%
good porosity	12-18%
excellent porosity	greater than 18%

b) Lithology—Dunham's classification.

OMEGA WASKADA 2-25
2-25-1-26 WPM
MC-3a

927.0—930.9 m	Anhydrite: dense, laminated (algal)
930.9—931.0 m	Lime mudstone: laminated
931.0—932.5 m	Dolomitic mudstone with algal laminated anhydrite interbeds
932.5—940.0 m	Biolastic packstone-grainstone: good interparticle porosity, brachiopod, crinoid fragments
940.0—941.5 m	Lime mudstone: algal laminated
941.5—943.0 m	Anhydrite: nodular with dolomite

OMEGA WASKADA 13-27
13-27-1-26 WPM
Lower Amaranth

917.0—918.3 m	Siltstone: reddish brown, tight with interbedded shale

MC-3b

918.3—920.3 m	Anhydrite: dense, massive, brecciated at top
920.3—923.5 m	Pelletal packstone: poor vuggy porosity with anhydrite infill
923.5—924.0 m	Lime mudstone: laminated
924.0—927.0 m	Oolitic pelletal packstone-grainstone: very good interparticle and vuggy porosity
927.0—927.7 m	Lime mudstone: dolomitic, vertical fractures, stylolites
927.7—930.6 m	Oolitic packstone: fair interparticle porosity, anhydrite infill, vertical fractures
930.6—935.0 m	Anhydrite: massive grading to dolomite with depth, interbedded laminated anhydrite, vertical fractures

CHEVRON STANDARD WASKADA 16-13
16-13-1-26 WPM
MC-1

3024—3029 feet (921.9—923.5 m)	Dolomitic mudstone: vertical and horizontal fractures
3029—3030 feet (923.5—923.7 m)	Pelletal packstone: dolomitic, tight
3030—3037 feet (923.7—926.0 m)	Oolitic packstone: dolomitic micrite matrix, excellent micro-vuggy porosity, oil-stained
3039.4—3047.5 feet (926.0—929.1 m)	Dolomitic Mudstone: thin anhydrite laminations
3047.5—3053.0 feet (929.1—930.7 m)	Pisolitic wackestone: recrystallized micrite matrix, excellent intercrystalline porosity
3053.0—3057.0 feet (930.7—932.0 m)	Bioclastic—oolitic packstone: good interparticle porosity; good vuggy porosity, crinoid, brachiopod fragments, oil-stained
3057.0—3079.0 feet (932.0—938.7 m)	Bioclastic packstone: good to excellent porosity; oil-stained, grades to wackestone at depth; increasingly chalky

ROXY ET AL WASKADA 9-26
9-26-1-26 WPM
MC-3a

928.7—929.0 m	Dolomite: microcrystalline, dense, slight oil stain
929.0—929.5 m	Sandstone: fine-medium grained, medium-well sorted, dolomitic
929.5—936.0 m	Oolitic packstone: good solution-enlarged porosity, increasingly anhydritic with depth, horizontal fractures
936.0—941.0 m	Core not logged
941.0—946.8 m	Anhydrite: massive-nodular with interbedded dolomitic mudstone, algal laminated mudstone, vertical fractures with hematite infill

NEWSCOPE WASKADA 10-7
10-7-1-25 WPM
MC-3b

944.25—946.1 m	Anhydrite: massive, dense, slightly mottled
946.1—946.5 m	Siltstone/anhydrite: brecciated
946.5—949.8 m	Anhydrite/dolomite: interbedded nodular anhydrite with dense crystalline dolomite
949.8—953.6 m	Pelletal packstone: dolomitic with abundant anhydrite infill
953.6—961.0 m	Bioclastic pelletal/packstone: tan, good solution porosity with some infilling of pores with anhydrite, stylolites