Province of Manitoba

Department of Mines and Natural Resources

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MISSISSIPPIAN STRATIGRAPHY OF MANITOBA

by

HUGH R. McCABE

WINNIPEG

1959

Province of Manitoba

Department of Mines and Natural Resources

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Preface

Mississippian strata do not outcrop anywhere in Manitoba or elsewhere in the Williston Basin. Their presence in Manitoba was first revealed in 1949 during drilling of the Souris Valley White 5-14-1-28 well. In the past 10 years, as a result of exploration for oil in the Mississippian rocks of the province, considerable data on this system have accumulated.

This report, in dealing with the Mississippian rocks in Manitoba, directs attention towards their relationship to equivalent formations in adjacent areas of the Williston Basin. In particular, problems of correlation and nomenclature, arising partly out of rapid facies changes basinward from the shelf areas, and partly as a result of pre-Jurassic erosion, are discussed.

A brief discussion of the occurrence of oil in the Mississippian strata, especially in the Lodgepole formation, in Manitoba is presented. It is noted that no oil production has been obtained from Lodgepole beds elsewhere in the Basin and, further, that although oil is recovered from the Mission Canyon and Charles formations in other parts of the Basin, there has been almost no production from these formations in Manitoba. Reasons for this distribution of oil are sought.

J. F. Davies,
Chief Geologist

October, 1959

MISSISSIPPIAN STRATIGRAPHY OF MANITOBA

Introduction

Beds of Mississippian age do not occur in outcrop anywhere in Manitoba or adjacent areas of Saskatchewan and North Dakota. As a result, the presence of Mississippian rocks in Manitoba was not established definitely until 1949 when several deep stratigraphic test holes were drilled in the extreme southwestern part of the province. In December 1951, the first oil discovery in Manitoba was made in the Daly area, with production from the Mississippian Lodgepole formation. This proved to be the discovery well for the Daly field, and the first commercial producing well in the Williston Basin area. Since that time there has been considerable expansion in oil exploration and development in Manitoba. Up to the end of 1958 a total of more than 1,600 wells had been drilled. This included more than 800 producing wells in three main fields and eleven smaller fields. In addition production has been obtained from a number of local areas outside of designated fields. Cumulative production to the end of 1958 has been approximately 25 million barrels, valued at over $46,000,000.

All oil production in Manitoba has been from strata of Mississippian age, even though these rocks form only a small percentage of the total sedimentary section in the province. This study was undertaken because of the economic importance of Mississippian rocks not only in the Province of Manitoba but also in neighboring areas. It is based entirely on examinaton of core, cuttings and mechanical logs from oil field wells and exploration wells drilled by oil companies in Manitoba. These wells provide the only direct source of information regarding the occurrence of Mississippian strata in Manitoba.

GEOLOGICAL SETTING

Manitoba is situated, geologically, on the northeastern edge of the Williston Basin, an area of approximately 100,000 square miles, centered in northwestern North Dakota (Fig. 1). The history of this area has been characterized by continued differential subsidence and accumulation of sediments since Ordovician time. Palaeozoic sediments of Ordovician to Mississippian age dip gently to the southwest towards the basin, at from 16 to 60 feet per mile, averaging 30 feet per mile. The Palaeozoic sequence, consisting almost entirely of carbonate rocks, is overlain with marked unconformity by Mesozoic sediments, of Jurassic and Cretaceous age, which dip less steeply to the southwest at about 12 feet per mile. The Mesozoic strata, in marked contrast to the underlying Palaeozoic rocks, consist largely of sands and shales. Flat-lying Cenozoic sediments are present locally in the Turtle Mountain area.

The entire stratigraphic succession has been subjected to Cenozoic erosion, especially Pleistocene glaciation. The resulting erosion surface shows a general dip to the northeast and this dip, combined with the southwesterly dip of the strata, has resulted in the exposure at the erosion surface of a series of long, linear, north-northwest trending outcrop belts with successively older strata exposed to the northeast. The entire stratigraphic succession has been truncated in the northern and extreme eastern parts of the province, exposing the Precambrian basement rocks.

Almost the entire area is covered with a mantle of late glacial and post-glacial deposits, up to about 450 feet in thickness.

With the exception of the Mississippian, all stratigraphic units present in the Manitoba section outcrop in this belt (Fig. 2). The Mississippian strata are buried underneath the overlapping Jurassic sequence, and are found only in the subsurface of the southwestern part of the province.

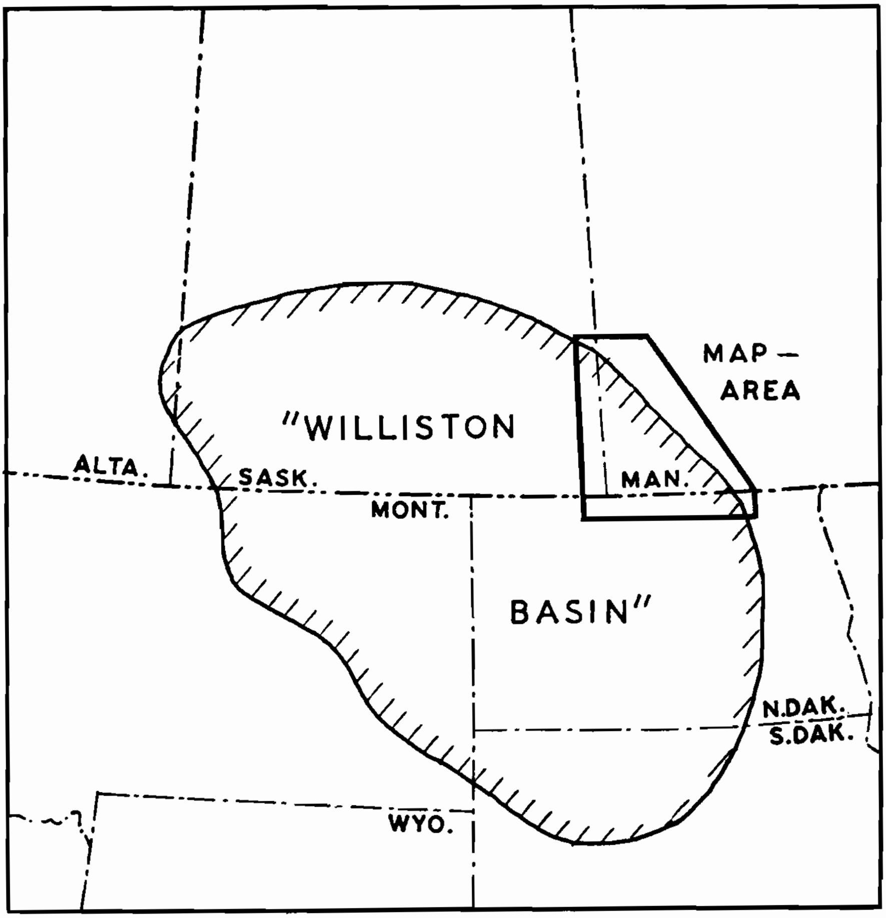


Figure 1. Outline map of the Williston Basin area showing relationship to the map area.

The presence of Mississippian strata in Manitoba was not determined until 1949, when a section of approximately 900 feet of predominantly carbonate rocks, occurring between sediments of known Jurassic and Devonian ages, was discovered in the Souris Valley White 5-14-1-28 well. These sediments were assigned by Kerr (1949) to the Mississippian system; subsequent subsurface exploration and palaeontologic evidence have proved these correlations correct.

Shortly after the discovery of Mississippian rocks in Manitoba the first producing well in the Williston Basin area, Calstan Daly 15-18-10-27, was drilled about eight miles southwest of the town of Virden in what eventually proved to be the Daly oil field. Production was obtained from crinoidal limestone beds of the Mississippian Lodgepole formation. This discovery stimulated intensive oil exploration in Manitoba and adjacent parts of Saskatchewan and North Dakota, and led to the discovery of numerous important oil fields in these areas. At present by far the largest amount of production in the basin is from the Mississippian, and in Manitoba production is obtained only from rocks of this system.

PURPOSE AND SCOPE

Considerable stratigraphic research on Mississippian strata has been carried out in Manitoba and adjacent areas, but relatively little has been published. Recently, however, several excellent papers dealing with more or less local areas or fields have been presented; these cover only parts of the total Mississippian section. The purpose of this report is to integrate these local stratigraphic studies, and to complete a regional stratigraphic study of the entire Mississippian sequence found in Manitoba. In addition, the relationship of the Manitoba section to the overall Williston Basin sequence and, especially, to adjacent areas in Saskatchewan and North Dakota is discussed in some detail. Problems of correlation and nomenclature are reviewed, and the relation of the various producing zones to the lithofacies and tectonic frameworks is considered. This report presents the results not of a detailed or exhaustive study of Mississippian stratigraphy in Manitoba, but rather of a general or regional stratigraphic analysis; much more lithologic and petrographic information remains to be compiled. It is hoped, however, that some of the correlations and interpretations presented in this report will contribute to the understanding of the complex history of Mississippian sedimentation as found in the Manitoba portion of the Williston Basin.

During the summers of 1954, 1955 and 1956, the writer carried out an extensive study of Mississippian Madison group sediments in the Williston Basin area, with particular emphasis on the northeastern corner, including Manitoba and adjacent areas of Saskatchewan and North Dakota. That work is to be the basis for a dissertation at Northwestern University, Evanston, Illinois. This report constitutes a more detailed study of Mississippian strata in the Manitoba portion of the basin.

PREVIOUS WORK

The first published report of Mississippian strata in Manitoba was by Kerr (1949) who noted the presence of a thick sequence of sediments between strata of known Devonian and Jurassic ages. Subsequently, Ower (1952) subdivided the Mississippian rocks in the Daly area into two units, A, an upper predominantly carbonate unit, and B, a basal shale and sand or silt unit. He discussed the lithology and correlation of each unit.

During the period 1949 to 1954 the terms Lodgepole, Mission Canyon and Charles came into common usage as stratigraphic subdivisions of the Mississippian system in Manitoba. The terms originated in central Montana where the type sections of these formations are found. Nordquist (1953) proposed the name Bakken for the black-shale and siltstone unit occurring at the base of the Mississippian section in the northern part of the Williston Basin.

Thomas (1954) proposed a breakdown of Mission Canyon strata into members MC-1 to MC-5 in inclusive, based on marker-bed correlations. Sediments overlying the Mission Canyon MC-5 member were correlated with the Charles formation.

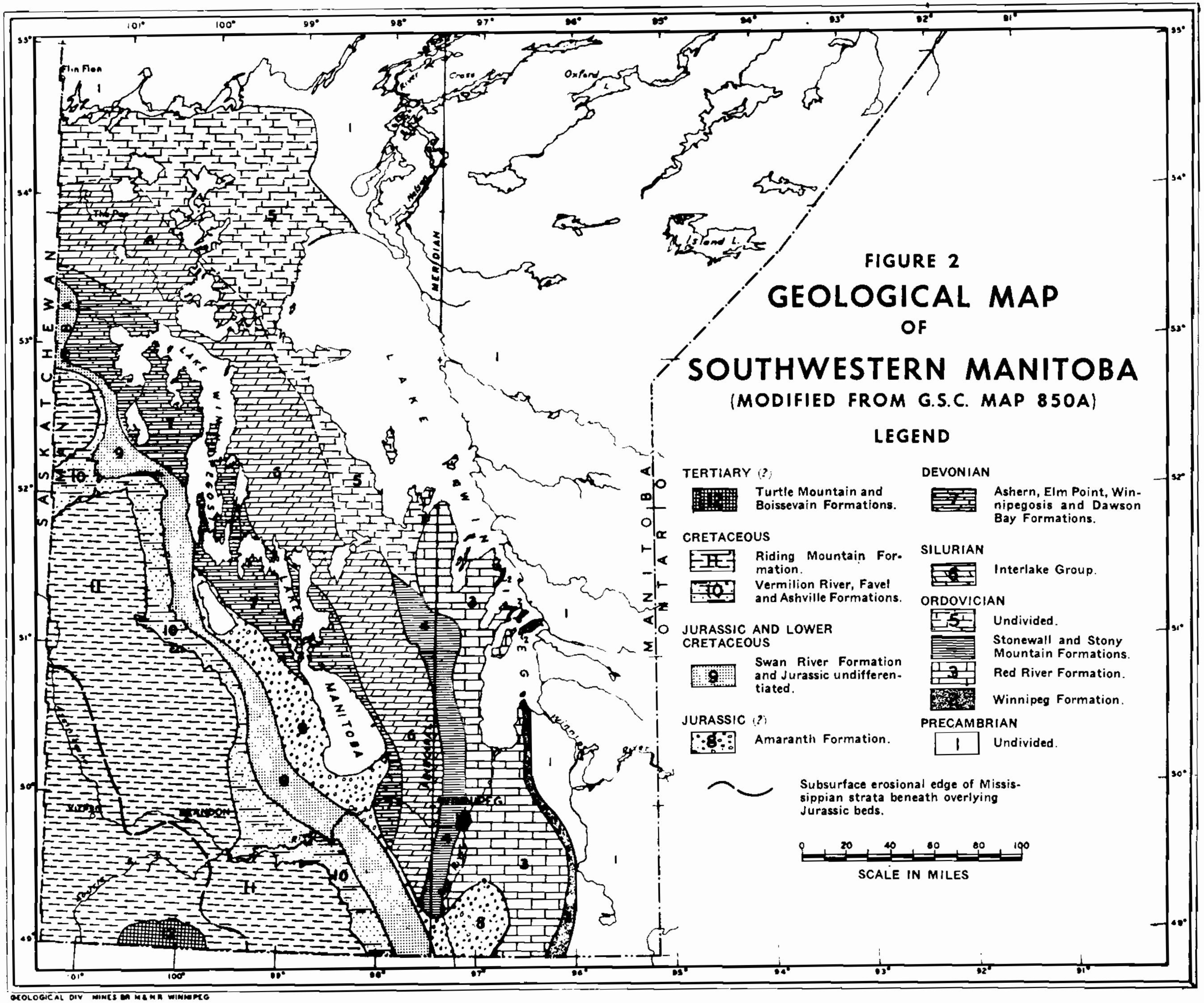


FIGURE 2
GEOLOGICAL MAP
OF
SOUTHWESTERN MANITOBA
(MODIFIED FROM G.S.C. MAP 850A)
LEGEND
TERTIARY (?)
Turtle Mountain and Boissevain Formations.
CRETACEOUS
Riding Mountain Formation.
Vermilion River, Favel and Ashville Formations.
JURASSIC AND LOWER CRETACEOUS
Swan River Formation and Jurassic undifferentiated.
JURASSIC (?)
Amaranth Formation.
DEVONIAN
Ashern, Elm Point, Winnipegosis and Dawson Bay Formations.
SILURIAN
Interlake Group.
ORDOVICIAN
Undivided.
Stonewall and Stony Mountain Formations.
Red River Formation.
Winnipeg Formation.
PRECAMBRIAN
Undivided.
Subsurface erosional edge of Mississippian strata beneath overlying Jurassic beds.
0 20 40 60 80 100
SCALE IN MILES
SASKATCHEWAN
MANITOBA
ONTARIO
MERIDIAN
LAKE WINNIPEG
LAKE WINNIPEGOSIS
LAKE MANITOBA
Flin Flon
The Pas
Oxford L.
Cross
Island L.
WINNIPEG
BRANDON
GEOLOGICAL DIV MINES BR M & N R WINNIPEG

This subdivision was intended primarily for use in North Dakota and Saskatchewan, but Thomas extended his correlations to the Anglo Ex Souris Valley Smart 4-1-1-26 well in southwestern Manitoba where he indicated the presence of all five MC units. More recent information shows correlation errors in Thomas' work. The MC-4 and MC-5 of Saskatchewan are not correlative with, but are stratigraphically higher than, the MC-4 and MC-5 of Manitoba.

In Thomas' system the odd-numbered units correspond to limestone beds, and the even-numbered units to evaporite beds. Unfortunately, the rapid lateral lithologic changes in these units make correlations difficult in some areas. For instance in Manitoba it is difficult or impossible to distinguish the MC-5 member as it has become predominantly evaporitic. In addition, evaporites occur stratigraphically within the MC-3 member in the Ango Ex Dando 3-32-1-25 and Calstan Imperial Dalny 8-10-2-26 wells. Thomas' numerical system thus becomes difficult or impossible to apply in Manitoba, because of the occurrence of progressively stratigraphically lower evaporites towards the east. The terms MC-1, MC-2, and MC-3 are, nevertheless, widely used in this area. In southeastern Saskatchewan some oil companies have expanded Thomas' subdivision of the Mission Canyon formation to include MC units 1 to 9 or more.

Thomas' use of the term Charles is questionable, as it is not, at least according to the writer's correlations, correlative with the type Charles, nor does it mark the base of the evaporite section. Thomas gives no reason for choosing the top of the MC-5 member as the base of the Charles.

Organ and Russin (1956) presented a detailed stratigraphic study of the Mississippian rocks in the Daly field area and proposed a comprehensive local stratigraphic nomenclature for that area (Fig. 3). They did not, however, attempt to show how the section at Daly correlated with the rest of the Manitoba section and stressed that the units as defined were applicable only in the immediate field area. Their subdivision of the Mississippian from top to bottom includes: an unnamed upper Lodgepole anhydrite-dolomite unit; the Daly member consisting of upper, middle and lower units of predominantly crinoidal limestone; Cruickshank shale facies; Cruickshank crinoid facies; Cromer shale facies; Basal limestone facies and Bakken formation. This type of lithologic subdivision recognizes the pronounced lateral or facies variation that is present in the lower part of the Lodgepole succession in this area. Detailed lithologic descriptions of the units proposed are presented in this report.

Stanton (1955) proposed a different stratigraphic breakdown of the Lodgepole formation into the Whitewater Lake, Virden, and Scallion members, and the Routledge shale, as shown in Figure 3. He presents excellent correlation charts and descriptions of these units, but indicates that the subdivision of the Lodgepole into these units is applicable only over a relatively limited area roughly parallel to the eastern erosional edge of the Mississippian subcrop. He also points out the cyclical nature of the units in the upper part of the Lodgepole.

A recent publication by Fuller (1956) of the Saskatchewan Department of Mineral Resources presents a comprehensive stratigraphic and lithologic analysis of the Mississippian in the southeastern part of Saskatchewan, and in particular shows the cyclical nature of sedimentation in late Mississippian time during which "Charles" type evaporitic sediments were deposited. He proposes a new system of nomenclature based on evaporite marker beds and drops the terms Lodgepole and Mission Canyon entirely (Fig. 3).

The Saskatchewan Geological Society (1956) published a set of detailed stratigraphic cross-sections of the Mississippian system in the southeast part of Saskatchewan and adjacent areas of Manitoba and North Dakota. A new system of nomenclature and subdivision (Fig. 3) which differs slightly from that of

Fuller was introduced. The original Mission Canyon, Lodgepole, and Charles units are discarded completely in the new system.

Berg (1956) presented a detailed discussion of the stratigraphy and structure in the Virden-Roselea and North Virden field areas, with special emphasis on the control of oil accumulation.

Several other papers have been published by Trowell and Magee (1952), Weiner (1955), Atkinson and Hegion (1955), and Milne and Nickoloff (1955); these deal largely with the engineering aspects of the petroleum geology in the Daly and Virden areas.

ACKNOWLEDGEMENTS

The writer is indebted to the National Research Council of Canada, and Northwestern University, Evanston, Illinois, for support in the regional study of the Mississippian of the Williston Basin.

Thanks are also extended to A. D. Baillie, who first suggested the study of the Mississippian and to the numerous geologists of the various oil companies operating in Manitoba, who have contributed much valuable information.

The writer is particularly grateful for the opportunity of discussion with John Fuller, formerly of the Saskatchewan Department of Mineral Resources, whose report on the Mississippian geology of southeastern Saskatchewan aided greatly in the study of the correlation problems.

The assistance and advice of Dr. L. L. Sloss, Professor of Geology, Northwestern University, Evanston, Illinois, in connection with the regional Mississippian study is also gratefully acknowledged.

Regional Correlation and Nomenclature

The lower Mississippian Madison group commonly has been subdivided into Bakken, Lodgepole, Mission Canyon, and Charles formations throughout almost the entire Williston Basin area. Recently, however, a great deal of disagreement has arisen regarding definition and usage of these terms, and as a result the latest subdivision of the Mississippian for the northeastern part of the Williston Basin area (Saskatchewan Geological Society, 1956) largely discards the older formational units, and proposes an entirely new subdivision into beds, or marker-defined units (Fig. 3). Several other systems of nomenclature also have been proposed for this area. The following discussion will attempt to show the relatonship between the various rock units shown in Figure 3.

The disagreement as to a uniform system of stratigraphic nomenclature and subdivision of the Mississippian stems primarily from the two distinctly different types of units defined in this area.

The first type of unit is a formation, that is, a mappable lithologic, genetic unit, the limits of which do not bear, necessarily, any time-stratigraphic relationship (Stratigraphic Commission, 1956). A formation, thus, is defined solely on the basis of gross lithologic characteristics.

The second type of unit is defined by marker beds and has no formal, generally accepted name, although many names such as format, bed, operational unit, and lithizone have been used (Forgotson, 1957; Moore, 1958; Fuller, 1956). The term format has been defined formally by Forgotson and, although this particular name may not be acceptable generally (Moore, 1958), the type of unit described is extremely useful in any regional stratigraphic study. This type of unit has been used wherever possible in the present study.

The vertical limits of a format (or bed) are defined by marker horizons which, in subsurface studies, commonly yield characteristic electric or gamma ray responses. These units may be classed as para-time-rock units (Moore, 1958) and are believed to correspond closely to true time-stratigraphic units. As such the units are extremely useful because of the geological interpretation that can be made from them. For example, thickness variations of formats represent true depositional variations in thickness and hence reflect the tectonic framework; structure contour maps based on format boundaries indicate true structure; and lateral lithologic variations or facies changes within formats indicate the lateral or areal changes in environment of deposition during a given period of geologic time, and can be used to determine the regional palaeogeographic pattern.

Early correlations in the Williston Basin area, including southwestern Manitoba, were made solely on the basis of gross lithologic similarity to known type sections of the Mississippian in central Montana. The primary three-fold lithologic subdivision of the Madison group, as applied in central Montana, was found to be applicable throughout most of the basin area. That is, the Mississippian generally can be subdivided into a lower argillaceous unit (Lodgepole formation), a middle clean porous fragmental limestone (Mission Canyon formation), and an upper evaporitic unit (Charles formation). These three lithologic units, or lithosomes, subsequently have been proven to be continuous mappable units throughout most of the basin and may be correctly termed formations.

Later studies based on increased subsurface information indicated that the contacts between the three main Mississippian rock types or formations showed marked variations in stratigraphic position, being in general much lower stratigraphically in the marginal or shelf areas. Because of this pronounced time-transgressive nature of the units, the terms Charles, Mission Canyon, and Lodgepole eventually were discarded by the Saskatchewan Geological Society (1956). Actually, however, Charles, Mission Canyon, and Lodgepole formations are valid units as long as they are defined according to the strict definition of a formation. They are, however, of relatively little use in regional stratigraphic studies because of the markedly transgressive, or diachronous, nature of the units. The most comprehensive system of nomenclature would appear to be one based on both formations and formats. In such a system the format would define the stratigraphic position of

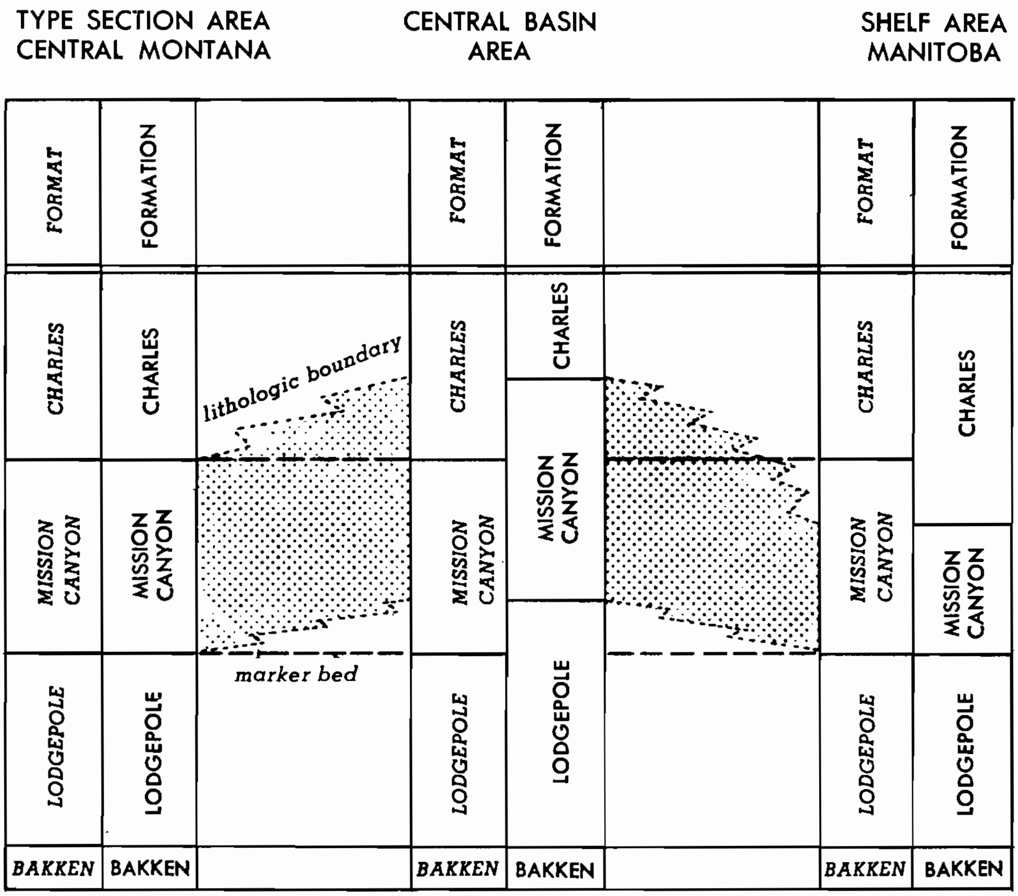


Figure 4. Relationship between FORMATS (marker defined units), and FORMATIONS (lithologically defined units) in the Mississippian Madison strata of the Williston Basin area.

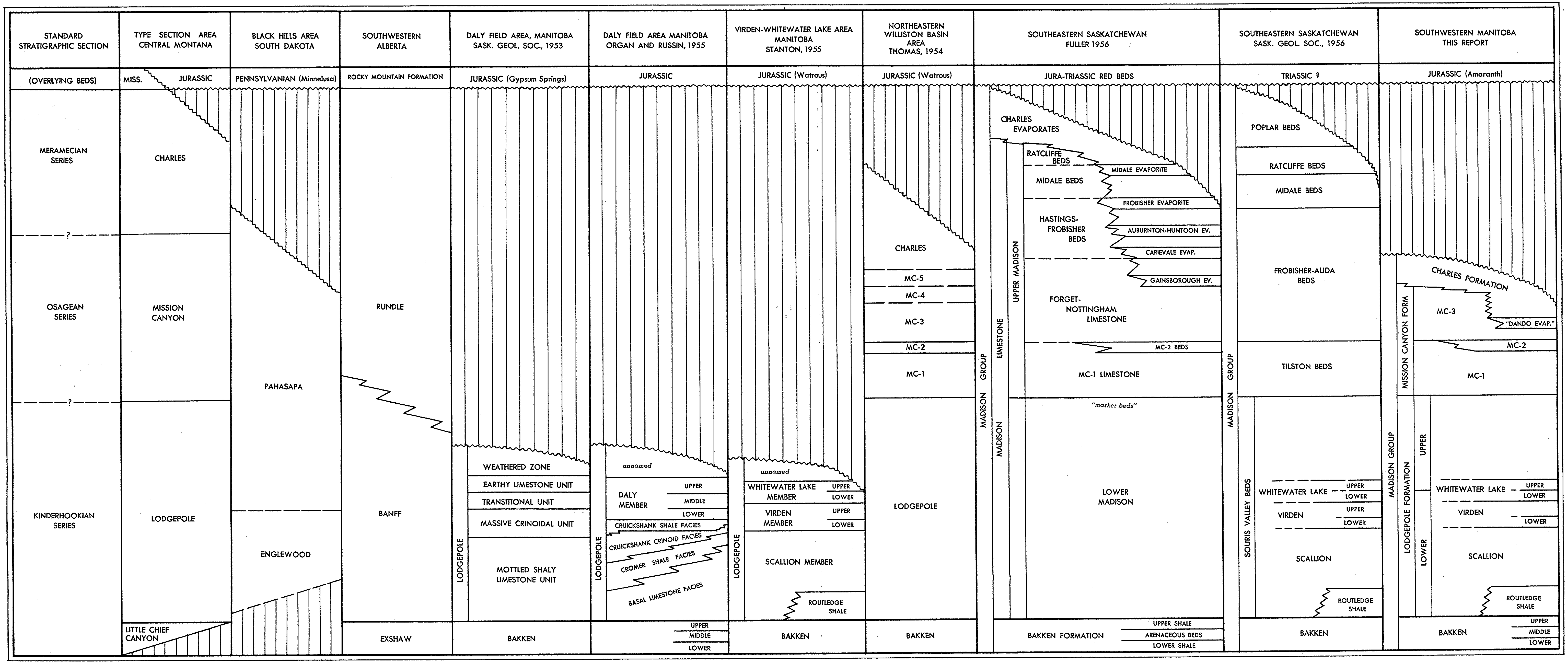


Figure 3. Correlation and Nomenclature Chart.

the unit, and the formation would indicate the rock type, or facies, developed in the area.

According to Forgotson (1957), both formats and formations can be defined from the same type section (Fig. 4). Outside of the type area, however, the boundaries of the two units may diverge markedly depending on the degree of diachronism of the formation. The writer has attempted to correlate the Lodgepole, Mission Canyon, and Charles type sections by means of marker beds. It appears that the "Lodgepole" as commonly used in Manitoba is not only the lithologic or formation equivalent of the type Lodgepole, but is also the time-stratigraphic or format equivalent. The Mission Canyon and Charles sections in Manitoba (ie. all Mississippian limestones and evaporites overlying the Lodgepole) are stratigraphically equivalent to only the lower part of the type Mission Canyon formation of Montana. The time-stratigraphic equivalent of the base of the type Charles formation appears to correlate approximately with the base of the Auburnton-Huntoon evaporite of Saskatchewan.

SUBDIVISION OF THE MISSISSIPPIAN USED IN THIS REPORT

Regional stratigraphic studies which attempt to determine the structure, palaeotectonics, and palaeogeography of a relatively large area must be based on marker-bed units or formats which approximate time-stratigraphic units; consequently, wherever possible, the units considered in this study are defined by marker beds.

The Bakken formation, as defined from the H. O. Bakken well in North Dakota (C SW NW Sec. 12, T. 157N, R. 95W), is directly correlatable into Manitoba. The Bakken formation as a whole does not appear to be transgressive in nature and is considered as a marker-defined unit or format in this report.

The Lodgepole formation, as commonly used in Manitoba, also constitutes a marker-defined unit or format. It is strictly equivalent to the Souris Valley beds of Saskatchewan (Saskatchewan Geological Society, 1956), but, because of the well-established usage of the term in Manitoba, and because it is apparently correlative with the type section, the term Lodgepole is retained.

The Lodgepole has been subdivided into two marker-defined units (i.e. formats) of lesser rank, the Upper Lodgepole, and the Lower Lodgepole. This was done in order to show the fundamentally different characteristics of the upper and lower parts of the Lodgepole formation. Correlation of these units is difficult, however, and it is not intended to introduce them as formal stratigraphic units, as this would only tend to further confuse the existing nomenclature. As will be shown later, however, the units have considerable significance in the geologic and tectonic evolution of the area and are extremely useful in such a regional stratigraphic analysis.

Because of the relatively limited areal extent of the units, and the extensive pre-Jurassic erosion, subdivision of the post-Lodgepole sequence of Manitoba into marker-defined units does not appear to be useful. The section in Manitoba is commonly subdivided into the Mission Canyon and Charles formations, and these units will be retained for this report. The use of the terms Mission Canyon and Charles appears to be justified on the basis of the foregoing discussion of the definition of a formation. The Mission Canyon formation is defined, in this report, as the predominantly "clean" carbonate section overlying the argillaceous marker bed at the top of the Lodgepole formation and underlying the main upper Mississippian evaporite sequence. As the MC-2 evaporite does not mark the base of the main evaporite sequence, it is included as a member of the Mission Canyon formation. The Charles formation comprises the main upper Mississippian primary evaporite sequence. Rather marked facies variations exist between these lithologic units, but an attempt has been made to place them in an over-all tectonic and environmental framework.

The lower part of the Mission Canyon formation (MC-1 and MC-2 members) is equivalent to the Tilston beds of Saskatchewan; the MC-3 member and Charles sections of Manitoba together correlate with the lower part of the Frobisher-Alida beds.

Descriptive Stratigraphy

UNDERLYING BEDS

Throughout the map-area Mississippian strata are underlain by the red to green shales of the Upper Devonian Lyleton formation. Lyleton sediments show a marked thinning to the east from a maximum of 115 feet in the Calstan Waskada 16-13-1-26 well to about 20 feet in the Royalite Triad et al Max Lake #1 well (4-36-1-21). As will be shown later, this thinning is probably due to both pre-Mississippian erosion and depositional thinning; it is possible that, near the extreme eastern edge of the subcrop, the Mississippian rocks rest directly on Devonian Nisku beds.

BAKKEN FORMATION

The type section for the Bakken formation is the interval 9,615 feet to 9,720 feet in the Amerada Petroleum Corporation H. O. Bakken #1 well in sec. 12, Tp. 157, Rge. 95W, Williams County, North Dakota (Nordquist, 1953). This well is located on the Nesson Anticline in the central part of the Williston Basin where Bakken sediments reach their maximum thickness. In that area the Bakken formation is subdivided into three members on the basis of lithology: the upper Bakken, consisting of 20 feet of fissile slightly calcareous black shale; the middle Bakken consisting of 60 feet of very fine-grained light grey calcareous sandstone with a few thin interbeds of dense limestone; and the lower Bakken, consisting of 25 feet of fissile slightly calcareous black, bituminous shale identical to the upper Bakken.

Both shales are characterized by extremely high radioactivity values, much higher than any other shale unit in the sedimentary section. Chemical analyses of equivalent black shales (Chattanooga of Pennsylvania: Bates and Strahl, 1957), indicate a relatively high uranium content. In the deeper parts of the basin both the upper and lower Bakken shales also show high resistivity values, apparently due to the extremely high organic content. This is in marked contrast to most shales which show very low resistivity. Conodonts, spore cases, and a few brachiopods constitute the fossil content of the shales. Towards the margins of the basin, the shales lose their high resistivity and some of their bituminous appearance, but the radioactivity remains high, although slightly decreased. The section in the Calstan Waskada 16-13-1-26 well in southwestern Manitoba is slightly thinner than, but otherwise essentially indentical to, the type Bakken.

Relation to Underlying Beds

To the west of the map-area, in Saskatchewan, and locally in the Waskada area, all three units of the Bakken are present, but throughout most of southwestern Manitoba the middle Bakken argillaceous siltstone appears to rest directly on the Lyleton shales, indicating that the middle and upper Bakken overlap the lower Bakken to the east. Because of the similarity in lithology between the two units, the Bakken-Lyleton contact is difficult to pick through most of the area; consequently no attempt was made to draw up an isopach map of the Bakken formation.

The Bakken-Lyleton contact appears to be unconformable, although no physical evidence of unconformity was seen in any of the cored sections examined by the writer. However, the absence of the lower black shale throughout almost all of southwestern Manitoba, with the exception of the Waskada area, indicates that there was at least an interruption in sedimentation between deposition of the Lyleton and Bakken sediments. It is possible that the lower black shale equivalent is present but has changed laterally to greenish or purplish shales similar to the Lyleton; however, the abrupt lateral disappearance of the lower black shale, coupled with significant thinning of the Bakken-Lyleton section in the Waskada area, suggests that an unconformity is present. Breccia beds within the Lyleton indicate erosional or non-depositional breaks within this unit as well as between the Bakken and Lyleton.

In southeastern Saskatchewan, Fuller (1956) reports a thin sand and phosphatic nodule zone below the Bakken. This zone, which presumably marks the unconformity, was not observed in Manitoba. Fuller also indicates a progressive eastward truncation of marker beds within the Lyleton. This is the best indication of a pre-Bakken unconformity.

Relation to Overlying Beds

The Bakken formation is overlain unconformably by the fossiliferous-fragmental and, in part, glauconitic limestone of the basal Lodgepole. In southeastern Saskatchewan a thin black shale identical to, and easily confused with, the upper Bakken shale is present about 20 feet above the Bakken. This shale apparently does not extend as far east as Manitoba. In southwestern Manitoba the lower part of the Lodgepole formation consists primarily of dark grey argillaceous limestone, but a thin bed of relatively clean limestone usually separates the shaly Lodgepole from the Bakken shale. To the east the Bakken formation is overlain in most areas by the "clean" Scallion limestone.

Correlation problems arise in two small areas near the subcrop edge of the Mississippian, in the vicinities of Virden and Max Lake. In these areas the basal Lodgepole sediments consist of black shale, the Routledge shale (Stanton, 1955), which is practically indistinguishable lithologically from the upper Bakken black shale. The Routledge, however, shows a somewhat lower radioactivity reading on the gamma ray log, and on this basis the Bakken-Routledge contact is picked at the top of the basal zone of highest radioactivity.

In several wells, such as Imperial Blossom 3-17-12-24, located at the erosional edge of the Mississippian, Watrous red beds rest directly and with marked unconformity on Bakken shales. The contact commonly is difficult to pick on mechanical logs, and samples generally are poor.

Only a comparatively few wells in Manitoba have cored the Bakken, and samples generally are poor; consequently, relatively little information is available. Several core descriptions are included in Appendix II, and a number of others are presented by Petrie (1956).

Lower Bakken

The lower Bakken is of very limited occurrence in Manitoba and apparently occurs only in the Waskada area. The gamma ray log for the Calstan Waskada 16-13-1-26 well shows a highly radioactive bed about 10 to 15 feet in thickness, immediately below the middle Bakken siltstone. Although samples are not too good in this interval, the radioactive bed appears to consist of black shale essentially the same as the upper Bakken.

Middle Bakken

In the southwestern corner of the map-area (Calstan Waskada 9-13-1-26 well) the middle Bakken consists of about 25 feet of greyish green pyritic argillaceous silty dolomite with a few thin interbeds of green and black shale and fine- to medium-grained sandstone. Some crossbedding was noted. Near the base of the unit is a three-inch intraformational breccia zone consisting of fragments of green and black shale in a matrix of greenish grey silty dolomite. The bottom of the core appears to be in the middle Bakken and no gamma ray log was run to ascertain if the lower Bakken is present. However, on the basis of correlation with the nearby Calstan Waskada 16-13-1-26 well, for which a gamma ray log was run, the lower Bakken appears to be present. If it is assumed that the lower Bakken is present, the breccia zone indicates a slight erosion break within the Bakken.

To the north, in the Calstan Scallion Prov 5-11-11-26 well, the middle Bakken section is very similar in thickness, but the sediments are slightly coarser grained than in the Waskada area, and consist of dolomitic siltstone grading to finely laminated fine- to medium-grained sandstone at the base. The Lyleton sediments in this well shed considerable light on the relationship between the Bakken and Lyleton formations. The 34 feet of section immediately below the Bakken are predominantly intraformational breccia beds consisting of light grey dolomite and grey to reddish shale with a small amount of greenish grey pyritic shale. Bands of dolomite containing angular fragments of shale, and bands of shale containing breccia fragments of dolomite are both present and appear to be strictly local in origin. One bed shows grey shale fragments included in dolomite fragments, which are in turn included in a grey shale matrix.

Underlying the breccia beds are 14 feet of bright red dolomitic shale or argillaceous dolomite, typical of Lyleton red bed lithology. These beds also show fine contorted pseudo-breccia or breccia-like structures. There are, as well, several bands of massive grey dolomite, identical to the dolomite occurring as bands and fragments in the overlying breccia bands.

The breccia beds indicate that there are probably numerous diastemic and/or erosional breaks within the Lyleton, as well as between the Lyleton and Bakken formations, at least in the peripheral areas. The thin breccia bed in the middle Bakken in the Calstan Waskada 9-13-1-26 well indicates that similar breaks also occur within the Bakken.

The grain size of the middle Bakken clastic sediments appears to increase to the north and east. In the Dome Nesbitt 11-19-7-18 well samples indicate that the middle Bakken member consists of approximately 30 feet of medium-grained unconsolidated or poorly consolidated sandstone.

To the north, in the Birtle area, the middle Bakken also consists predominantly of relatively clean fine- to medium-grained dolomitic sandstone (Dome Birtle 16-17-17-27; Homestead Birdtail 10-8-15-27; S.A.M. Victor #1, 6-29-17-29). Oil staining was present in the less well-cemented beds in the Victor #1 well.

Reddish coloration is very prominent in some of the northern wells such as Homestead Birdtail 10-8-15-27 and Dome Birtle 16-17-17-27, but the red colour may be secondary rather than primary. The Lodgepole cover is thin in the northern part of the map-area, and it is possible that the red colour is due to secondary oxidation of originally black shales during the period of pre-Jurassic erosion. No definite evidence supporting either a primary or a secondary origin for the red colour was seen in any of the cored sections.

Petrographic studies of the middle Bakken sandstone from the Dome Birtle 16-17-17-27, Homestead Birdtail 10-8-15-27, and S.A.M. Victor #1 6-29-17-29 wells indicate that the middle Bakken sands and silts are composed almost entirely of quartz. The quartz grains are predominantly unstrained or show only slight strain extinction. The maximum grain size is in the order of 0.02 mm. (medium-grained sand), but most of the material is very fine sand or coarse silt. Microcline and plagioclase feldspars, and probably also orthoclase, were observed in thin section, but the total feldspar content appeared to be less than 5 per cent. It should be noted, however, that the fine-grained nature of the sediments made identification of the feldspars difficult, and it is possible that the feldspar content may be somewhat higher than indicated.

The shape of the coarser sand grains is predominantly sub-rounded; minor amounts of well-rounded and angular grains are present. The finer silt-sized grains generally are angular to sub-angular as would be expected for such fine particles. In general, the grains are moderately to well rounded for their size.

The degree of sorting varies considerably in different samples. The material in the S.A.M. Victor #1 (6-29-17-29) well is well sorted, and contains little or no fine argillaceous material, whereas, in the other wells examined, the sorting is poor and argillaceous material is abundant along with the silt and fine sand. The surface texture of the grains is generally polished or glassy; very little frosting or pitting was observed.

The matrix varies from relatively pure dolomite in the well-sorted areas (eg. S.A.M. Victor well) to dolomitic shale in the poorly-sorted areas. The samples from the Victor well show, in part, sand grains "floating" in a dolomite matrix; the sediment in this instance approaches a sandy dolomite.

Several quartz grains in the Dome Birtle 16-17-17-29 well showed what appeared to be irregular, eroded quartz overgrowths on rounded grains, suggesting a possible second-cycle derivation of these grains from pre-existing sediments. However, the "secondary overgrowths" could not be identified positively as such, and no other overgrowths were observed in any of the other samples examined.

Petrographically, the middle Bakken would be classed as a dolomitic argillaceous sandy quartzose to slightly feldspathic siltstone.

Upper Bakken

In the Calstan Scallion Prov 5-11-11-26 well, the upper Bakken consists of 11 feet of dark silvery grey to jet black massive shale with a smooth, conchoidal to flat fracture. Conodonts and brachiopods are common in the upper part. This lithology is generally typical throughout the southern part of the map-area.

The rocks at the Routledge-Bakken contact were cored in the Royalite Triad et al Max Lake 4-36-1-21 well. In this area both the Routledge and upper Bakken are black to dark grey shales that are practically indistinguishable from one another. The Routledge is slightly blacker and more fissile than the upper Bakken. The contact can be picked only from the gamma-ray log, which indicates a considerably higher radioactivity for the lower Bakken shale.

To the north, in the area of the Homestead Birdtail 10-8-15-27 well, the upper Bakken appears to have thinned considerably and consists of only three feet of medium grey to slightly reddish and yellowish shale, showing a bright red streak. The red colour, which is also apparent in the middle Bakken, seems to be fairly characteristic of the northern peripheral area; it has also been noted in several places in Saskatchewan (Fuller, 1956).

LODGEPOLE FORMATION

The Lodgepole formation comprises the lower argillaceous section of the Mississippian limestones, as distinguished from the underlying Bakken clastics and the overlying clean or non-argillaceous, fragmental limestones of the Mission Canyon formation. The contact with the Mission Canyon is marked by a very consistent argillaceous marker bed that is easily recognizable throughout the map-area (Fig. 5). Within the map-area the Lodgepole format and formation are the same, and can be considered a marker-bed or time-stratigraphic unit.

When considering the over-all lithologic aspect of the Lodgepole in Manitoba, it becomes evident that there is a rather pronounced difference between the upper and lower parts of the unit. The main difference is that the lower part of the Lodgepole shows very pronounced lateral variations in lithology, grading from predominantly clean limestone in the eastern part of the map-area to almost entirely argillaceous limestone in the western part; in contrast to this, the upper part of the Lodgepole generally is uniform throughout the map-area. An attempt was made to ascertain if there were any correlatable units within the Lodgepole that could be carried throughout the entire map-area. The units proposed by Stanton (1955) for the eastern part of the area provided a logical starting place. Although Stanton stated that his subdivision was applicable to only a relatively narrow belt parallelling the eastern erosional edge of the Mississippian, additional subsurface information acquired since 1955 indicates that it is possible to correlate at least one marker bed, the Roselea shale or basal Lower Whitewater Lake shale, throughout most of the map-area with reasonable accuracy. Although correlations are difficult due to the marked lateral variations in lithology, the use of all available well control and closed correlation traverses permits reasonably accurate correlations to be made. Isopach and lithofacies data obtained from an analysis of the upper and lower marker-bed units of the Lodgepole confirm the belief that these units are fundamentally different both in tectonic framework and environment of deposition. Consequently, for the purposes of this report, the Lodgepole is divided into two "operational", marker-defined units, the Upper Lodgepole and the Lower Lodgepole.

Lower Lodgepole

DEFINITION

The Lower Lodgepole (format) is defined here as that section of the Lodgepole between the top of the Roselea shale marker bed (basal Lower Whitewater Lake) and the top of the upper Bakken black shale. Correlations are shown in the stratigraphic cross-sections (Figs. 5, 6 and 7) and in the correlation chart (Fig. 3). The Roselea shale, as used in this report, consists of the main shaly zone of the Lower Whitewater Lake and its correlatives throughout the map-area. This particular unit was chosen to mark the top of the Lower Lodgepole operational unit because:

(1) It appears to mark the approximate stratigraphic horizon above which the Lodgepole sediments no longer display marked lateral variations in lithology.

(2) Although the top of the shaly interval shows slight local variations in stratigraphic position, it is probably the easiest marker bed to correlate throughout the map-area.

The top of the Roselea shale correlates approximately with the "first crinoidal" (Middle Daly, or Transitional zone) of the Daly area.

Correlation of the Lower Lodgepole is rather difficult, especially in the extreme western part of the map-area, and in the area north of the Daly field; throughout the latter area the top of the unit is close to the erosion surface. Extensive secondary effects related to the erosion, coupled with the removal of the marker beds of the Upper Lodgepole and thinning of the shaly marker bed, cause this difficulty in correlation.

In the western part of the map-area the general increase in argillaceous content of the Lower Lodgepole makes correlation of the Routledge shale marker difficult. In the Tilston area almost the entire Lower Lodgepole section becomes argillaceous. The Whitewater Lake limestone, immediately overlying the Roselea shale, appears to be stratigraphically the lowest correlatable limestone bed, in the Lodgepole, that does not grade westward to argillaceous limestone.

ISOPACH

The total Lodgepole isopach for the area where the Lodgepole shows true depositional thickness and has not been subjected to post-Mississippian erosion is shown in Figure 8. The general trend of the isopach lines is east with some slight thinning towards the west near the Saskatchewan boundary. Figure 9 shows the overall basin isopach of the Lodgepole format. Figure 10 shows the isopach of the total Mississippian section in Manitoba.

The isopach pattern of the Lower Lodgepole (Fig. 11) is markedly different from that of both the total Lodgepole (Fig. 8) and the Upper Lodgepole (Fig. 12). The isopach trend of the Lower Lodgepole is roughly north, to more nearly north-west in the southern part of the map-area. The unit shows a very pronounced thinning to the west, as much as 130 feet in the Tilston area. This thinning trend continues for at least a short distance west into Saskatchewan. In the most south-easterly wells, such as Homestead et al Turtle Mountain 10-26-1-20, the Lower Lodgepole shows a slight decrease in thickness, suggesting a reversal in trend, with thinning in the extreme east; however, the Mississippian is truncated before the presence of such a trend can be established definitely. It is possible that the thinning is due to differential compaction of the Routledge shale.

LITHOLOGY

The lithology of the Lower Lodgepole is exceedingly variable, consisting of black shale, red and grey calcareous shale to argillaceous limestone, cherty limestone, glauconitic limestone, dolomitic limestone, and dolomite. Because of the rapid lateral or facies variation of the above lithologies no general description for the unit as a whole is possible.

The argillaceous content is the most important variable in the composition of the Lower Lodgepole sediments. In general, well samples are of such a poor quality that quantitative estimates of argillaceous content from samples alone are impossible. Therefore, all estimates of argillaceous content were made from electric and gamma ray logs. Figure 11 shows the variation in argillaceous content of the Lower Lodgepole.

Interpretation of argillaceous content from electric and/or radiation logs is subject to considerable personal interpretation. In order to avoid, as much as possible, errors due to inconsistency, all estimates of shale content were made at the same time. Rechecking of a number of wells indicated that the estimates were consistent within themselves. Because of the personal interpretation factor, the absolute values for the argillaceous content are undoubtedly somewhat inaccurate.

Spontaneous potential (SP), resistivity, and radioactivity log curves for the Lower Lodgepole interval were compared with known curves for shales and limestones on the same log, and the relative amounts of argillaceous material and the thickness of the shaly beds were estimated and recorded. In this way difficulties due to differences in mud salinities and sensitivities between different wells were avoided.

The argillaceous material of the Lower Lodgepole occurs in two distinctly different stratigraphic positions in the section, in the Roselea and Lower Virden members and in the western argillaceous equivalents of the Scallion. The shale content of the Roselea shale and the Lower Virden and equivalents is relatively constant throughout the map-area, although the shale beds show a slight thickening to the east. These argillaceous beds provide a regional background shale content of about 5 per cent for the Lower Lodgepole.

The greater part of the Lower Lodgepole shale occurs in the western argillaceous equivalents of the Scallion Member. The argillaceous content of the Scallion equivalent is concentrated near the Saskatchewan border in a north-trending band which passes through the Waskada and Daly areas, where the argillaceous content reaches as high as 45 per cent (Fig. 11). The band increases in width towards the south, and can be traced as far as southwestern North Dakota where the trend swings to the southwest towards the Black Hills area. The argillaceous band or facies of the Lower Lodgepole of Manitoba thus constitutes part of a great band of argillaceous material rimming the entire eastern edge of the Williston Basin (Fig. 9).

The vertical distribution of the argillaceous material within the shaly band shows a fairly well-defined pattern, both in Manitoba and in North Dakota. Within the shaly zone, the argillaceous beds appear first in the upper part of the Lower Lodgepole unit at the eastern edge of the shaly facies, and the base of the shaly beds in general drops stratigraphically to the west. This behaviour of the shale lithosome is possibly very important in determining the depositional history of the area.

Two other local areas of high argillaceous content are the Virden and Turtle Mountain areas near the subcrop edge of the Mississippian. The shale content in these places is due primarily to the local occurrence of the Routledge shale.

For convenience, the Lower Lodgepole has been subdivided areally into two facies, an eastern limestone facies and a western argillaceous facies. The limestone facies corresponds approximately to the area included in Stanton's report (1955), and is arbitrarily bounded on the west by the ten per cent shale contour on the lithofacies map (Fig. 11). The western limit of the shale facies coincides almost exactly with the Manitoba-Saskatchewan border. West of this, in Saskatchewan, the Lower Lodgepole equivalents once more become predominantly clean, or non-argillaceous, cherty limestones.

EASTERN LIMESTONE FACIES OF THE LOWER LODGEPOLE

The areal extent of this facies is shown in Figure 11. In the eastern area the Lower Lodgepole is relatively uniform in lithology and is readily subdivided into a number of units — the Scallion member, Routledge shale, Virden member, and the Roselea shale.

Scallion Member:

The type section of the Scallion member, as proposed by Stanton (1955), is the Calstan Scallion Prov. 5-11-11-26 well, in which the entire Lower Lodgepole section was cored (see Appendix II for core descriptions).

The Scallion member consists of limestones that are white to light or medium grey, or various greys tinged with yellow, green, purple, red, or pink. Some of the limestones are mottled in shades of these colours. The texture may be microcrystalline, finely crystalline, microgranular, chalky, saccharoidal, or microfragmental. Finely crystalline, granular and chalky limestones are the most common types. A few thin bands of crinoidal limestone and minor amounts of crinoid and other fossil debris are scattered throughout the section. Chert, cherty limestone, and silicified fragmental limestone are common to abundant throughout most of the unit, and in some bands constitute 30 per cent or more of the rock. Porosity varies from very fine intergranular to vuggy. A thin bed of glauconitic limestone commonly is reported near the base of the unit.

The mottled reddish and purplish limestones probably are slightly to moderately argillaceous in places, but the argillaceous content is, in general, very low, as shown by the high SP values and the low radioactivity characteristic of this unit. This lithology appears to be typical of Scallion beds in the eastern part of the map-area. One interesting and unusual section occurs in the Baysel Calstan Boissevain 3-20-3-19 well in the basal Scallion beds. It consists of 12 feet of very coarsely fossiliferous, porous limestone with a reefoid appearance. Fossils constitute the main mass of the rock, and consist of bryozoa, brachiopods, and abundant brachiopod and/or echinoid spines. These fossils are not comminuted, and even the fragile branching bryozoa are perfectly preserved in what appear to be growth positions. Most of the section has little or no matrix, and the unit consequently shows extreme porosity, yielding large volumes of salt water but no oil, on drill stem test. The lithology of this section contrasts markedly with the fragmental fine-grained comminuted nature of most of the Scallion limestones. The Calstan Boissevain 3-20-3-19 well is situated near the area of Routledge shale occurrence, and the reefy (?) limestone may be genetically related to the Routledge shale accumulation.

To the north, in the Birdtail area (Homestead Birdtail 10-8 well), the upper part of the Scallion becomes a reefoid finely crystalline siliceous dolomite with excellent fine to medium vuggy porosity.

Routledge Shale:

The type section of the Routledge shale, as described by Stanton (1958), is found in the Calstan Routledge 13-29-9-25 well. The unit appears to be a lateral or lithofacies equivalent of the lower part of the Scallion limestone, and is limited areally to two separate lobe-shaped bodies, one in the vicinity of Virden and the other in the Turtle Mountain or Max Lake area. The shale attains a maximum thickness of about 90 feet. Both areas are marginal to the Mississippian subcrop edge and occur in re-entrants or indentations along this edge. In all wells which have penetrated it, the Routledge shale has been overlain by limestones of the upper Scallion and rests with apparent conformity on the upper Bakken black shale. It is probable, however, that the Routledge is overlain unconformably by Amaranth or later Jurassic sediments at the subcrop edge of the Mississippian.

To the writer's knowledge, Routledge or Routledge-type fringing black shales are limited to two small areas, Virden and Turtle Mountain, shown in Figure 11. The latter occurrence extends southward for a short distance into North Dakota. No other Routledge-type shales are known with certainty in the Williston Basin area. The Englewood of the Black Hills might possibly be correlative with the Routledge, but the lithology is different, and the Englewood is probably equivalent to the more basinal shaly facies of the Lodgepole (ie. the western argillaceous facies of the Lower Lodgepole).

The Routledge consists of rather uniform, dark brown to brownish black soft massive shale that is slightly calcareous and silty. It becomes harder and better consolidated toward the base. According to Stanton (1955) some reddish shale has been reported from this interval, but this may be only shale cave. Short sections of the Routledge shale were cored in the Cleary Province 6-21-1-19 well and Royalite Triad et al Max Lake #1 (4-36-1-21) well (see Appendix II). In core from both wells, the Routledge consisted of dark grey to black shale.

The rate of lateral facies change from Scallion limestone to Routledge shale is rather rapid, occurring over a distance of only about three miles, and there is apparently no interfingering or gradation between the two types of lithology.

As far as can be determined from the present subsurface data, the two areas of Routledge shale occurrence are completely separated from one another; however, they are of such similar lithology and stratigraphic position that they are considered to be correlative units.

Aside from the areas of Routledge shale occurrence, the first major break in the predominantly limestone sedimentation of the eastern area occurred at the close of Scallion deposition, when interbeds of red argillaceous limestone to calcareous shale became a prominent constituent of the sediments. These argillaceous limestone bands mark the beginning of a series of cyclic or rhythmic sediments

(Stanton, 1958). A cycle consists of a basal section of red, grey, and purplish gr argillaceous limestones interbedded with oolitic and bioclastic limestones whi grade upward to clean bioclastic limestone. Only two such cycles are well develo ed, and these have been designated as the Virden and Whitewater Lake membe of the Lodgepole formation by Stanton, who formally defined the units and pr sented detailed descriptions.

Virden Member:

The type section of the Virden member is defined in the Calstan Virden CPF 9-25-10-26 well as the interval 1911-1968 feet (Stanton, 1955). The Virden is subdivided into two units, the Lower Virden, an argillaceous unit (1927-1968 feet) and the Upper Virden, a clean fragmental limestone unit (1911-1927 feet). Together the two units constitute a complete sedimentary cycle.

The Lower Virden is distinguished from the underlying Scallion member, in the eastern area, by the marked increase in argillaceous content (Figs. 5, 6). With the exception of the locally developed Routledge shale, the Lower Virden shaly beds were the first clastic sediments to be deposited in significant amounts in the eastern area after upper Bakken time. The change from the relatively clean Scallion limestone to the argillaceous Lower Virden strata shows up well on the SP and radioactivity logs, but the break becomes increasingly more difficult to pick towards the west, due to the increase in argillaceous content of the upper Scallion equivalents. In the area of the western argillaceous facies the Virden and Scallion, in general, are indistinguishable, although the equivalent intervals usually can be estimated approximately.

The Lower Virden maintains a relatively constant thickness of approximately 45 feet throughout most of the eastern area. There are some local variations in thickness, but no regional changes in a northerly direction parallel to the subcrop edge. The unit, however, appears to thin towards the west in the Daly area.

The Upper Virden shows a marked thinning to the north, from 45 feet at Max Lake to 15 feet in the Virden area. It also appears to thin somewhat towards the west.

A detailed description of the Virden member, as found in the Calstan Scallion Prov 5-11-11-26 well, is given in Appendix II. The Lower Virden consists essentially of cyclically interbedded clean limestone and argillaceous limestone. The clean limestone is mostly light buff, fine-grained oolite with some crinoidal bands. The argillaceous limestone is mottled in shades of light grey to reddish, greenish, and purplish grey, and contains some thin crinoidal bands and scattered crinoid fragments. Individual beds average 3 to 5 feet in thickness. In the Virden area the Lower Virden has been subdivided into a number of sub-units or lentils, namely the Sandhill and the first, second, third, and fourth oolites (Fig. 6). These units are local terms and are not intended for use outside of the field areas.

To the south of the Virden area the argillaceous material in the Lower Virden is concentrated primarily at the top and bottom of the unit, and the middle of the unit is a relatively clean fragmental limestone. To the west, the percentage of shale in the Lower Virden appears to increase due to the absence of the oolitic limestone interbeds.

The Upper Virden in the Calstan Scallion Prov 5-11-11-26 well consists of 15 feet of crinoidal fragmental limestone grading to finely crystalline and, in part, somewhat granular limestone. A few thin bands of reddish to greenish grey argillaceous limestone, and a few green calcareous shale partings occur in the limestone. Traces of anhydrite, which is probably secondary, are present also. The lower five feet of the unit are cherty, and contain some bands of partly silicified crinoidal limestone. The unit is predominantly oil stained and shows fair intergranular porosity.

South of the Virden area, in the Max Lake area, the Upper Virden maintains its general lithologic character, although beds of oolitic limestone become increasingly common, especially towards the top of the unit. The Upper Virden shows a considerable increase in thickness to the south; in part, this is the result of facies changes from shaly limestone to non-argillaceous limestone. Some of the thickening also is due to differential subsidence.

In most areas the Upper Virden, because of the low shale content, shows a characteristic high blocky SP trace, and low radioactivity.

"Roselea Shale":

The "Roselea shale" marks the top of the Lower Lodgepole operational unit, or format. As defined by Stanton (1955), the Roselea shale comprises the basal shaly part of the Lower Whitewater Lake unit, and the term originally was intended to be used only locally in the Virden area. As used in this report, the term is expanded to include not only the Roselea shale as originally defined for the Virden area, but also equivalent shales throughout the map-area. It is defined here as the main shaly bed of the Lower Whitewater Lake, and correlative shales throughout the map-area. This main shaly bed is not always sharply defined and, in some places, shows slight variations in stratigraphic position within the Lower Whitewater Lake beds; however, such variations are minor, and the shale forms a relatively good marker bed throughout most of the map-area.

Whitewater Lake Member:

Although only the basal part of the Whitewater Lake member is included in the Lower Lodgepole, a brief description of the total Whitewater Lake unit is included at this point for the sake of completeness, as it constitutes a fairly well-defined lithologic unit and has been defined formally in the literature.

The type section for the Whitewater Lake is the interval 2545 - 2585 feet in the Calstan Whitewater 10-17-3-21 well (Stanton, 1955).

Although not as sharply defined as the Virden member, the Whitewater Lake member represents a repetition of the sequence occurring in the former. The top of the Whitewater Lake is difficult to determine in the northern part of the map-area because of marked secondary alteration associated with pre-Jurassic erosion which has changed the electric-log characteristics of the unit. To the south, erosion did not penetrate as deeply into Mississippian strata and the Whitewater Lake beds were largely protected from secondary alteration.

The Lower Whitewater Lake shows a pronounced thinning to the north, from 40 feet in the Whitewater Lake area to only 15 feet in the Virden area. Correlations to the west are uncertain, but the unit apparently thins in this direction as well. The Upper Whitewater Lake appears to show variations in thickness similar to those of the Lower Whitewater Lake.

In the type section (Calstan Whitewater 10-17-3-21 well) the Lower Whitewater Lake consists of relatively thin-bedded (2 to 5 feet) oolitic to bioclastic limestone, and greenish grey to reddish grey and maroon argillaceous limestone and calcareous shale. The unit, however, shows rather marked facies changes. The general facies pattern seems to be one of interbedded oolite and shale in the extreme east, with the unit thinning to the west and becoming increasingly argillaceous, probably due to disappearance of the oolitic beds. The shale content commonly is concentrated towards the base of the unit where it constitutes the Roselea shale.

The type section of the Upper Whitewater Lake, in the Calstan Whitewater 16-17-3-21 well, consists of about 40 feet of fossiliferous fragmental and oolitic limestone with a few thin argillaceous partings. In most places in the Virden area the Upper Whitewater Lake has been completely altered to finely crystalline dolomite, and the original texture is almost impossible to determine. Bands and facture fillings of secondary anhydrite constitute up to 25 per cent or more of the unit.

WESTERN ARGILLACEOUS FACIES OF THE LOWER LODGEPOLE

The facies change from cherty limestones with relatively low shale content in the eastern part of the map-area to predominantly argillaceous limestone to calcareous shale in the west is rather sharply defined, as shown in the cross-sections (Figs. 5, 6 and 7). It occurs approximately at the 10 per cent shale contour on the lithofacies map. To the west of this line the Lower Lodgepole becomes a complex of interfingering beds of argillaceous limestone to calcareous shale, and clean fragmental to finely crystalline limestone. Some individual limestone and shale beds can be correlated over relatively local areas, but, in general, there are no well-defined correlatable units within this argillaceous limestone complex.

The approximate stratigraphic equivalents of the Scallion, Virden, and Whitewater Lake units can be identified in the western part of the map-area but, as pointed out by Stanton (1955), they are so poorly defined in this area that they do not constitute valid lithologic units. Nevertheless, in the lithologic description of the Lower Lodgepole in this area an attempt will be made to describe these units wherever possible so that regional variations in lithology can be shown.

The increase in shale content of the Lower Lodgepole to the west is accompanied by a marked thinning; however, in the extreme western part of the map-area, where the unit is thinnest, the sediments once more become clean cherty limestones identical to the Scallion limestones of the east (Fig. 11).

The lithology in the Souris Valley White 5-14-1-28 well, in the extreme southwestern part of Manitoba, is typical generally of the Lower Lodgepole in this area. The Roselea shale is difficult to define and may actually split up into a number of thinner shale units (Fig. 5). The Upper Virden equivalent appears to be a crinoidal limestone, and the Lower Virden a finely crystalline to granular limestone or argillaceous limestone with some crinoidal bands. The Scallion equivalent consists of medium dark to medium light grey earthy argillaceous limestone or calcareous shale; in part it is dolomitic and contains some scattered bands of cherty limestone and some interbands of finely crystalline clean dense limestone. A thin basal Lodgepole unit of light grey, finely crystalline to granular, clean limestone immediately overlies the Bakken shale.

To the west, in the Calstan Waskada 9-13-1-26 well (Fig. 5), the lithology is similar but the lower 80 feet of the Scallion equivalent, which consists of very argillaceous limestone in the White well, has graded laterally to relatively clean, mostly finely crystalline to dense limestone with very abundant chert and cherty limestone and only a few thin argillaceous breaks.

To the north, in the Daly area, the complete Lower Lodgepole section has been cored in the Can Sup Cruickshank 14-4 well (14-4-10-28 WPM) (See Appendix II). In this area the argillaceous content is considerably lower than to the south, due in part to the development of a thick 80-foot "bank" of crinoidal limestone in the beds equivalent to the upper part of the Scallion. This forms the so-called Cruickshank Crinoid Bank, or the Cruickshank Crinoid Facies (Organ and Russin, 1956). This lithologic sequence is somewhat anomalous, as few wells in the area show such a thick development of crinoidal limestone. The lateral shape and extent of the crinoid bank cannot be determined with the control available.

The following is a general description of the lithology of the Lower Lodgepole in the Daly area, as shown in the Can Sup Cruickshank 14-4 well (14-4-10-28); correlations with the Virden area are indicated in Figures 3 and 6. The Middle and Lower Daly beds of Organ and Russin (1956) comprise the uppermost part of the Lower Lodgepole; these strata consist primarily of crinoidal to finely crystalline and slightly argillaceous limestone. They are underlain by the Cruickshank Shale Facies, which consists of red, purplish red, and greenish grey, mottled and streaked, finely crystalline, moderately argillaceous limestone containing abundant scattered crinoid fragments. The few bands and patches of anhydrite present probably are secondary in origin and related to the period of pre-Jurassic weathering.

The Cruickshank Shale Facies is underlain by the Cruickshank Crinoid Facies, which consists primarily of medium to coarse crinoidal limestone with some beds of finely crystalline, granular to saccharoidal, slightly dolomitic limestone, and a few bands of chert and argillaceous limestone. The unit is predominantly oil stained in this area. Below the Cruickshank Crinoid Facies is the Cromer Shale Facies (or Daly shale), which consists of an upper unit of 30 feet of mottled greenish grey to purplish, fine crystalline, granular to fine fragmental, slightly argillaceous limestone or calcareous shale containing a few scattered crinoid and fossil fragments. This red colour appears to be typical of the Lower Lodgepole shaly facies in the northern part of the map-area.

The Cromer Shale Facies is underlain by 40 feet of Basal Limestone Facies. The Basal Limestone Facies consists of finely crystalline to somewhat granular, slightly argillaceous, cherty limestone which is mottled in shades of purplish red to brownish grey. A few thin shaly partings are present, and chert nodules are abundant throughout most of the section.

The reddish to greenish and purplish grey colour of the argillaceous limestone in the Daly area contrasts markedly with the dark grey colour of the argillaceous limestones of the southern part of the map-area, and indicates a considerable change in the environment of deposition. It is interesting to note that a similar colour change takes place in the underlying Bakken formation in the northern part of the map-area.

In summary, the Lower Lodgepole sediments constitute a reasonably well-defined stratigraphic unit throughout most of the map-area, even though the lithology varies greatly from east to west. Along the eastern edge of the Mississippian, the section consists of relatively clean, white to light reddish and purplish mottled, cherty, fine-grained limestone with only minor amounts of fragmental limestone, and several thin argillaceous beds near the top. In the Virden and Max Lake areas, marginal black shales of the Routledge are developed locally.

The clean cherty Scallion limestone shows a fairly abrupt lateral westward change to argillaceous limestone and calcareous shale that are grey in colour in the southern part of the map-area, and predominantly reddish to purplish in the north, with the argillaceous content decreasing somewhat to the north. The facies trend of the argillaceous limestone is almost due north as shown on the lithofacies map (Fig. 11), and is approximately parallel to the isopach trend of the unit. In the eastern part of the map-area, the argillaceous limestone appears first in the upper Scallion equivalents, and progressively replaces the Scallion-type limestone to the west. The Manitoba-Saskatchewan boundary appears to be the approximate westward limit of the argillaceous limestone facies, and also marks the approximate westward limit of the Lower Lodgepole as a correlatable unit.

Upper Lodgepole

Definition and Correlation

The Upper Lodgepole marker-bed unit, as defined in this report, consists of the section from the top of the Roselea shale to the top of the characteristic argillaceous marker bed which is picked throughout the eastern part of the Williston Basin area as the top of the Lodgepole formation, or the top of the Souris Valley Beds (Saskatchewan Geological Society, 1956, Fig. 3). As the contact between the argillaceous limestones of the Lodgepole and the overlying non-argillaceous limestone of the Mission Canyon is somewhat gradational, there exists some difference of opinion regarding its exact position. Several thin bands of argillaceous limestone occur above the main argillaceous bed. In Manitoba the top of the Lodgepole commonly is picked at the top of a prominent shaly break about 15 feet above the main argillaceous bed (Fig. 5). In North Dakota the top is picked slightly lower in the section, at the top of the main argillaceous break.

The Upper Lodgepole is preserved completely only in a relatively small area in the southwestern corner of the province, where Mission Canyon strata are present (Fig. 15). Elsewhere it has been subjected to varying amounts of pre-Jurassic erosion throughout its subcrop belt. The zero edge of the unit can be considered accurate only in the central and southern parts of the map-area. North of the Daly area correlations are very uncertain and the erosional edge of the unit is based largely on general interval and isopach considerations.

Isopach

Figure 12 is an isopach map of the Upper Lodgepole in the area where Mission Canyon strata are present, and consequently indicates true depositional thickness variations. The isopach lines show an approximate northerly trend with the unit thickening towards the west. The rate of thickening increases near the Saskatchewan border. The increase in thickness of the Upper Lodgepole coincides with a thinning of the underlying Lower Lodgepole. Thickening seems to be confined to the clean porous fragmental limestone beds rather than to the more argillaceous beds.

Lithology

The lithology of the Upper Lodgepole is relatively uniform throughout the map-area; this is in marked contrast to the rapid facies changes characteristic of the Lower Lodgepole. In the Upper Lodgepole section there are no good marker horizons that can be correlated throughout the map-area, but there are several local markers, especially in the western part of the area, that are valuable in correlation.

Unfortunately there are no good core sections of the Upper Lodgepole in the southwestern part of the province where the complete section is present. One of the best core sections is from the Souris Valley et al McInnes 8-20-4-25 well, and good samples were taken in the Calstan Waskada 9-13-1-26 and Souris Valley White 5-14-1-28 wells. In the northern part of the area, the Upper Lodgepole has been partly cored in many wells; however the upper part of the unit has been eroded in this area and the cores intersect only the lower part of the section. Core has been taken in the Calstan West Butler 1-31-9-28, the Can Sup Creekside Mitchell 10-32-9-27, and the Imperial Compton 5-3-10-27 wells. Core descriptions for the above wells are included in Appendix II. The general lithology of the unit is presented below.

In the Calstan West Butler 1-31-9-28 well, in the northern part of the map-area, approximately the lower half of the Upper Lodgepole section was cored. The section consists of finely crystalline, slightly to moderately granular, slightly argillaceous limestone with some chert bands and nodules. Colours vary from light grey and yellowish grey to mottled shades of reddish and purplish grey. Almost no coarse crinoidal limestone is present in the unit except in the basal part of the section (Daly crinoidal equivalent). To the east of the Butler well, in the Imperial Compton 5-3-10-27 well, the lithology is much the same, but a few bands of medium to coarse crinoidal limestone are present, especially in the upper part of the unit. This indicates a slight increase in average grain size relative to the section in the Compton well.

In the central part of the map-area, the upper 170 feet of the Upper Lodgepole section was cored in the Souris Valley et al McInnes 8-20-4-25 well. The section consists predominantly of finely crystalline, slightly granular, somewhat argillaceous limestone, mottled in shades of grey, buff, red, and purple. Medium and coarse crinoidal limestone interbeds, however, are very abundant, indicating a considerably coarser average grain size than in the more westerly well described previously. It should be noted, however, that the strata described in the McInnes well are, in part, stratigraphically higher in the section than those described in the Butler and Virden wells.

In the southern part of the map-area, study of samples indicates that there is a similar increase in the average grain size of the Upper Lodgepole carbonates to the east, with a corresponding slight decrease in the argillaceous content.

The general lithofacies pattern thus appears to be one of increasing grain size and decreasing shale content towards the east, although the variations are relatively minor. There is also a slight increase in argillaceous content towards the south. In northern North Dakota the increase in argillaceous content is quite pronounced, and shaly interbeds comprise up to 50 per cent of the section. There is, however, even in this area, little tendency for lateral differentiation or segregation of the shale from the coarser bioclastic carbonates, such as characterize Lower Lodgepole sediments.

The interbedding of clean bioclastic limestone and finer-grained argillaceous limestone in the Upper Lodgepole probably represents a continuation of cyclical deposition somewhat similar to that developed in the Virden-Whitewater Lake sequence, but the units are not as well developed.

Comparison of Upper and Lower Lodgepole Units

The Upper and Lower Lodgepole units are seen to be markedly different in type of sediment, in distribution of sedimentary types, and in isopach pattern. This marked contrast suggests that the units adopted here may be of some genetic significance. The following is a detailed comparison:

(1) The isopach trends of both the Upper and Lower units are approximately the same, i.e. approximately north, and both are markedly discordant to the overall Lodgepole isopach trend which is east.

(2) The upper unit thickens to the west whereas the lower unit thickens towards the east, but the amount of thickening is practically the same in both units, hence the total Lodgepole isopach shows little variation in an easterly direction.

(3) Sediments of the Upper Lodgepole show little or no significant lateral variation in lithology, but the lower unit shows very pronounced lateral variation.

(4) The over-all argillaceous content is probably considerably greater in the lower unit than in the upper.

(5) The over-all grain size of the sediments is somewhat larger in the upper unit.

MISSION CANYON-CHARLES SUCCESSION

In this report the terms Mission Canyon and Charles are formational names used to indicate, respectively, the lower predominantly carbonate section and the upper predominantly evaporitic section of the upper Mississipian strata of Manitoba (Fig. 13). The two units are, in part, lateral, or time-stratigraphic equivalents.

The limestone-evaporite section of the Mission Canyon-Charles of Manitoba marks the beginning of a complex cyclical sequence of interbedded carbonates and anhydrite. Because of extensive pre-Jurassic erosion, only the lowest part of this sequence is preserved in Manitoba; however, in adjacent areas of Saskatchewan and North Dakota the cycles are very well developed and have not been as extensively eroded. Consequently the following discussion of the relationship of the various lithologic units in Manitoba is based to some extent on extrapolation of depositional trends established in the better preserved sections of Saskatchewan and North Dakota.

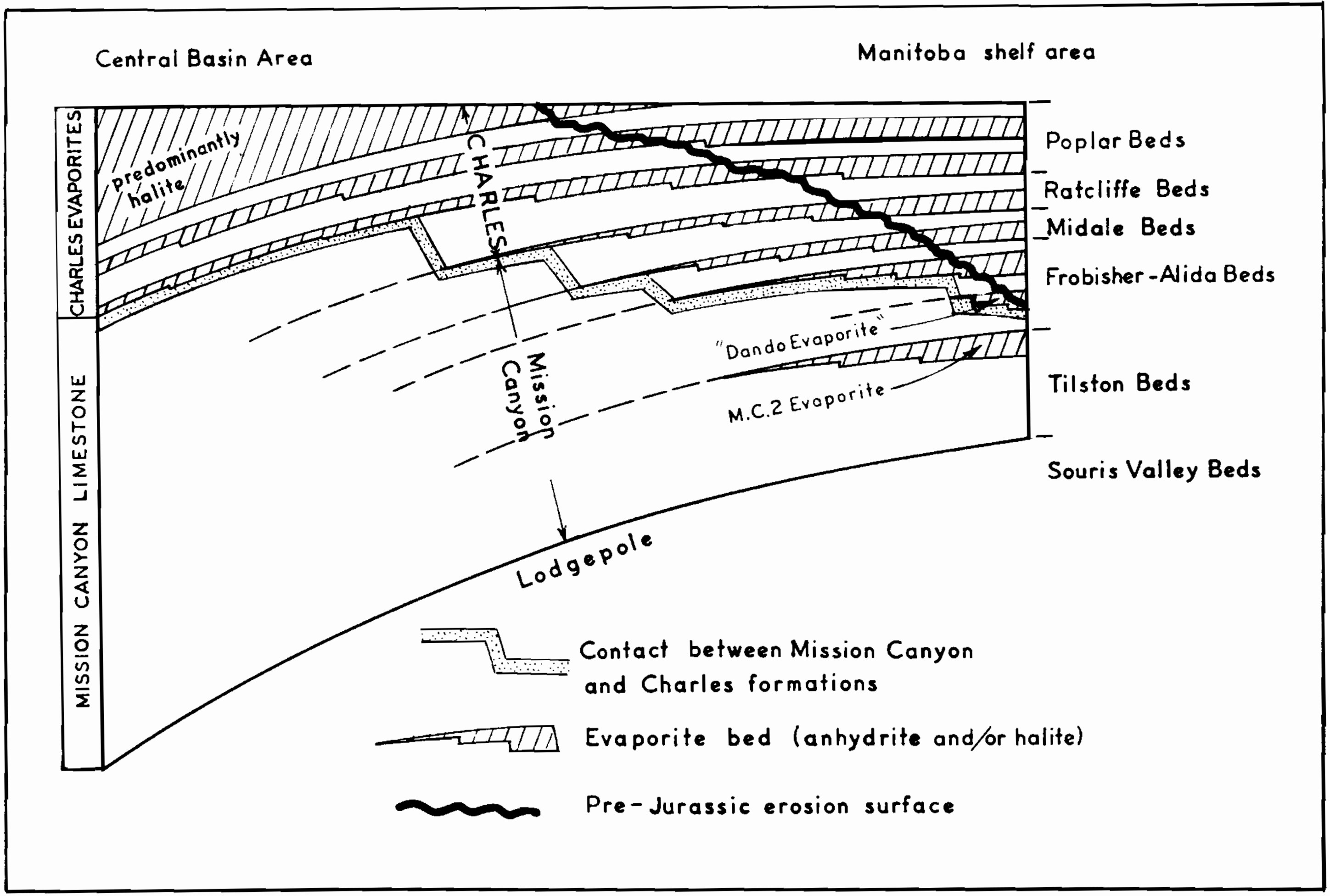


Figure 14. Diagrammatic cross-section showing relationship between Mission Canyon limestone and Charles evaporites on the northeastern flank of the Williston Basin. Datum is the depositional top of the Charles strata, and the cross section indicates the approximate structure at the end of Madison deposition. Strata removed by pre-Jurassic erosion in southwestern Manitoba have been reconstructed.

The general relationships of the evaporites and carbonates are shown schema-cally in Figure 14. The evaporites are of the basin margin type, and occur as ands fringing the edge of the basin and grading basinward to carbonate rocks. The vaporites are, for the most part, interbedded with carbonates in a definite cyclical sequence, with, in general, each succeeding younger evaporite extending farther towards the basin. The one exception is the lowest, or MC-2, evaporite which shows an anomalously great basinward extent. Consequently, near the western limit of its occurrence, the MC-2 evaporite is overlain by a thick section of "Mission Canyon-type" limestone, and cannot be said to mark the base of the main evaporite sequence. It is for this reason that the MC-2 is included as a member of the Mission Canyon rather than as the basal unit of the Charles formation.

In the uppermost Charles strata of the central basin areas, the type of evaporite deposition changed from marginal to central basin, and this change was accompanied by increased restriction of circulation and consequent deposition of halite. These halite-bearing strata, however, are not present in Manitoba.

The following is a detailed discussion of the lithologic units comprising the Mission Canyon-Charles sequence, as contrasted with the marker-defined units discussed previously. The extensive truncation of the units and the lack of good marker beds, except for the MC-2, make marker-bed subdivision impractical. Throughout much of the area the units probably approximate marker-bed units, but in the extreme eastern part of their occurrence rather marked facies changes from carbonates to evaporites take place (Fig. 13).

MISSION CANYON FORMATION

Definition

The Mission Canyon formation as defined here consists of the predominantly clean fragmental carbonate sediments overlying the argillaceous strata of the Lodgepole and underlying the main evaporite beds of the upper Mississippian Charles formation (Fig. 13). The Mission Canyon is subdivided into three members, the MC-1, MC-2 and MC-3. The terms MC-4 and MC-5 are not used in this report; these beds are included in the "Charles Evaporites." The reason for this is that Thomas' correlation of the MC-4 and MC-5 beds to Manitoba is now believed to be incorrect; in addition, the MC-4 and MC-5 indicated by Thomas for the Anglo Ex Souris Valley Smart 4-1-1-26 well are not correlatable units within the map-area.

MC-1 Member

The clean limestones and dolomites of the MC-1 member form the basal unit of the Mission Canyon formation, and are overlain by the argillaceous, evaporitic sediments of the MC-2 member, which is the lowest evaporite unit in the Mississippian. The MC-1 is characterized on electric logs by its very high and uniform negative SP curve which indicates a very low argillaceous content. The resistivity curve is extremely variable; because of the low shale content of the limestone the resistivity curve can be used as an indicator of porosity.

The MC-1 limestones show considerable thinning to the east. The thickness of the section between the MC-2 argillaceous marker and the top of the Lodgepole marker, however, is constant throughout the map-area; this indicates that the thinning of the MC-1 is due to lateral or facies change from carbonates to anhydrite rather than due to differential subsidence. This east to west facies change from carbonates to anhydrite is typical of the evaporite cycles developed in the upper Mississippian sediments in this part of the Williston Basin area.

A good set of core and samples is available from the Calstan Waskada 9-13-1-26 well which shows typical development of MC-1 lithology (see Appendix II).

Unfortunately the MC-1 is almost at the pre-Jurassic erosion surface in this well and the unit may have been affected somewhat by secondary alteration associated with the unconformity, but such alteration appears to be relatively minor. Approximately 10 feet of MC-2 beds are present, and these relatively tight impermeable shales and anhydrite apparently protected the MC-1 strata from extensive alteration and weathering.

The section is rather variable, and consists of limestone, dolomitic limestone, and dolomite in approximately equal amounts. The limestone is predominantly crinoidal-fragmental, and oolitic or calcarenitic. Some sediments show the outward appearance of oolites but in general no internal structure is visible in hand specimen. Much of the limestone and dolomitic limestone is finely crystalline, granular-appearing, and originally may have been fragmental; however, the primary texture appears to have been obscured to a great degree, by secondary recrystallizaion. Some bands are typical granular to saccharoidal dolomites, and are characterized by low resistivity responses on the electric logs.

A small amount of anhydrite is scattered throughout the section. It occurs as secondary fracture fillings, and also as cement in the fragmental limestones.

The lithology described above appears to be generally representative of the MC-1 limestone in southwestern Manitoba.

The uppermost part of the MC-1 beds is rather variable in nature. In the area where the MC-1 is overlain by the MC-2 evaporites, there is commonly an intermediate zone, directly below the evaporites, consisting of finely crystalline to finely saccharoidal dolomite containing irregular inclusions of anhydrite. This zone may constitute a secondary alteration zone related to deposition of the MC-2 anhydrites, or it may be a primary deposit formed under conditions of salinity intermediate between those prevailing during deposition of the MC-1 and MC-2. The former appears more likely; consequently, the dolomite-anhydrite zone is included in the MC-1. In the Souris Valley Meggison 10-14-1-25 well, a bed of massive dense, evaporitic(?) dolomite is present immediately below the MC-2 anhydrite. Because of the lack of anhydrite, this unit also is included in the MC-1.

In some areas, the dolomite-anhydrite zone is not present below the MC-2 and the anhydrite passes directly into the MC-1 limestone, which shows only slight porosity infilling by anhydrite.

MC-2 Member

The MC-2 is defined as the first or lowest evaporite-shale member of the Mission Canyon formation (Thomas, 1954). The MC-2 constitutes the top of the Tilston Beds (Saskatchewan Geological Society), and is called the Middle Anhydrite member of the Mission Canyon by the North Dakota Geological Survey.

The shaly break at or near the top of the MC-2 is an excellent marker horizon and is correlatable for a considerable distance southwest of the depositional edge of the MC-2 evaporites. As indicated previously, the MC-2 unit shows a marked facies relationship to the underlying MC-1, with the MC-2 evaporites being replaced to the west by MC-1 limestones. A similar, though less pronounced, facies relationship exists between the MC-2 and overlying MC-3. The uniformity in thickness of the interval between the MC-2 and the Upper Lodgepole marker beds (Fig. 13) shows that, within the map-area, the variations in thickness of the MC-2 evaporites are due entirely to facies change rather than differential subsidence.

Two complete cored sections of MC-2 were taken in the Rio Prado Souris Gibson 2-14 (2-14-3-28) and Souris Valley et al Meggison 10-14-1-25 wells, situated near the eastern and western limits respectively of MC-2 occurrence in Manitoba. The marked differences in lithology and thickness between these two wells probably is typical of the eastward facies changes in the evaporite cycles.

The strata in the eastern, Gibson well consist of two beds of anhydrite and red argillaceous dolomite, each approximately 4 feet thick, with a thin interbed of earthy to dense argillaceous dolomite. The anhydrite associated with the dolomite has a pronounced brecciated or breccia-like appearance which appears to be common in primary evaporites. The section is predominantly anhydrite, up to 80 per cent, with red argillaceous dolomite as interstitial filling between large, irregular, rounded fragments or inclusions of anhydrite.

The MC-1 beds immediately below the MC-2 anhydrites show development of a thin, secondary zone of medium-grained, saccharoidal, slightly anhydritic dolomite, and light grey, finely crystalline to dense dolomite with some large, irregular, rounded inclusions or fragments of anhydrite.

The MC-2 lithology in the Meggison well (see Appendix II) is similar to that in the Gibson well, but with a thicker development of evaporites. On the basis of regional trends, this greater thickness of evaporites in a more easterly area is to be expected. The dolomite-anhydrite "breccia" zone is the same in thickness and lithology as that in the Gibson well; however, it is overlain by a three-foot bed of anhydrite, and underlain by 18 feet of dolomitic anhydrite. Both of these anhydrite beds are facies equivalents of the Mission Canyon limestone in the Gibson well. The dolomitic anhydrite lithology is typical of many of the Charles and Mission Canyon evaporite beds; it consists of an extremely fine-grained dense to lithographic rock which grades in composition from relatively pure dolomite to relatively pure anhydrite. In the Meggison well, the basal dolomitic anhydrite unit grades from relatively pure crystalline anhydrite at the base to anhydritic dolomite at the top. Colours vary from medium brown and reddish brown in the dolomitic sections, to white in the pure basal anhydrite. It is difficult to determine the anhydrite content unless an insoluble residue test is run, but the anhydritic beds usually show a thin white zone of surface alteration to gypsum on the outside of the core. In thin section, the dolomitic anhydrite is seen to consist of a cryptocrystalline mixture of dolomite and anhydrite.

The anhydrite is in turn underlain by the transitional beds of the MC-1 consisting of light grey to white, finely crystalline to dense and lithographic dolomite with stringers and inclusions of white crystalline anhydrite in the upper part.

Together the MC-1 and MC-2 constitute a complete evaporite cycle consisting, in ascending order, of:

(1) limestone, fragmental, algal-oolitic.

(2) anhydrite and dolomitic anhydrite.

(3) argillaceous dolomite and anhydrite breccia.

(4) anhydrite.

(5) limestone, as in unit (1), basal unit of succeeding cycle.

There is commonly, though not always, a transitional zone between units (1) and (2) consisting of dolomite (dolomitized limestone?) and anhydrite. Unit (4) is present only in the more easterly, or shelfward areas.

MC-3 Member

The MC-3 unit, as used in this report, consists of the limestone beds overlying the MC-2 and underlying the evaporites of the "Charles formation", or Charles evaporite facies, as shown in Figure 13. The MC-3 is thus not a marker-defined unit, or format, but a strictly lithologic unit that is markedly time transgressive, especially in the eastern part of the map-area.

The MC-3 beds are equivalent to the lower part of the Frobisher-Alida beds (Saskatchewan Geological Sociey, 1956) and to the "Upper Mission Canyon" of the North Dakota Geological Survey.

The facies relationship between the MC-3 and MC-2 has been noted. The MC-3 also shows a similar pronounced facies relationship to the overlying Charles as shown in the cross-section (Fig. 13); the MC-3 limestones grade eastward to evaporites. Throughout most of the area, the stratigraphic position of the base of the evaporites appears to be relatively constant. The gradual changes in thickness of the MC-3 could be tectonically controlled but, on the basis of the uniformity in thickness of the underlying Mission Cayon strata, and the marked facies variations known to be present in adjacent areas of Saskatchewan and North Dakota, it seems much more likely that variations in thickness of the MC-3 limestones are controlled primarily by facies changes. This is particularly true in the Anglo Ex Dando 3-32-1-25 and Calstan Imperial Dalny 8-10-2-26 wells where the base of the Charles is stratigraphically very low.

The MC-3 has only a very limited occurrence in the extreme southwestern part of the province as shown by the subcrop map (Fig. 15). Except for the marked facies thinning to the east in the Dando and Dalny wells, and the slight facies thickening to the west in the Poplar Gas Ex Admiral Antler #1 (8-15-1-29) well, the unit is relatively uniform in thickness throughout most of the limited area of evaporite cover.

In those areas where the overlying Charles evaporites are present, and a complete section is available, only a few wells have penetrated the complete MC-3 section. Most of the unit was cored in the Rio Prado Souris Hill 16-9-2-28 well (see Appendix II) and the samples appear to be typical of the lithology in Manitoba. In this well the MC-3 has been largely protected from post-Mississipian weathering by the thin cover of impermeable shale and evaporites of the Charles formation. The exact lithology of the MC-3 is difficult to determine. It is predominantly a fragmental limestone, with some dolomitic limestone, medium saccharoidal dolomite, and earthy limestone. For the most part, the fragmental limestone cannot be called algal, oolitic, or crinoidal, although some algal and oolitic material as well as a few scattered crinoid fragments are found. The limestone appears to be primarily a microbreccia, or calcarenite, with irregular to rounded fragments of structureless limestone in a finely crystalline, granular, dolomitic matrix. The overall texture is very finely crystalline, granular to saccharoidal suggesting extensive recrystallization. Fossils are abundant in several bands, and include brachiopods, crinoids, horn corals, and bryozoa. Patches of anhydrite occur scattered throughout the limestone. The section in non-argillaceous and generally shows good porosity.

CHARLES FORMATION

Definition

The Charles formation is defined in this report as the main upper Mississippian evaporite sequence, and consists of anhydrite and dolomite, in part argillaceous and sandy. This usage corresponds to the original definition by Seager (1942), and Perry and Sloss (1943).

Correlation

The Charles evaporites of the extreme southwestern part of the map-area are time-stratigraphically correlative with the upper part of the type Mission Canyon formation of Montana; with the middle part of the Frobisher-Alida beds of Saskatchewan; with the "Charles" of the North Dakota Geological Survey; and approximately with the Gainsborough and Carievale evaporites of Fuller (1956). Correlations are difficult because of the removal of the upper Charles marker beds by pre-Jurassic erosion. The evaporites in the Calstan Imperial Dalny 8-10-2-26 and Anglo Ex Dando 3-32-1-25 wells, at the eastern limit of Charles occurrence, are stratigraphically lower than any known evaporites in Saskatchewan (see cross-section, Fig. 13).

Relation to Overlying Beds

The Charles formation, as shown by the subcrop map (Fig. 15), has the most limited occurrence of any Mississippian unit in Manitoba. The unit is overlain everywhere with marked unconformity by lower Amaranth red beds consisting of argillaceous, sandy, anhydritic siltstones. The upper limit of the unit is easily picked, in most wells, on the basis of the marked difference in lithology between the Charles evaporites and Amaranth red beds; in some wells, however, Amaranth sediments rest directly on red sandy shales of the Charles. In such areas, the Amaranth sediments in general contain much more coarse clastic material (i.e. sand and silt), and less shale than do Mississippian red beds, although in some beds the lithology is essentially identical. The contact, in some places, is marked by a brecciated and weathered zone, with red sand, shale, and silt filling fractures in the Mississippian strata. In other places, the contact is sharp with practically no evidence of unconformity.

Relation to Underlying Beds

The Charles evaporites show a marked facies relationship to the underlying MC-3 — the evaporites replace MC-3 carbonates in the eastern part of the subcrop area. The contact between the MC-3 carbonates and the Charles evaporites is surprisingly sharp in some wells where anhydrite rests directly on porous fragmental limestone that shows only slight porosity infilling with secondary crystalline anhydrite. Other wells show a transitional zone of earthy dolomite or dolomitized limestone containing abundant inclusions or fragments of anhydrite.

Lithology

The lithology of the Charles formation shows considerable lateral variation, and no generalized lithologic description is possible. Complete core sections were taken in a number of wells, and detailed descriptions are included in Appendix II; generalized descriptions are presented below. The wells are listed in order of location, from west to east, in order to show the marked facies changes in this direction.

Cleary Souris Valley Hallam 15-5

The evaporite section is 116 feet thick. The contact with the overlying Amaranth red beds is fairly sharp, with several bands of chert breccia near the base of the Amaranth. At the contact of the evaporite with the underlying MC-3 a 6-foot transition zone of granular to saccharoidal dolomite contains abundant inclusions of anhydrite, and some chert. The underlying oolitic limestone shows good porosity with only slight infilling by secondary, crystalline anhydrite.

The Charles consists of approximately 30 per cent anhydrite and dolomitic anhydrite, and 70 per cent dolomite and argillaceous dolomite. The high dolomite content contrasts with that in wells to the east where anhydrite is the predominant evaporite. The upper 20 feet consists of dense dolomitic anhydrite which varies in colour from tan to grey, purple, brown, and reddish brown with much streaking and mottling. It is underlain by 80 feet of hard, dense to lithographic dolomite, varicoloured as above, with a few thin bands of dolomitic anhydrite and chert. The dolomite is underlain by 6 feet of dolomite streaked with anhydrite, and 10 feet of dense dolomitic anhydrite.

Cleary Souris Valley Moore 11-13

In the Moore well, pre-Jurassic erosion has cut more deeply into Mississippian strata, and the Charles section is only 40 feet thick. Correlations with the Hallam well (Fig. 13) indicate that the base of the evaporite section in the Moore well is at approximately the same stratigraphic position, or possibly slightly higher than in the Hallam well. Accurate correlations, however, are impossible because there are no markers above the MC-2.

The exact contact with the Amaranth is difficult to pick in this well because red sandy siltstone of the overlying Amaranth formation rests directly on red and green mottled, sandy, dolomitic shale that is very similar in appearance to the Amaranth red beds. The sandy shale is included in the Mississippian primarily because of the high argillaceous content which is not at all characteristic of the basal Amaranth. (The lower part of the Amaranth red beds, especially in the southwestern part of the map-area, are primarily medium- to fine-grained sandstone and siltstone with relatively little argillaceous material). The contact between the Charles and the MC-3 is sharp, and the evaporites rest directly on porous fragmental limestone which shows partial anhydrite infilling of porosity; the transitional, dolomitic zone is not developed.

In marked contrast to the Hallam well, the Moore section consists almost entirely of anhydrite and dolomitic anhydrite, with little dolomite. A thin band of dolomitic sandstone is developed near the base of the unit. This sandstone apparently is not present in the Hallam well.

Souris Valley McKague 2-27-1-27

The Charles evaporites are 93 feet thick in this well. This thickness is considerably greater than in nearby wells (Fig. 13). The McKague well appears to be located on a structural low, as indicated by structure contours on the MC-2 member. In addition, the area is also a slight topographic high on the erosional surface as indicated by the thinner section of overlying Amaranth red beds. The anomalously thick evaporite section is thus due to a combination of both structure and topography. The section shows some fracturing and slight faulting, which may be either related to the structure, or primary depositional features.

The base of the evaporites appears to occur at approximately the same stratigraphic horizon as in the Moore and Hallam wells, with little or no indication of changes in thickness due to facies variations between the rocks encountered in the three wells. The contact with the MC-3 is quite sharp. There is only slight interbedding of limestone and anhydrite; a 1-foot bed of limestone occurs 2 feet above the base of the evaporites. The fragmental limestone immediately below the evaporites shows good porosity and only slight secondary infilling by anhydrite.

The lithology of the McKague section differs considerably from the preceding sections in that the red colour in the upper part of the unit is more pronounced than in the other sections, and the clastic content, especially sand, is considerably higher. Interbedded argillaceous dolomite and anhydrite are present in approximately equal amounts; the anhydrite is more abundant towards the base. A 2-foot bed of dolomitic sandstone near the base of the unit may correspond to the sandy bed in the Moore well.

Anglo Ex Souris Valley Smart 4-1-1-26

The thickness of the evaporites is 40 feet, and the base of the evaporite section is at approximately the same stratigraphic horizon as in the McKague and preceding wells.

The contact with the overlying Amaranth is sharp, is not marked by a breccia zone, and displays little or no evidence of unconformity. Amaranth sediments rest on a 3-foot bed of grey dolomitic sandstone, which is included in the Mississippian but could possibly be basal Amaranth.

The lithology is similar to that of the McKague well and consists of roughly equal amounts of anhydrite and argillaceous dolomite to dolomitic shale. Red colour is prominent in the upper part of the unt; a 3-foot bed of sandstone near the base appears to correlate with similar sandstone beds in the Moore and McKague wells.

Anglo Ex Dando 3-32-1-25

The Dando well shows a 17-foot section of Charles evaporites, which are stratigraphically much lower in the section than in any of the preceding wells: the evaporites occur only 35 feet above the MC-2, in contrast to 115 feet in the near-by Smart well. The rocks consist almost entirely of anhydrite and dolomitic anhydrite with only a small amount of fine granular dolomite. The lower 9 feet of anhydrite show a pronounced breccia-like structure with fine granular to saccharoidal stringers of dolomite.

Petrography of the Charles Sands

As indicated in the foregoing description, minor sandy beds are developed in the Charles strata of southwestern Manitoba. These sands probably are lithologically similar to, although stratigraphically lower than, the better developed Kisbey sandstones of southwestern Saskatchewan. Petographic examinations were made of sandstone samples from four wells, Cleary Souris Valley Moore 11-13-1-28, Souris Valley McKague 2-27-1-27, Rio Prado Souris Hill 16-9 (16-9-2-28 WPM,), and GLCC Coulter 12-22-1-27. All samples proved to be similar in lithology and texture.

The most prominent feature of the Charles sands is the poor degree of rounding shown by the grains, most of which are angular to sub-angular; few well-rounded grains were observed. The grain size of the sands is predominantly in the range of fine to very fine sand, but medium-sized sand grains are common. The sorting of the Charles sands generally is good; little or no fine (clastic) matrix is present. The sand commonly has a coarsely crystalline anhydrite cement, or microcrystalline dolomite matrix. Sand grains "float" in a dolomite matrix in some instances.

Although the Charles sands are composed primarily of quartz grains, the feldspar content is also relatively high in most samples, probably 10 to 20 per cent. Quartzite and chert(?) grains are also common in all samples. Because of the relatively high feldspar content, the Charles sands are classed as feldspathic to arkosic sandstones. Many of the quartz grains show very pronounced strain extinction.

The Charles sands are thus seen to differ markedly from the Bakken sands and silts. The Charles sands generally are coarser grained, more angular, much more feldspathic, and contain many quartzite grains.

In summary, the Charles evaporites show a fairly marked lateral variation in lithology, grading from primarily dense varicoloured dolomite and anhydritic dolomite in the western part of the map-area to predominantly anhydrite with some interbedded dolomite in the east. The clastic content, including both sand and argillaceous material, and also red colour show an increase to the east. The base of the evaporite section shows a pronounced stratigraphic drop in the section at the extreme eastern limit of its occurrence. Throughout the rest of the area, the base of the evaporites maintains a relatively uniform stratigraphic position with a maximum variation of less than 50 feet, probably due to facies change.

Westward into Saskatchewan, and towards the centre of the Williston Basin, the base of the Charles evaporites shows a gradual, more or less continuous stratigraphic rise in the section due to progressive lateral facies change of "Charles" evaporites to fragmental "Mission Canyon" limestones. The rate of facies change appears to be more rapid and more pronounced in the northeastern corner of the Williston Basin, in Manitoba, southeastern Saskatchewan, and north-central North Dakota, than anywhere else in the basin area. Regional studies indicate that the evaporites in the Anglo Ex Dando 3-32-1-25 and Calstan Imperial Dalny 8-10-1-21 wells are probably the lowest known stratigraphic occurrence of "Charles" evaporites in the basin.

A recent report by Anderson (1958), shows rather abrupt thickening and thinning of some of the Mississippian strata of North Dakota; Anderson ascribes these changes in thickness, at least in part, to salt collapse associated with the Devonian Prairie Evaporite. In the present report it is assumed that the "Dando evaporite" is a facies of the MC-3. This assumption is based on the relative uniformity in thickness of both the MC-1 and MC-3 units throughout the rest of the map-area. It is possible, however, that there was a rapid thinning of the MC-3 in the Dando area (3-32-1-25), possibly due to salt collapse phenomena, and the "Dando evaporite" is actually equivalent to the Charles strata of the more westerly wells.

WEATHERED ZONE

Associated with the pre-Jurassic erosion surface, in almost all areas where Mississippian strata are overlain by Amaranth sediments, is a zone of secondary alteration or weathering. In this zone the Mississippian limestone commonly is altered to dolomite and anhydrite, and in many areas is profusely cut by bands and veinlets of anhydrite. This zone is similar to the transitional dolomitic zone sometimes found beneath the MC-2 and Charles evaporites.

The thickness of the secondary zone is extremely variable, ranging from only a few feet in such wells as the Royalite Triad et al LuLu Lake #1 (16-14-10-28 WPM) to possibly 150 feet in the Cruickshank 14-4 (14-4-10-28 WPM) well in the Daly area (see Appendix II). The limits of this zone of alteration are, in some instances, difficult to define. Wells showing a thick Amaranth section seem to have thinner weathered zones. For instance, the Can Dev Mitchell East Daly 10-32-9-27 well is located off the eastern flank of the Daly structure, and shows a well-developed red bed section. In this well the zone of anhydrite and dolomite alteration is only about 25 feet thick, and anhydrite stringers are present only to a depth of about 40 feet below the erosion surface. In contrast, the Calstan Cromer Prov 8-27-8-28 and Cruickshank 14-4 wells, located relatively high on the Daly structure, have a thin Amaranth section and show relatively thick alteration zones of approximately 70 feet and 60 feet respectively; furthermore, in the Cruickshank well, traces of presumably secondary anhydrite are present in the section as fracture fillings to a depth of 150 feet below the erosion surface. The anhydrite occurring along fractures far below the erosion surface is, in many instances, accompanied by a bordering zone of dolomitized limestone. The deep fracturing probably is related to the Daly structure.

As shown by the section in the Calstan Treat Prov 15-29-15-28 well (Fig. 7), the secondary anhydrite-dolomite zone is not present in the area north of Daly. It is also locally absent in the Wawanesa (tp. 8, rge. 18) and Hartney (tp. 5, rge. 24) areas. In all these areas Mississippian strata are overlain directly by upper Jurassic (Reston or Melita) shales rather than Amaranth sediments. In the southern part of the map-area, where the Amaranth red beds are relatively thick, the alteration zone commonly is very thin.

Interpretative Stratigraphy

GENERAL WILLISTON BASIN PALAEOGEOGRAPHY

The Williston Basin comprises a single, essentially complete depositional realm, whereas the Mississippian strata in southwestern Manitoba comprise only a small portion of the total Williston Basin Mississippian sequence. Consequently the stratigraphic relationships shown in Manitoba are more easly understood when considered in the overall framework of the total basin. The following section is a generalized discussion of the regional aspects of Mississippian sediments in the Williston Basin.

The entire lower Mississippian or Madison sequence in the Williston Basin area comprises one major sedimentary cycle of marine transgression and regression. The cycle commenced with the advance of Mississippian seas over the slightly eroded surface of the Devonian Qu'Appelle sediments. The seas, advancing from the west or northwest, deposited the basal black shales and siltstones of the Bakken formation over a flat, tectonically stable, cratonic area.

Further transgression and deepening of Mississippian seas took place during Lodgepole time* when a sequence of thick, predominantly argillaceous limestone beds was deposited. During this time the Williston Basin area underwent comparatively rapid subsidence resulting in the development of a relatively steep depositional slope and consequent pronounced lateral differentiation of lithologic facies, especially on the eastern flank. The maximum extent of Mississippian seas probably was reached during the middle Lodgepole time.

During Mission Canyon (Osage or late Kinderhook) time the rate of subsidence in the Williston Basin area decreased, and bottom slope also decreased; relatively shallow-water fossiliferous, fragmental, algal-oolitic, and calcarenite limestones were deposited throughout most of the area. Cyclical fluctuations in sea level during this time had a pronounced effect on the sedimentary facies, resulting in the formation of fringing biostromal and calcarenite shoals during periods of shallow water. Evaporites and clastics were deposited in the marginal lagoons. During periods of deeper water, widespread uniform sheets of limestone were deposited. Because of the gradual decrease in the rate of subsidence in the Williston Basin area, the lagoonal evaporite facies showed a continued retreat or regression towards the basin during Mission Canyon and early Charles time.

By late Charles time evaporites had been deposited throughout the entire basin area during periods of lowered sea level. Although the rate of subsidence was gradually decreasing during Charles time, and Mississippian seas were gradually retreating towards the basinal areas, the degree of tectonic differentiation of the basin increased with the result that thick halite beds were deposited during latest Charles time in the central basin area.

Subsequent to deposition of these upper Charles halite beds, Mississippian seas withdrew completely from the basin area and the Williston Basin became tectonically stable. Thin non-marine sandstone beds of the upper Mississippian Kibbey formation were deposited throughout the basinal area. These marked the close of the major sedimentary cycle that began in the earliest Kinderhook time

*refers to the time of deposition of the type sections or formats.

with the deposition of the Bakken beds. Subsequent pre-Jurassic erosion resulted in removal of the upper part of the Mississippian sequence from Manitoba and adjacent parts of the basin.

MANITOBA STRATIGRAPHY

Bakken Formation

Age

Throughout this report the Bakken formation has been included as the basal unit of the Mississippian system. Palaeontologic or chronologic correlations, however, are very uncertain at present. In Alberta, black shales underlying the Mississippian Banff formation, and apparently lithologically correlative with the Bakken, are believed to be Devonian in age (Warren, 1937 and 1956). This has been challenged by Crickmay (1956). Raasche (1956) indicates that faunally there is no break between Devonian and Mississippian deposition in the Stetler area of Alberta, and that it is impossible to apply a definite Mississippian or Devonian age to the Exshaw. This is also questioned by Crickmay (1956). Raasche points out the possibility that the Exshaw is a time transgressive unit. Knechtel et al (1953) indicate a Mississippian age for the black shale in central Montana.

The absence of the lower Bakken in Manitoba, and the slight erosion of the upper Devonian Lyleton beds indicate that probably there was a slight time break between Bakken and Lyleton deposition in areas peripheral to the Williston Basin, but that the break may or may not correspond to the Devonian-Mississippian contact.

Tectonic Framework

Although a detailed isopach study of the Bakken formation was not attempted in the map-area, regional basin studies by Nordquist (1953), Fuller (1956), and the writer, along with data from the few wells that cored the Bakken in Manitoba, indicate that thickness variations of the Bakken are very minor, and it is probable that most of the apparent variations in thickness are due to deposition over slight irregularities developed on the pre-Bakken erosion surface. The widespread distribution, and uniformity in thickness and lithology indicate that the tectonic framework during deposition of the Bakken must have been extremely stable.

Environment

The cyclical marine carbonate-evaporite deposition characteristic of Devonian sedimentation in the Williston Basin area (Baillie, 1953) culminated in Upper Devonian Qu'Appelle time with deposition of the shallow marine to terrestrial sediments of the Lyleton formation; these, together with the Bakken beds, represent the first main influx of clastic detritus into the basin since deposition of the Ordovician Stony Mountain and Winnipeg formations. Lyleton sediments were deposited in a pronounced oxidizing environment as shown by their bright red colour. The irregular texture and structure, including crossbedding and intraformational breccia beds, indicate a shallow-water to possibly terrestrial origin for these deposits.

Devonian seas probably withdrew completely from the Williston Basin area at the end of Devonian time but, as indicated by Warren (1956), there was very little time lapse between deposition of Devonian and Mississippian sediments. Minor erosion of the Lyleton beds took place in this interval in peripheral areas such as Manitoba and eastern Saskatchewan (Fuller, 1956), but in the deeper parts of the basin area there is little or no evidence for any break in sedimentation.

The nature of the Bakken sediments indicates a pronounced basin-wide change in environment of deposition, from highly oxidizing during Lyleton time to highly reducing conditions during Bakken time. The exact environment in which black shales such as the upper and lower Bakken are deposited is problematical; such shales can be formed under conditions varying from deep-water marine to terrestrial swamp (Pettijohn, 1949; Twenhofel, 1950). Certainly, restricted euxinic conditions with little or no aeration of waters and low Eh and pH are indicated by the very high organic content and the presence of considerable pyrite.

Fuller (1956) suggests that the Bakken black shales were laid down in a vast swamp area subsequent to withdrawal of Devonian seas. Raasche (1956) proposes a stagnant marine marginal lagoon environment. MacDonald (1956) suggests a deep-water marine environment with deposition below wave base.

The writer believes that the lithologic associations of the Bakken shales give an indication of the probable environment of deposition. The argillaceous, dolomitic middle Bakken siltstones or sandstones, in places showing good bedding or crossbedding with some cut-and-fill structures, probably was deposited under very shallow marine to possibly terrestrial conditions, at least in peripheral areas such as Manitoba. The underlying Lyleton red beds are also of very shallow marine to terrestrial origin, and the overlying Lodgepole fossiliferous fragmental limestones are of relatively shallow marine origin. The intimate association of the Bakken black shales with the above-described shallow marine to terrestrial sediments suggests that the black shales are probably also shallow marine to terrestrial in origin.

The most likely environment would appear to be a widespread marine swamp with restriction of circulation due to prolific organic development (Krumbein and Sloss, 1951, p. 181) rather than due to a physical barrier such as is present in the case of the marine black shales of the Black Sea and the Norwegian Fjords (Kuenen, 1950). Climatic conditions may also have been an important environmental factor.

The black-shale swamp apparently was drowned or flooded during the time of middle Bakken deposition by an influx of shallow marine clastics throughout the area, but restricted stagnant conditions apparently persisted in most places, as indicated by the presence of abundant pyrite in the sandstone (Twenhofel, 1950, p. 432). The source of the clastic material is difficult to determine. The clastics may have been derived from the underlying Devonian Lyleton sediments which probably were subjected to at least mild erosion in marginal areas during Bakken and pre-Bakken time. The apparent increase in grain size and thickness to the north and east in Manitoba suggests a marginal source for the sand and silt; however, the Lyleton sediments present in these peripheral areas show only a low content of coarse clastic material and do not appear to be likely source rocks for the middle Bakken clastics. Earlier Palaeozoic clastics such as the Winnipeg sandstone, or, possibly, Precambrian rocks may have been the source rocks.

The petrography of the Bakken clastics is not sufficently characteristic to indicate a particular type of source area. The relatively well-rounded quartzose silts and sands could have been derived from either Precambrian rocks or earlier Palaeozoic sediments.

The influx of clastics probably indicates mild tectonic uplift in peripheral areas. Following deposition of the middle Bakken sediments, the peripheral tectonism apparently ceased, no further coarse clastic material was supplied to the basin, and stagnant swampy conditions under which the upper Bakken black shale was deposited were re-established. It is also possible that a relative lowering of sea level was a factor contributing to the peripheral erosion.

There are two possible explanations for the development of the very prominent reddish colour of the Bakken beds in the northern part of the map-area (e.g. Homestead Birdtail 10-8-15-27, and Dome Birtle 16-17-17-27). The red colour may be primary, indicating a change in environment of deposition from strongly reducing in the southern part of the map-area to strongly oxidizing in the northern part. The increase in grain size and presence of crossbedding and cut-and-fill structures suggest a decrease in depth of water and, possibly, approach to a contemporaneous shoreline, in which case the change to oxidizing conditions would be expected. The second possibility is that the colour is secondary and is related to the period of pre-Jurassic weathering and erosion. The cover of Lodgepole sediments over the Bakken beds is comparatively thin in the areas where red colour is developed.

Because of the accompanying change in grain size and the presence of cross-bedding and cut-and-fill structures, it is believed that the red colour is largely primary, although this cannot be proven. No relict patches of unoxidized Bakken sediments were noted. Undoubtedly however, pre-Jurassic weathering had some effect in and near the subcrop areas. In the area of the Homestead Birdtail 10-8 well (10-8-15-27 WPM), the thickness of the Lodgepole cover (220 feet) would seem to preclude the possibility of a secondary origin for the red colour. It should be noted, however, that the area was a pronounced topographic "high" during much of Jurassic time and stood 200 to 300 feet above the depositional surface relative to adjacent areas to the east. This may have permitted relatively deep penetration of ground waters that resulted in formation of a deep zone of secondary oxidation which affected the Bakken.

Within the map-area the middle and upper Bakken units show a marked overlap with respect to the lower Bakken, with both upper units extending much farther to the east. This overlap of the middle and upper Bakken units appears to be general in the Williston Basin and probably reflects the first stages of Mississippian marine transgression.

Lodgepole

Age

The age of the Lodgepole formation in Montana has been indicated by Laudon and Severson (1953) and others as Kinderhookian or early Mississippian. If the writer's regional correlations are correct, that is, if the Lodgepole of Manitoba is the time-stratigraphic, marker-bed equivalent of the type Lodgepole of Montana, the Lodgepole of Manitoba is also of Kinderhookian age.

Palaeontologic correlations by Crickmay (private communication) support the suggested stratigraphic correlations. A number of fossil collections from Lodgepole cores in Manitoba were identified by Crickmay as correlative with the type Lodgepole fauna of Montana. A study of the Mississippian Lodgepole spiriferid fauna of Manitoba by Zaborniak (1956) indicates a Kinderhookian to possibly lower Osagian age. The Manitoba fauna shows a somewhat closer affinity to the Alberta fauna of western Canada than to the faunas of either the type Lodgepole of Montana or the type Kinderhook of the Mississippi and Ohio Valley areas. The Manitoba fauna is considered to be intermediate in type between the Alberta and the Mississippi Valley faunas, and may represent an intermediate stage in the eastward migration of the fauna.

Regional Tectonic Framework

The regional Williston Basin isopach-lithofacies map of the total Lodgepole (Fig. 9) is useful in explaining the tectonic and isopach patterns indicated in Manitoba. The total Lodgepole isopach, in the area where the unit has not been subjected to pre-Jurassic erosion, shows a rather poorly-defined nose or embayment of the Williston Basin extending from north-central North Dakota towards Manitoba. Pre-Jurassic erosion to the north makes delineation of the limits of the embayment difficult. This minor isopach feature corresponds approximately with the area of development of the high-shale facies, indicating that the embayment was an important factor in controlling deposition during Lodgepole time. It is proposed to name this feature the Mandak Embayment.

The northern extension of the Mandak Embayment in Manitoba is indicated by Walker (1957) as an area of Mississippian to Triassic salt collapse. He suggests that Devonian salt beds were dissolved (by intrastratal solution) prior to the period of pre-Jurassic erosion. The Devonian and Mississippian strata overlying the Devonian salt beds collapsed, and consequently a thicker sequence of Mississippian beds was preserved in the structurally low area of salt collapse. It should be noted, however, that the depositional thickening of the Lodgepole beds, as shown by the isopach map (Fig. 19), indicates that at least part of the subsidence and thickening took place during Mississippian Lodgepole time.

Cross-sections and isopach maps (Figs. 5, 6, 16) show there is no thickening of the uppermost Mississippian strata to the east, as would be expected if salt collapse had taken place after Mississippian beds had been deposited. The rate of truncation of Mississippian strata decreases somewhat in southwestern Manitoba, indicating that slight post-Mississippian subsidence may have taken place; however, the thickening appears to be primarily the result of depositional rather than erosional phenomena. It is possible that salt collapse was the controlling factor in either case; this will be discussed in a later section.

Regional Lithofacies

The regional isopach-lithofacies map of the total Lodgepole section for the Williston Basin (Fig. 9) shows a prominent north-trending band of high argillaceous content in central North Dakota. The argillaceous material occurs almost entirely in the lower part of the Lodgepole. The high-shale facies of the Lower Lodgepole of western Manitoba represents the northward continuation of this band. In North Dakota the isopach and lithofacies trends are more or less accordant; however, in Manitoba the total Lodgepole trends appear markedly discordant, although, as indicated previously, there is some minor "nosing" to the north related to the Mandak Embayment. As will be shown later, the apparent discordance does not exist when the Upper and Lower Lodgepole units are considered separately. The factors controlling Lodgepole deposition in Manitoba are best discussed in the framework of the individual units.

Lower Lodgepole

Tectonic Framework

The tectonic framework of the Lower Lodgepole is interpreted from the isopach map on the assumption that the defined unit is a true time-stratigraphic unit, and consequently that thickness variations are primarily the result of contemporaneous subsidence. Southwestern Manitoba appears to be situated either on the eastern flank of a positive area centred in southeastern Saskatchewan, or on the western flank of a north-trending trough or embayment, the eastern flank of which has been removed by pre-Jurassic erosion. The latter would appear to be more probable; the thickening is probably related, regionally, to the Mandak Embayment discussed previously.

Environment

In the map-area, and the Williston Basin in general, Lower Lodgepole sedimentation was characterized by pronounced lateral variation as shown by the facies map (Fig. 11), and appears to have been closely controlled by the tectonic framework.

ROUTLEDGE SHALE

The fringing black shales of the Routledge member indicate deposition in a restricted, euxinic type of environment essentially the same as that for the Bakken. The very abrupt lateral gradation to clean or non-argillaceous cherty relatively normal marine limestones of the Scallion member is difficult to explain. Two possibilities arise:

(1) Some local barrier such as a reef or shoal developed in earliest Lodgepole time, causing local restriction of circulation with resultant formation of euxinic back-reef deposits.

(2) The Routledge shale is not of Lodgepole age at all, but represents thickened Bakken sedimentation in local basins.

The presence of a few feet of very porous, extremely fossiliferous reefoid material in the basal Lower Lodgepole of the Baysel Calstan Boissevain 3-20-3-19 well (see Appendix II) is the only indication known by the writer of anything resembling reef material in lower Scallion beds near the area of occurrence of the Routledge shale. However, considerable thicknesses of extremely porous fossiliferous reefy-appearing dolomite are present in the upper part of the Scallion in several wells in the northern part of the map-area (e.g. Homestead Birdtail 10-8-15-27). Although these dolomites are not related to the occurrence of the Routledge shale, their presence suggests that reef development in the basal Scallion beds is possible and could have resulted in the formation of back-reef black shale deposits.

However, if fringing reefs or shoals were the controlling factor in formation of the Routledge shale, the reefs must have been of limited areal extent because, as far as is known to the writer, no deep wells in the Virden area have encountered "reefy" beds. It is doubtful that the fine-grained Scallion limestones, as found in the Virden area, could have formed any sort of reef or shoal deposits.

Strata identical to the Scallion beds are present in North Dakota, but fringing black shales appear to be absent, indicating that the "Routledge" shales are probably unique in the Lodgepole sediments of the Williston Basin area.

The alternative explanation is that the Routledge shale is actually Bakken in age and was deposited in local basins during upper Bakken time. The difficulty with this explanation is that the thickness of the Lower Lodgepole is uniform throughout the area of Routledge shale occurrence. Thus, if the Routledge shales were deposited in local basins, the surrounding areas must also have undergone the same amount of subsidence during later Lodgepole time. Such basin formation would be almost impossible to account for by normal tectonics but could be explained by salt collapse due to solution of underlying Devonian salt beds. Several other features of Lodgepole sediments possibly could be explained by this mechanism. A more detailed discussion is presented in a later section on salt tectonics.

On the basis of presently available information, both the foregoing explanations for the occurrence and distribution of the Routledge shale are equally plausible, but the "back-reef" origin probably is more acceptable.

SCALLION LIMESTONE

The cherty limestone beds of the Scallion member, which comprise the greater part of the eastern limestone facies of the Lower Lodgepole, consist largely of very fine-grained, microfragmental to chalky limestone (calcilutite to calcisiltite) with only a relatively small amount of coarse clastic crinoidal and fossil debris. It is possible, however, that the limestone is in part a chemical or biochemical precipitate. The general lithology of the Scallion appears to correspond to the open marine shelf, intershoal deposits of Edie (1958), and the sediments probably were deposited in shallow to moderate depths of water, as indicated by the relatively fine grain size. Open circulation, oxidizing conditions were prevalent, as shown by the pinkish, purplish, and reddish colour.

It is possible, indeed probable, that the Scallion limestones have undergone some degree of recrystallization, as suggested by the finely crystalline, granular to saccharoidal textures, and the moderate degree of dolomitization in some of the granular beds. Although the original carbonate texture has been in part obscured by diagenetic or possibly syngenetic recrystallization, it seems likely that the original texture was as fine grained, or finer grained, than the present texture. The coarser-grained crinoid fragments have not been affected by secondary recrystallization.

The origin of the abundant chert in the Lower Lodgepole, and especially in the Scallion member, is not known definitely. The distribution of the chert, which shows no relation to the pre-Jurassic erosion surface, and the lack of evidence that the silica was introduced indicate that the silica is almost certainly a primary constituent of the rock. The widespread distribution and the relatively high percentage of chert throughout the basin also suggest a primary origin. It does not seem possible that through-going intrastratal solutions could have introduced such a large amount of silica so uniformly over such a large area.

Although the silica probably is a primary constituent of the rock, the present nodular occurrence is secondary or diagenetic in origin and has resulted from redistribution of the primary silica, as indicated by the extreme irregularity in shape of the nodules, and by replacement of fossil fragments. Some beds of dense chert possibly may be primary. The original silica could have been deposited either as an organic precipitate such as sponge spicules, as a chemical precipitate, or as a very fine quartz silt. The areas showing high chert concentration generally are marginal to areas of high shale concentration; this would seem to indicate that the silica probably was deposited, at least in part, as a very fine silt; however, the subsequent solution, recrystallization, and nodule formation make determination of the nature of the original silica distribution almost impossible. MacDonald (1956) reports abundant sponge spicules in insoluble residues from Saskatchewan.

The abundance of the chert nodules indicates much diagenetic movement of silica in solution (?) in the interstitial fluids, and it would seem likely that much recrystallization of the comparatively soluble carbonate minerals, as well as some dolomitization, took place at the same time.

WESTERN ARGILLACEOUS FACIES

As indicated previously, the well-defined, predominantly limestone units of the Scallion, and to a lesser degree Virden, grade westward by facies change to a heterogeneous assemblage of calcareous shale and argillaceous limestone in which no stratigraphic units can be defined. The relationship of this argillaceous facies is best understood if it is considered in terms of the regional framework.

The regional distribution of the argillaceous material in the total Lodgepole unit of the Williston Basin area is shown in Figure 11. As the argillaceous content of the upper part of the Lodgepole is relatively uniform, the variations in shale content of the total Lodgepole may be assumed to be due to variations in argillaceous content of the Lower Lodgepole unit. The general gradation from relatively coarse fragmental limestone in the shelf area of North Dakota to argillaceous limestone along the eastern edge of the basin and finally to dark, less argillaceous limestone in the deepest parts of the basin is apparently due to a decrease in grain size of the sediments with increasing depth of water away from a shoreline, to the east, that was supplying fine argillaceous detritus. This is indicated by the similarity of the patterns shown by the isopach and lithofacies maps. The pronounced lateral differentiation of sedimentary types indicates that the slope of the depositional surface during early Lodgepole time was sufficiently steep for the wave-energy gradient to effect a relatively clean separation of the coarse- and fine-grained clastic material.

The argillaceous band, or facies, in Manitoba is a northward extension of the above-described band in North Dakota, and it might appear that the explanation of the shale distribution would be the same; however, the Manitoba section differs in that the argillaceous band is bordered on both the east and west by clean limestones of the Manitoba and Saskatchewan shelf areas and is also markedly discordant to the total Lodgepole isopach. It is thus evident that some additional controlling factor must have determined the shale distribution within the map-area. It seems likely that local subsidence in the Mandak Basin was the prime controlling factor.

Although the patterns of the total Lodgepole isopach and lithofacies maps are markedly discordant or divergent in Manitoba (Fig. 9) examination of isopach-lithofacies maps of sub-units within the Lodgepole shows that the isopach and lithofacies trends of these sub-units are accordant (Fig. 11). The apparent discordance, when considering the total Lodgepole unit, is due to the westward shift of the centre of deposition of the Mandak Embayment; this shift masks the detailed depositional pattern. Shale accumulation apparently was controlled by subsidence and resultant increase in depth of water, as in the case of the shale facies in North Dakota, but the depth of water was controlled, not by the regional subsidence of the Williston Basin, but by the local subsidence of the Mandak Embayment.

Even though the isopach and lithofacies patterns of the Lower Lodgepole in Manitoba are generally accordant, the shale distribution is difficult to explain, because the shale is concentrated on the western flank of the Mandak Embayment rather than in the centre, or on the eastern flank adjacent to the probable source area. That is, the Lower Lodgepole limestones are non-argillaceous in both the eastern part of the area where the unit is thickest, and in the extreme western part of the area where it is thinnest (Fig. 11). It thus appears possible that the argillaceous material could have been derived from a westerly source area, the Saskatchewan shelf. This, however, would be in marked contrast to the relationships shown by the shaly facies in North Dakota, where the source of the argillaceous material is definitely from the east. It is possible that complex subsidence patterns due to salt collapse may have been important in controlling sediment distribution.

The general transgression to the east of the shale facies during Lower Lodgepole time (Figs. 5, 6, 7), especially in North Dakota, probably indicates a progressive transgression or deepening of the Mississippian seas, which apparently reached a maximum depth and areal extent at the end of Scallion time.

VIRDEN - WHITEWATER LAKE BEDS

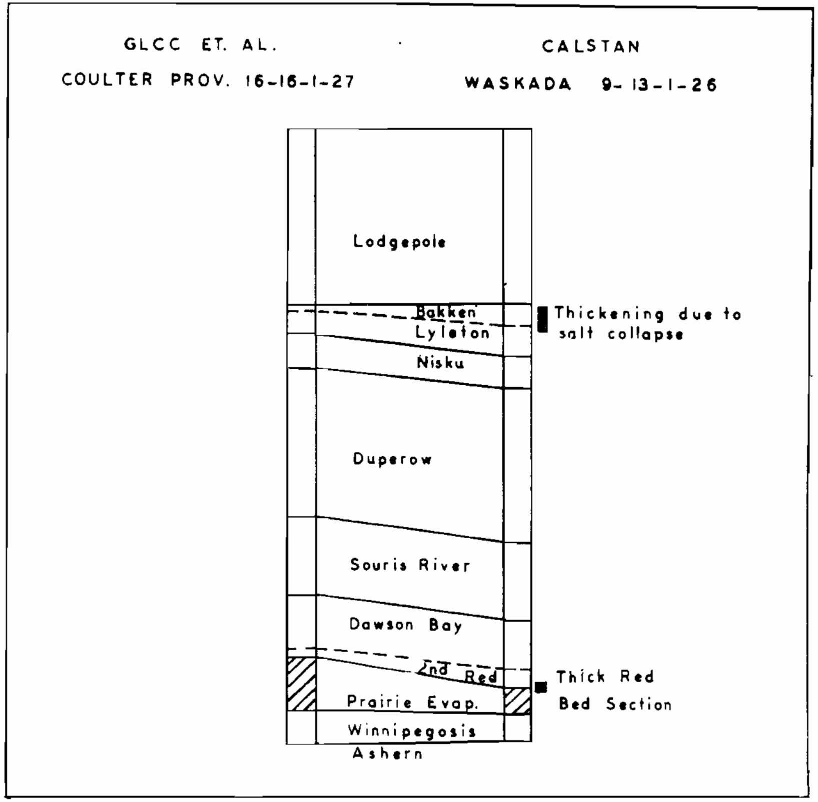
The upper part of the Lower Lodgepole section, including the Virden and Lower Whitewater Lake equivalents, marks the beginning of a major change in conditions of deposition throughout the map-area. The influx of coarse crinoidal limestone, oolitic limestone, and red calcareous shale of these units indicates a relatively abrupt drop in sea-level and was probably associated with regression of Lodgepole seas from parts of the peripheral shelf area. It is possible that the present eastern limit of the subcrop belt is relatively close to the depositional edge or shoreline established during Virden-Whitewater Lake time. The Virden-Whitewater Lake sediments were deposited in very shallow, agitated waters under strongly oxidizing conditions. Slight restriction of circulation with resulting increase in salinity and development of penesaline conditions (Sloss, 1953) is indicated by the presence of oolites and traces of anhydrite. The restriction probably was due to the shallow widespread nature of the seas and development of oolitic and/or crinoidal shoals (see Appendix I). The decrease in oolite content to the west indicates progressively deeper-water conditions with decreasing restrictions.

The repetitive sequence of shale and oolitic-crinoidal limestone is the first obvious occurrence of cyclical sedimentation in Lodgepole beds. This cyclical development becomes progressively more pronounced in later Mississippian time throughout the entire Williston Basin area. The bottom slope and consequently the degree of lateral sedimentary differentiation decreased markedly during deposition of the Virden-Whitewater Lake beds.

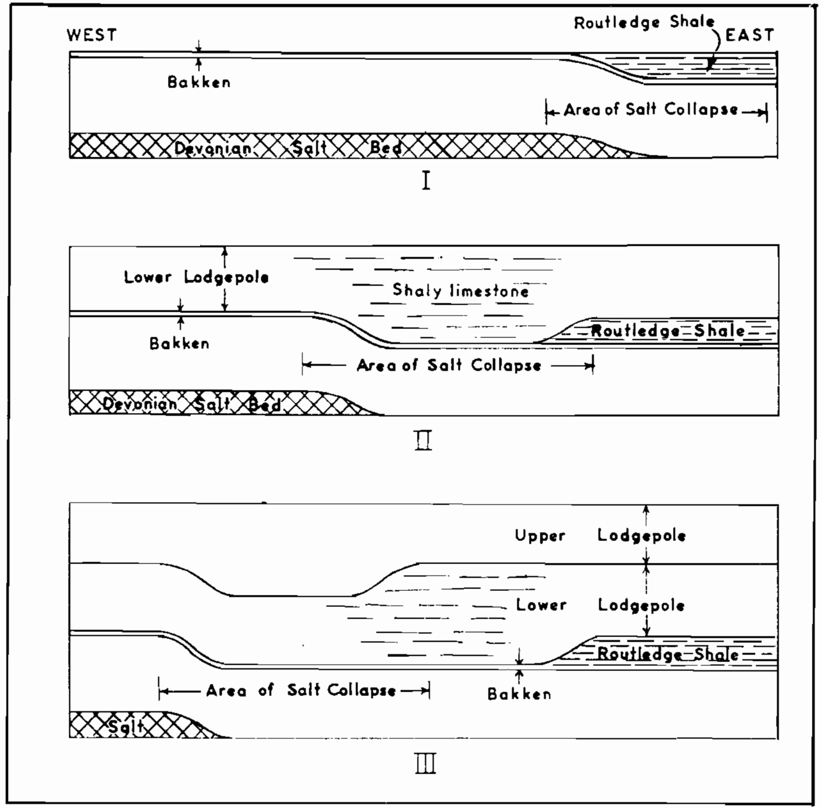
Upper Lodgepole

Tectonic Framework

The tectonic framework of the Upper Lodgepole was markedly different from that of the Lower Lodgepole. The Mandak Embayment retained the northerly trend, but the centre of subsidence shifted to the west and occupied what was



(A) Stratigraphic correlations between the Coulter and Waskada wells. The indicated thickening of the Bakken and Second Red Bed sections in the Waskada well possibly is due to salt collapse during Bakken time.



(B) Diagrammatic east-west cross-section showing possible progressive advance of salt collapse area to the west during Mississippian time, and the resulting effect on the type and thickness of the Mississippian sediments. (I) Salt collapse during upper Bakken time, with formation of the Routledge shale; (II) Salt collapse during Lower Lodgepole time, possibly related to the development of the shaly facies in the Mandak Embayment; (III) Salt collapse during Upper Lodgepole time.

Figure 17. Salt collapse tectonics.

previously the eastern edge of the Saskatchewan shelf; the area of the Lower Lodgepole basin became a relatively stable shelf area with correspondingly thin deposits (Fig. 12). The amount of differential subsidence in the western part of the area during Upper Lodgepole time almost exactly equalled the amount of subsidence in the east during Lower Lodgepole time; consequently, the total Lodgepole section shows little east-west variation in thickness, and the isopach trend of the total Lodgepole shows little relation to the isopach trends of its constituent units. The total Lodgepole isopach pattern is more similar to the over-all basin isopach, although the regional pattern is itself rather irregular (Fig. 9).

As stated previously, there is a possibility of miscorrelation or time transgression of the marker horizons, but correlation control is good and it is believed that correlations are accurate to within about 20 feet in most areas. The similarity in pattern of the lithofacies and isopach maps suggests that the correlations are correct, since it would be expected that such pronounced facies variations would be reflected by the isopach pattern. It should be noted that correlation errors would have little or no effect on the overall lithofacies pattern and the interpretations derived therefrom. Organ and Russin (1956) indicated a local thinning to the west in the lower part of the Lodgepole in the Daly area; this thinning supports the present correlations.

Salt Tectonics

The apparent tectonic pattern shown by the Upper and Lower Lodgepole units can be explained by normal deep-seated basement tectonics which affected the entire section at the time of tectonism. However, several features of the "tectonism" affecting Mississippian sediments are somewhat anomalous. Such features are: the pronounced shift in the centre of deposition of the Mandak Basin; the extremely localized nature of the minor structures as in the Virden area and their irregular distribution in time; and the apparent reversal of structure in local areas. An example of local structure reversal is shown in the Bay Canadian Superior Horn 4-12 well (Fig. 6). This area was structurally and topographically high during Jurassic time, whereas the "Second Specks" (Cretaceous) at present are 100 feet low relative to regional structural trends. No structure is evident in the uppermost Cretaceous beds. These features suggest that some factor other than tectonism was at least a partial controlling factor. A mechanism such as solution of salt from Devonian evaporites with resulting collapse of the overlying strata might explain the features mentioned above.

In the extreme case, salt "tectonics" could be invoked to explain the entire tectonic pattern shown by Mississippian strata in Manitoba, as illustrated in Figure 17. This is a possible but rather improbable explanation for the entire tectonic pattern; however, it is likely that salt solution and collapse were controlling factors in at least some local areas. If salt collapse was the principal controlling factor of Lodgepole tectonism, the overall picture was one of progressive salt solution towards the west with resultant progressive westward shift of the basin. The Routledge shale could thus be explained by local salt solution and basin formation during upper Bakken time, with resultant thickening of the black shales. Equal subsidence in adjacent areas, due to solution of a similar thickness of salt, would account for the relatively uniform thickness of the Lower Lodgepole section. This mechanism would also explain the apparent sharp lateral gradation from Routledge shale to Scallion limestone and the lack of interfingering of the Scallion and Routledge lithologies, and would remove the necessity for development of restrictive reefs or shoals in the basal Scallion beds. Similarly, the area of thick Upper Lodgepole sediments would represent the area of salt collapse during Upper Lodgepole time. It should be noted that such "salt tectonics" would be superimposed on the overall Williston Basin subsidence.

The Waskada area is the only place in Manitoba where there is any direct evidence suggesting that salt collapse took place during Mississippian time; elsewhere there is not sufficient deep well control. Correlation between the Calstan Waskada 9-13-1-26 and GLCC et al. Coulter Prov 16-16-1-27 wells (Fig. 17) shows that the thickness of the section between the base of the Devonian (Ashern) and the top of the Bakken is almost identical in both wells. However, in the Coulter well the Elk Point Group is 130 feet thicker than in the Waskada well due to the presence of a thick bed of salt, which is not found in the Waskada well. The Devonian section overlying the Prairie Evaporites correlates uniformly between the two wells, with only a slight thickening in the Coulter well, which would be expected on the basis of regional trends. The Bakken section, however, is approximately 100 feet thicker in the Waskada well. The thickening of the Bakken section, along with complementary thinning of the Devonian salt section by almost the same amount, is very strongly suggestive of salt collapse in the Waskada area during early Bakken time. This would account for the local occurrence of the lower Bakken black shale in this area. In addition, the Devonian Second Red in the Waskada well is unusually thick (60 feet) suggesting that the added thickness is the insoluble residue from the dissolved salt beds.

A recent report by Anderson (1958) shows that salt collapse also has taken place in North Dakota, in the area of the Blanche Thompson well (Sec. 31, 160N, 81W). In this area the thickening took place during deposition of the upper Lodgepole and Mission Canyon beds rather than during deposition of the Bakken beds, as was apparently the case in the Waskada area.

The rapid thinning of the Devonian salt along the eastern flank of the Devonian Elk Point evaporite basin, the coincidence of this thinning with the area of thickening of the lower part of the Mississippian section, and the presence of several areas of known (?) salt collapse along this trend all suggest that salt collapse probably has played an important role in controlling Mississippian sedimentation in this area.

Milner (1956) and Walker (1957) indicate that similar salt collapse structures are common in Saskatchewan. Walker suggests a post-Mississippian to Triassic age for the salt collapse area in Manitoba; the above data, however, suggests that salt collapse took place at least in part during Mississippian time.

Environment

Upper Lodgepole sediments are of relatively limited occurrence in the map-area but show general homogeneity wherever they occur throughout southwestern Manitoba. The interbedded crinoidal to microfragmental limestones and reddish mottled slightly argillaceous limestones indicate an over-all increase in grain size, probably resulting from deposition under marine conditions shallower than those prevailing during deposition of the Lower Lodgepole. Oxidizing conditions were prevalent as shown by the prominent red colour. The Upper Lodgepole strata show a tendency towards cyclical type of sedimentation, but the cycles are not as well developed as in the Virden-Whitewater Lake sequence.

The over-all decrease in argillaceous content of the Upper Lodgepole with respect to the Lower Lodgepole indicates a more stable tectonic framework with relatively little peripheral uplift and erosion. The slight eastward increase in average grain size and amount of crinoidal material within the Upper Lodgepole probably indicates slightly shallower water conditions in that direction, but the rate of facies changes and, hence, depth gradient is less apparent than in the Lower Lodgepole. That is, the depositional surface was relatively flat and the wave-energy gradient was insufficient to bring about marked lateral differentiation of sediments as in the Lower Lodgepole. The Upper Lodgepole beds appear to mark the beginning of the gradual withdrawal of Mississippian seas which continued throughout the rest of Madison time.

The end of Lodgepole deposition was marked by an abrupt, basin-wide influx of argillaceous material which formed the characteristic Upper Lodgepole shaly marker bed.

Mission Canyon — Charles Succession

Although the following discussion concerns lithologic or formational units rather than marker-defined units an attempt has been made to indicate the time-stratigraphic relationships between the various lithologies or lithosomes.

Age

As far as the writer knows, no information has been published concerning the age of the Mission Canyon-Charles beds in southwestern Manitoba or adjacent areas. Consequently, age relationships must be based, in part, on stratigraphic marker-bed correlations with dated outcrop sections of Montana. Deiss (1933) indicated an Osage age for the "Mission Canyon" of western Montana. Laudon (1948), however, found no evidence of an Osage fauna in Montana and suggested, as did Holland (1952), a late Kinderhook age for the "Mission Canyon". "Mission Canyon" strata examined by these workers are approximately equivalent to the Mission Canyon-Charles strata of Manitoba.

A small fossil collection from the Souris Valley et al McKee 1-15-3-25 well was examined by Crickmay, who indicated that the fauna was apparently correlative with that of the Mission Canyon of Montana, and with the Burlington limestone of the Mississippi and Ohio Valley areas (personal communication). Inasmuch as the Burlington is middle Osage in age (Weller et al, 1948), the Mission Canyon of Manitoba should also be Osage in age. This apparently disagrees with the conclusions of Laudon.

Fuller (personal communication) indicates that preliminary faunal studies in southeastern Saskatchewan suggest an Osage age for the Midale beds, which are stratigraphically above the "Charles" of Manitoba.

It thus seems likely that the entire Mission Canyon-Charles sequence of Manitoba is late Kinderhook to Osage in age.

Tectonic Framework

Because of the limited occurrence of Mission Canyon and Charles formations in the map-area, it is difficult to establish a definite tectonic framework. The uniform thickness and lithology of the section between the MC-2 shaly marker and the marker bed at the top of the Lodgepole indicate that the area was tectonically stable during deposition of these strata. The area probably was stable during deposition of the MC-3 and Charles as well, although this cannot be proved because of lack of subsurface information and extensive pre-Jurassic erosion. The tectonic stability contrasts markedly with the unstable shelf to basin tectonics that prevailed in the area during deposition of the early Lodgepole sediments.

Although the tectonic framework of southwestern Manitoba appears to have been stable during deposition of the Mission Canyon and Charles sediments, the over-all basin picture is one of increased degree of basin differentiation. That is, the strata show a higher degree of thickening towards the basin; however, the rate of subsidence apparently decreased so that sedimentation kept pace with subsidence. Consequently, relatively shallow-water sediments were deposited throughout most of the basin area, and the slope of the depositional surface approached base-level.

Environment

The change from argillaceous and crinoidal limestones of the Lodgepole to the non-argillaceous, granular to oolitic and algal limestones and dolomites of the lower Mission Canyon reflects one of the greatest environmental and lithologic changes during Mississippian (Madison Group) sedimentation. This change apparently was due to decrease in water depth of Mississippian seas, relative stabilization of the tectonic framework, and decrease or cessation in the supply of detritus (shale) to the basin. This change was nearly basin-wide but was more pronounced on the Manitoba and North Dakota shelf areas.

Along the northern edge of the Williston Basin, in central and western Saskatchewan, the entire Madison sequence consists primarily of relatively clean limestones, and it is not possible to correlate the Lodgepole and Mission Canyon units in the area.

The coarse grain size and the lack of any fine argillaceous material in the Mission Canyon limestone indicate deposition under very uniform, shallow-water, relatively high-energy conditions with no source area to supply any appreciable amount of clastic (argillaceous or sandy) material. A slightly higher than normal salinity prevailed, as indicated by the occurrence of oolitic limestone (a chemical precipitate) and traces of anhydrite. This type of sediment indicates deposition in a penesaline environment (Sloss, 1953). The mild restriction of circulation which caused the increase in salinity probably was due to the very widespread shallow nature of the Mission Canyon seas rather than to any marked physical barriers to circulation (see Appendix I), although broad, low biostromal or oolitic shoals probably were present and may have been partially responsible for the restriction. Beds of porous saccharoidal dolomite may represent primary dolomite precipitate, contemporaneous dolomitization, or post-depositional alteration along more porous or favourable beds.

The very shallow-water environment of the Manitoba shelf area graded basinward to slightly deeper-water conditions with normal salinity, in which clean crinoidal limestones were the predominant sedimentary type. Still farther basinward the stratigraphic equivalents of the Mission Canyon of Manitoba become darker, finer grained, and rather bituminous in appearance, acquiring what might be described as a basinal aspect. Because of their lithologic characteristics the basinal strata commonly have been included in the Lodgepole formation even though they are stratigraphically correlative with the Mission Canyon of the shelf areas.

The Mission Canyon limestones of Manitoba are similar in lithology to Lodgepole beds of the extreme eastern shelf areas of North Dakota (Fig. 9), indicating that the lithologic change between the Mission Canyon and Lodgepole resulted from a pronounced basinward shift of facies at the end of Lodgepole time. This basinward shift of facies is characteristic of upper Madison sediments and is the result of the gradual decrease in water depth and regression of the Mississippian seas towards the central basin areas. The regression, however, was not continuous but cyclical in nature, as shown by the pronounced interbedding of carbonates and anhydrite.

Evaporite Cycles

Following deposition of the MC-1 limestone, there was a further (eustatic?) drop in sea-level throughout almost the entire Williston Basin area. This resulted in further regression of Mississippian seas from the Manitoba shelf, and establishment of evaporitic or saline conditions in widespread shallow marine marginal lagoons fringing the basin. The anhydrites and clastics of the MC-2 and Charles strata were deposited in such lagoons. The factors controlling evaporite deposition are discussed briefly in Appendix I.

In Manitoba, the evaporite beds, especially the Charles, show a tendency to become increasingly argillaceous and sandy towards the east, but pre-Jurassic erosion has truncated the section and such a trend cannot be established definitely. In North Dakota, however, some of the evaporites are seen to grade completely to clastics in the east; this gradation is accompanied by a considerable thinning of the unit. The clastics probably represent very near-shore to possibly terrestrial deposits formed during periods of maximum marine regression. Fuller (1956) has reported plant remains from similar but stratigraphically higher argillaceous horizons in southeastern Saskatchewan.

Subsequent to deposition of the MC-2 sediments, sea-level rose again, and the shallow marine carbonate rocks of the MC-3 were deposited throughout the area under relatively normal to slightly penesaline conditions essentially the same as for the MC-1. The thin evaporite unit overlying the MC-2 shaly marker in the Souris Valley et al Meggison 10-14-1-25 well appears to have formed during the initial stages of the marine transgression (relaxing restricted hemicycle, Sloss; 1953).

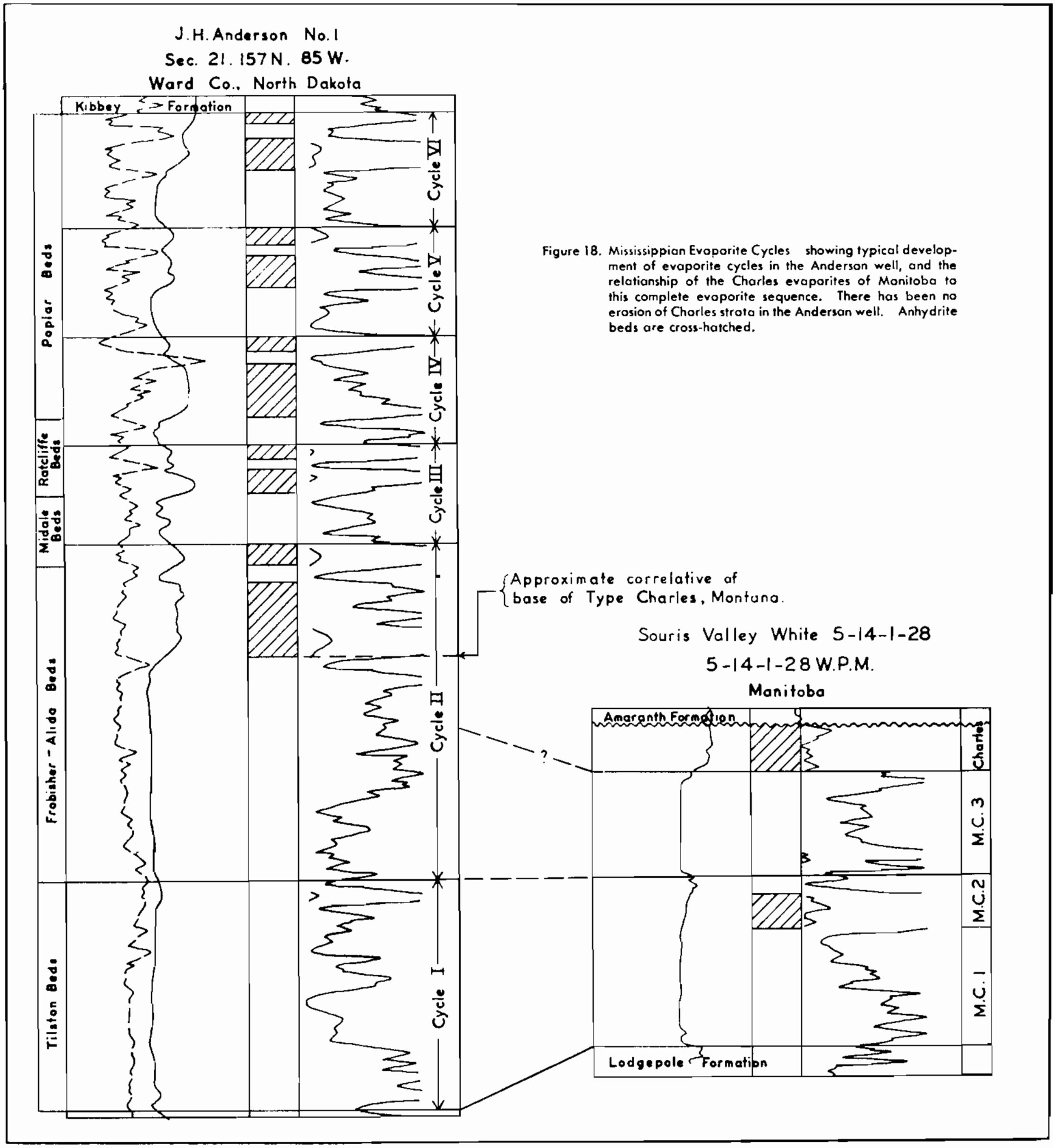


Figure 18. Mississippian Evaporite Cycles showing typical development of evaporite cycles in the Anderson well, and the relationship of the Charles evaporites of Manitoba to this complete evaporite sequence. There has been no erosion of Charles strata in the Anderson well. Anhydrite beds are cross-hatched.

Sediments deposited during a complete sequence of marine transgression and regression constitute an evaporite cycle (Fig. 18); the detailed environmental and depositional changes taking place during an evaporite cycle are as follows:

UNIT I. LIMESTONE.

The initial limestone beds were deposited under normal marine to slightly penesaline conditions (Sloss, 1953). Slightly higher than normal salinity is indicated by the presence of oolitic limestones. The absence of anhydrite indicates the salinity was less than four times normal.

UNIT II. DOLOMITE-ANHYDRITE.

This zone probably was formed by contemporaneous dolomitization and anhydritization of limestones of Unit I, as a result of increased restriction and salinity. Salinity was approximately four times normal.

UNIT III. LOWER ANHYDRITE.

This unit was deposited under penesaline conditions, with salinity maintained in the range of 4 to 10 times normal; if salinity exceeds 10 times normal, salt is precipitated. Restriction probably increased gradually throughout the period of deposition of this unit, although the salinity remained within the range required for the deposition of anhydrite. Decrease in water depth and consequent basinward retreat of the shoreline resulted in a relatively high shale content. (At this point in the cycle salt is developed in the upper Charles evaporites of the central basin area.) Apparently, the more saline conditions which developed in the later part of this stage in Manitoba, are favourable for dolomite deposition, as dolomite becomes considerably more abundant towards the top of the unit in the cores examined. Units I, II and III comprise the advancing restricted hemicycle of Sloss (1953).

UNIT IV. ARGILLACEOUS, SILTY DOLOMITE AND LIMESTONE.

These beds probably represent deposition under relatively normal to slightly saline conditions during the initial stages of marine transgression and rising sea-level. An alternative explanation is that they represent a near-shore "dilution" stage (Sloss, 1953), where pseudo-marine conditions were developed by inflow of land-derived fresh water. In this case, the silty limestones and dolomites would represent beds deposited during the period of maximum marine regression. In some areas complete withdrawal of Mississippian seas may have occurred, as indicated by the presence of plant remains (Fuller 1956). The unit is only poorly represented in the MC-2 beds of Manitoba, probably because of the relatively basinward facies developed in this area.

UNIT V. UPPER ANHYDRITE.

In Manitoba this unit is developed only at the eastern limit of MC-2 occurrence but it is generally present in most Mississippian cycles elsewhere in the basin. It appears to be the result of temporary re-establishment of restricted conditions during the period of marine transgression and deepening of water (relaxing restricted hemicycle of Sloss). This unit is always thinner than the lower anhydrite (Unit II), indicating that the transgression of the sea probably was considerably more rapid than the regression. This would be expected if cyclic (eustatic?) fluctuations in sea-level were superimposed on a uniformly subsiding basin. Subsidence and lowering of sea-level would partly counterbalance one another during regression, whereas subsidence and rising sea-level would act together to bring about comparatively rapid transgression.

UNIT VI. LIMESTONE.

This unit is the same as Unit I and marks the end of the evaporite cycle.

Several different interpretations of the observed evaporite cycles are possible. For instance, the anhydrite and dolomite of Unit II could be interpreted as a primary evaporite deposit, rather than secondary alteration products from limestone. A number of features, however, indicate a secondary origin. Similar units in southeastern Saskatchewan contain large brown crystals (porphyroblasts?) of anhydrite with relict scattered dolomite inclusions (Fuller, 1956). These crystals undoubtedly are secondary in origin and have been formed by replacement of dolomite or limestone. Veinlets and fracture fillings of anhydrite are also definitely secondary. The origin of the irregular, rounded inclusions of anhydrite is uncertain, and could be either primary or secondary. Evaporitic dolomite and dolomitic anhydrite of Unit III are markedly different in texture from the dolomite of Unit II; the evaporitic dolomite is extremely dense and fine grained to cryptocrystalline, whereas the dolomite of Unit II is porous and earthy or micro-saccharoidal in appearance. This textural difference suggests that the dolomites are of different origin. It would thus appear that the dolomite-anhydrite zone of Unit II is probably of secondary origin.

Physical-chemical factors controlling formation of such a secondary zone are discussed in Appendix I. The distribution and thickness of this alteration zone probably were controlled by minor topographic irregularities on the depositional surface, and by the susceptibility (porosity, permeability, and grain size) of the original limestone.

Although Units I to VI have been interpreted as a single cycle of marine transgression and regression, it is possible that this sequence actually represents a composite or double cycle of transgression and regression with Units IV to VI comprising the second cycle. Such a composite cycle has been proposed by Wheeler and Murray (1957) for typical Pennsylvanian cyclothems. They suggest that the Pennsylvanian cyclothems are the result of eustatic fluctuations in sea-level superimposed on a regional tectonic framework of uniform basin subsidence. The eustatic fluctuations in sea-level are believed to be related to Simpson's solar radiation glacial cycle. Evaporite cycles in the upper Mississippian Charles formation of the Williston Basin could be explained by the same mechanism, although the previous suggestion of a simple, single cycle of regression and transgression is somewhat more plausible.

After a relatively short period of carbonate deposition (MC-3) sea-level dropped again, Mississippian seas retreated partially from the shelf areas, and fringing lagoons in which the basal Charles evaporites were deposited were developed once more. However, the amount of regression and drop in sea level was less than for the MC-2 because the basal Charles evaporites, as determined from the Anglo Ex Dando 3-32-1-25 well, do not extend as far towards the basin as do the MC-2 evaporites.

In Manitoba the cyclical development of the typical Charles strata is not well shown because the palaeogeographic history ends with the deposition of the basal Charles evaporites; all younger Mississippian strata have been removed by pre-Jurassic erosion. However, cyclical evaporite deposition, similar to that resulting in the MC-2, continued throughout all of later Madison time in other areas of the basin, and undoubtedly most of these upper Madison (Charles) strata were deposited throughout much of the map-area.

Figure 18, for the Anderson well (Sec. 21, 157 N, 85W, North Dakota), shows a typical development of the cyclical upper Charles sediments as found to the southwest of the map-area, where Charles strata have not been subjected to post-Mississippian erosion. The relationship to the Manitoba section is also shown. Because the Anderson well is located basinward from the map-area, the base of the evaporite section in this well is much higher stratigraphically than it is in Manitoba. As a result, equivalents of the Charles evaporites of Manitoba are represented in the Anderson well by only slight changes in carbonate lithology within the Mission

Canyon limestone. The MC-2 argillaceous marker horizon is recognizable in the Anderson well, but no evaporites are associated with it in this area.

Although all Charles evaporites in Manitoba are marginal lagoon deposits, other types of evaporites are found in some areas. The upper Charles evaporites (Fig. 18; cycles 4, 5, and 6 in the Anderson well) are of the central-basin type; these evaporites are not limited to the peripheral areas of the basin but extend throughout all of the central basin area, where thick salt beds were deposited. The development of central-basin evaporites indicates that the entire Williston Basin became restricted in late Charles time. The lithologic sequence of the central-basin evaporite cycles is, however, essentially the same as for the marginal evaporites, except that a prominent salt bed is present in the upper part of Unit III in the most basinward wells.

Origin of the Charles Sands

The origin of the sandy beds of the Charles is somewhat controversial. The petrography of the sands in Manitoba is similar to that of the sands of southeastern Saskatchewan (marked angularity, high feldspar content). Fuller (1956) suggests that the Charles sands of Saskatchewan were derived from the Bakken sands and silts which, he believes, were subjected to erosion in an area about 100 miles northeast of the present erosional edge of the Mississippian. This hypothesis seems unlikely for two reasons. Firstly, the character of the Charles and Bakken sands, at least on the basis of petrographic examination of samples from Manitoba, are markedly different. The Bakken sands are finer grained, better rounded, much less arkosic, and contain no chert (?) or quartzite grains. The Bakken clastics are relatively mature quartzose sediments, whereas the Charles sands are immature and arkosic. It thus seems unlikely that the Charles sands could have been derived from the Bakken beds. Furthermore, there is no evidence that significant peripheral erosion of Mississippian beds took place during deposition of the Charles strata. It is true that the marginal evaporite facies shows a marked stratigraphic drop to the northeast, but it does not follow that any significant erosion of previously deposited Mission Canyon and Lodgepole beds took place in peripheral areas. Erosion requires uplift, and the shrinkage of the basin, as indicated by Fuller, does not necessarily imply uplift. The shrinkage is due to a decrease in the rate of subsidence, and gradual filling of the basin by Mississippian sediments. To the south, in central North Dakota, pre-Jurassic erosion has not been as deep, and the relatively complete Mission Canyon-Charles succession in this area shows no significant peripheral erosion of Mississippian strata during Charles time, even though the facies relationships are identical to those in Saskatchewan.

A Precambrian source appears most likely for the immature arkosic Charles sediments. It is possible that some of the fine-grained "quartzite" grains are actually chert; thus some of the clastics could have been derived from earlier Palaeozoic rocks such as the Scallion cherty limestones. The general appearance of the quartzite grains, however, is that of a meta-quartzite. The pronounced straining of the quartz grains, and the presence of quartzite grains suggests, at least in part, a metamorphosed Precambrian terrane probably situated far to the north or northeast.

If Mississippian or other Palaeozoic rocks were being eroded during deposition of the Charles, the site of the erosion was probably much farther to the north or northeast than indicated by Fuller.

SUMMARY OF MISSISSIPPIAN PALAEOGEOGRAPHY IN MANITOBA

The environments of deposition of the different rock types have been discussed in the preceding section. These environments can now be placed in a regional time-stratigraphic framework, and the over-all environmental and palaeogeographic pattern can be determined. The following section briefly outlines the shifting palaeogeographic pattern recorded in the Mississippian strata of southwestern Manitoba.

Subsequent to the withdrawal of seas from the map-area at the end of Devonian time there was minor erosion of Lyleton sediments on a broad, low, uniform subaerial erosion surface. The beginning of the major cycle of Mississippian sedimentation is marked by the transgression of Mississippian seas from the west, and by the development of an extremely widespread marine euxinic swamp, in which the lower Bakken black shales were deposited. This marine advance did not, in general, extend as far east as Manitoba, and lower Bakken beds are found only locally in the Waskada area.

At the end of lower Bakken time, Mississippian seas advanced eastward throughout the map-area and contemporaneous mild tectonic uplift in peripheral areas caused erosion of some of the Lyleton beds, and probably earlier rocks as well. The fine sands and silts resulting from this erosion were deposited throughout the area as a thin, relatively uniform blanket of middle Bakken sediments. Restricted, reducing conditions prevailed in all but the peripheral areas to the north, where shallower-water, near-shore oxidizing conditions prevailed.

The end of middle Bakken time was marked by a decrease in the rate of erosion in peripheral areas, and probably also by a decrease in the depth of water, resulting in re-establishment of euxinic, swampy conditions in the upper Bakken. However, in contrast to the lower Bakken swamp, that of the upper Bakken extended throughout the map-area, indicating that Mississippian seas were much more widespread in upper Bakken time.

Local subsidence may have taken place in the Max Lake and Virden areas during upper Bakken time, resulting in the thickening of the black-shale section in these areas (ie. the Routledge shale).

Lodgepole time marks the beginning of the main phase of the Mississippian marine transgression; this is indicated by a marked increase in deep-water deposits throughout the map-area. The maximum extent of the Lodgepole seas during the cycle of transgression is unknown; the northern and eastern limits of Mississippian strata in Manitoba mark the erosional, not depositional, edge of those rocks.

The rates of transgression and subsidence were sufficiently great during Lower Lodgepole time that a comparatively steep sea-bottom slope was developed; this steep slope caused marked lateral segregation of lithologic types. The area of local subsidence of the Mandak Embayment in western Manitoba was apparently the area of deepest water, and the finest argillaceous sediments were trapped in this basin. The source area from which the fine clastics were derived probably was situated a considerable distance to the east and northeast of the map-area, although no direct evidence for this is available. To the east of the shale basin the seas were somewhat shallower, and the sediments deposited in this area of higher wave energy were the "calci-siltites" of the Scallion beds. Locally, small (patch) reefs or shoals were developed in this area of otherwise fine-grained limy silts and muds. The Routledge shales possibly may have been deposited in local, restricted lagoons formed by these reefs or shoals.

The deepening and associated eastward transgression of the Mississippian seas apparently continued throughout Lower Lodgepole time, as indicated by the general eastward shift of the area of shale deposition; Mississippian seas apparently reached their maximum areal extent and depth in late Scallion time.

During later Lower Lodgepole time the Mississippian transgression appears to have ceased, the tectonic framework stabilized somewhat, and the depositional slope decreased (markedly). There also appears to have been a marked decrease in water depth, as shown by the occurrence in the eastern part of the area of thin, sheet-like deposits of oolitic and crinoidal limestones and associated red shales. In addition, rhythmical fluctuations in sea-level resulted in a cyclical interbedding of

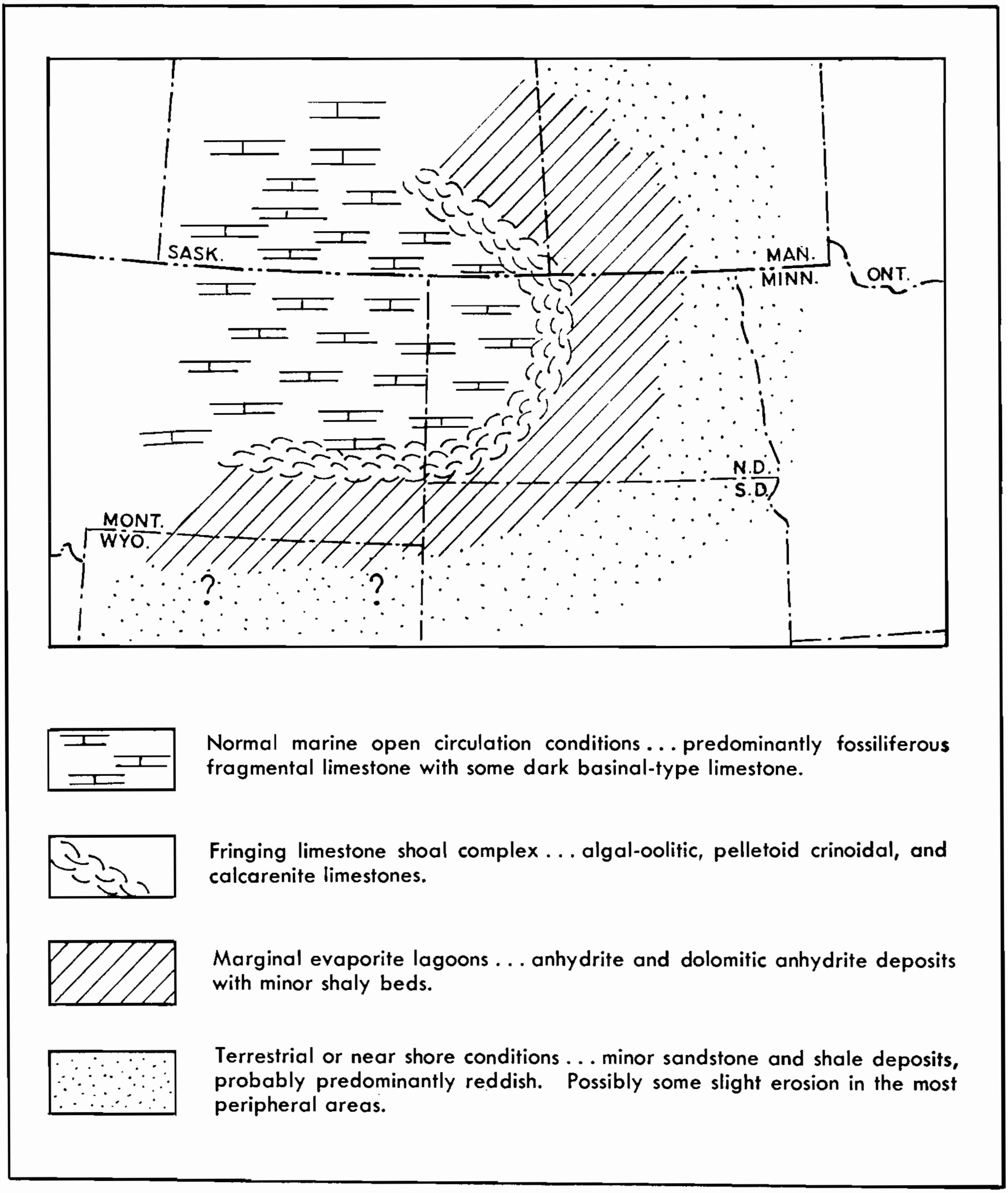


Figure 22. Palaeogeographic map showing postulated environmental pattern during deposition of the MC-2 beds in the Williston Basin area.

the sediments. These sediments, the Virden and Whitewater Lake beds, probably represent the first stages of regression of Mississippian seas, which continued throughout later Mississippian time.

Subsequent to deposition of the Virden-Whitewater Lake beds, water depth apparently increased once more, although the seas were probably somewhat shallower, and possibly less extensive than during most of Lower Lodgepole time. The decreased rate of subsidence relative to sedimentation resulted in a filling up of the basin, and development of a flatter depositional surface; consequently there is little lateral lithologic variation in the Upper Lodgepole sediments. Widespread biostromal, crinoidal limestone beds alternate with finer-grained argillaceous limestone beds, suggesting minor cyclic fluctuations in sea-level or water depth. As in the case of the Lower Lodgepole, mildly positive peripheral areas, probably situated far to the east and north, were subjected to erosion and supplied argillaceous detritus to the basin. However, the amount of uplift and erosion was apparently considerably less than during Lower Lodgepole time.

An abrupt basinwide decrease in depth of Mississippian seas occurred at the end of Lodgepole time and was probably accompanied by a regression of the seas towards the basin area. During deposition of the Mission Canyon and Charles beds, shallow shelf-type seas prevailed throughout most of the basin, including all of the present map-area. The type of carbonate deposition was very similar to that of the present-day Bahama Banks, as described by Illing (1954).

During the time of deposition of the Mission Canyon-Charles beds of Manitoba, the entire basin area was subjected to a marked cyclic series of fluctuations in sea-level, with resultant periodic transgression and regression of the seas. The fluctuations in sea-level appear to have been eustatic, or at least basinwide, in nature, and were superimposed on a tectonic framework showing a gradually decreasing rate of subsidence. The result was that, in most instances, during each succeeding period of regression the strand line advanced farther towards the basin. There is no definite evidence that the shoreline advanced as far as the area of Mission Canyon-Charles occurrence in Manitoba, but relatively near-shore conditions are indicated by the thin clastic interbeds of the MC-2 and Charles. Figure 22 shows the postulated palaeogeographic pattern during the MC-2 period of regression.

Offshore barrier shoals or reef complexes developed during periods of lowered sea-level and resulted in the formation of marginal lagoons fringing the basin. Restricted evaporitic conditions prevailed in these shallow lagoons, and salinity was maintained in the range 4 to 10 times normal; this resulted in deposition of the Charles anhydrites and dolomites.

In Manitoba, pre-Jurassic erosion has removed all of the upper part of the Charles strata, but undoubtedly the entire Charles sequence was deposited under essentially the same conditions as prevailed during earlier Charles deposition. The record of this later Mississippian palaeogeography is preserved in the less deeply eroded strata of North Dakota and indicates a continuance of the cyclic or rhythmic withdrawal of the Mississippian seas, which culminated in deposition of thick salt beds in the central part of the basin during the last stages of regression.

PRE-JURASSIC EROSION

Almost the entire Palaeozoic section in Manitoba has been truncated by extensive erosion which occurred between late Mississippian and Jurassic-Cretaceous time. The erosion apparently was the result of differential uplifting of the northeastern part of the Williston Basin, as shown by the regional Mississippian isopach and subcrop maps (Figs. 9, 19). The southern part of the basin underwent relatively slight uplift, and erosion has removed only the most peripheral Mississippian strata. The Mississippian subcrop in Manitoba consequently represents a much more basinal facies than does the subcrop to the south, in North Dakota.

The time during which erosion took place cannot be dated accurately from stratigraphic evidence within the map-area but, on the basis of regional studies of post Mississippian strata by Zieglar (1956), it would appear that most of the erosion took place in late Triassic to early Jurassic time. In the northern part of the map-area erosion of Mississippian strata continued until upper Jurassic and possibly early Cretaceous time.

It is impossible to give more than a rough estimate of the amount of pre-Jurassic erosion; however, as Mississippian strata show only a slight indication of depositional thinning towards the east in Manitoba, it appears probable that the amount of erosion was approximately equal to the total Madison thickness. Thus the amount of eroded section would be in order of 1,000 feet along the edge of the Mississippian. In addition, almost the entire Charles section ,and possibly post-Charles sediments as well, has been eroded; this probably would bring the total thickness of eroded Mississippian sediments to well over 1,000 feet.

The amount of erosion increased towards the northeast where Devonian, Silurian, and Ordovician strata in turn are truncated by pre-Amaranth (Watrous) erosion. In south-central Manitoba, Jurassic Amaranth beds in the Dominion City well (sec. 33, tp. 2 rge. 5 EPM) rest directly on basal Ordovician Winnipeg shales. The amount of erosion in these more marginal areas probably amounts to several thousand feet, although extrapolation of isopach trends for this distance is very approximate at best.

Eroded Mississippian strata were overlapped by the terrestrial to shallow marine deposits of the Amaranth formation. The topography on the erosion surface is reflected in the Amaranth isopach pattern (Fig. 20). The Amaranth red beds, and in places the upper Amaranth evaporites as well, are thin over topographic "highs". Throughout much of the map-area, the indicated local topographic relief is in the order of 20 feet although, in a few areas such as Wawanesa, the local relief is as great as 300 feet. Considering the amount of erosion the resulting surface is extremely flat.

The topographic "highs" on the erosion surface consist of three different types. The first type represents merely an erosional remnant in isostructural strata. The second type of "high" is the result of pre-Amaranth structural or tectonic activity. The fact that the structural "highs" are also, in many instances, topographic "highs" suggests that the structures originated for the most part subsequent to the period of erosion, and immediately before or during Watrous time; this is especially the case where the amount of structural relief is the same as the topographic relief. If the structure had originated before or during the period of erosion it would have been largely or completely truncated by the erosion. The third type of topographic "high" is stratigraphically controlled by the variation in lithology and resistance to weathering of the different units, and tends to result in escarpments or cuestas, roughly parallel to the trend of the subcrop belt.

The most prominent topographic "highs" on the Mississippian erosion surface, as indicated by the Amaranth isopach map (Fig. 20), are:

(1) The Daly-Madeline trend, extending north from the Daly and Virden fields.

(2) The peripheral zone of the Mississippian escarpment

(3) The Hartney area: possibly a topographic "low" in the central part of the area (Calstan Hartney 16-33-5-24).

A pronounced topographic and structural "high" on the Amaranth depositional surface existed in the Daly area. Relief was sufficient so that practically no red beds were deposited in this area, and the Amaranth evaporites rest almost directly on eroded Lodgepole strata. The thinning of the Amaranth, and hence the relief on the erosion surface, was approximately 60 to 100 feet. North of the Daly area the Amaranth sediments and also the overlying upper Jurassic beds pinch out on a Mississippian topographic "high". Some structure may also be associated with this "high", and to further complicate the picture, the "high" is bordered on the east by the Mississippian escarpment. In the Madeline area the eroded surface of the Mississippian remained well above depositional base-level and was, consequently, subjected to erosion until upper Jurassic time, as indicated by the very thin Jurassic section. It is possible that, farther still to the north, Mississippian strata underwent continuous erosion until Cretaceous (?) Swan River time.

Amaranth red bed isopachs indicate a general, somewhat irregular thinning towards the erosional edge of the Mississippian, and abrupt thickening immediately to the east of the erosional edge, especially in the areas northeast of Oak Lake (tp. 8, rge. 25WPM) and Wawanesa (tp. 7, rge. 17WPM). This thinning suggests that the edge of the Mississippian constituted an escarpment on the erosion surface, probably due to the differential erosion of the underlying, relatively unresistant Bakken-Lyleton (and Routledge ?) section. Local relief of up to 300 feet is developed in some places along the escarpment.

Although, because of lack of subsurface control, the position of the Mississippian erosional edge cannot be defined exactly there appear to be two principal re-entrants or identations along this edge. The best developed re-entrant occurs to the northeast of Oak Lake (tp. 8, rge. 25WPM), and the other, less well defined, to the northeast of Max Lake (tp. 1, rge. 20 WPM). These two areas appear to be closely related to the two areas of Routledge shale occurrence, and it is possible that the presence of the comparatively soft and easily eroded Routledge shale was the controlling factor in the formation of these features. The local occurrence of the Routledge shale may have been important in establishing the regional drainage pattern, and hence the erosional pattern that developed on the pre-Jurassic erosion surface.

The lithologic sequence in the Hartney area is completely anomalous, and a comprehensive discussion is beyond the scope of this paper. Briefly, the entire Mississippian section, as well as approximately 300 feet of Devonian strata, are missing in the Calstan Hartney 16-33-5-24 well, and in their place is 800 feet of interbedded sandstone and shale. The sandstone and shale filling this "hole" do not resemble the Amaranth beds but appear to be more similar to the Cretaceous or upper Jurassic beds; however, this relationship is uncertain, and it is possible that the 800 feet of clastics are Amaranth equivalents. Dips as high as 40 degrees are recorded in this part of the section.

Peripheral to the Hartney "hole", Mississippian strata were apparently topographically "high" on the pre-Jurassic erosion surface, and no Amaranth strata were deposited. In the Madison Lauder 1-19-5-24 well the Devonian section appears to be badly faulted, with the Lyleton beds repeated two or three times in the section; however, this is difficult to prove from samples and electric logs alone. The base of the Devonian (Ashern) appears to correlate uniformly throughout the area, as does the Cretaceous Swan River formation. The Hartney structure is, thus, apparently limited to the stratigraphic interval between the Ashern and Swan River beds.

The nature of the Hartney structure cannot be determined at present, but it appears to be closely related to faulting, and it apparently existed as a topographic "high" during the time of deposition of the Amaranth beds. It is possible, however, that the Amaranth is missing because of faulting. The Hartney structure also has been considered by some workers as an erosional feature on the pre-Jurassic surface, but no evidence for such extreme local erosional relief is known, especially in an area of uniform Mississippian strata.

Pre-Jurassic "Weathering"

Deposition of the Amaranth sediments has had a slight to very pronounced effect on the underlying Mississippian sediments. Amaranth sediments contain varying amounts of anhydrite, indicating deposition in a restricted environment. Saline (ground-water?) solutions associated with deposition of the Amaranth sediments have caused recrystallization, leaching, and replacement of Mississippian limestones by dolomite and anhydrite, as indicated by Berg (1956). Where Mississippian strata are overlain by red beds with a relatively low anhydrite content, the altered or weathered zone may be very thin. The thickness of the zone probably is controlled by the original porosity and permeability of the Mississippian sediments, the topography, and the type of overlying strata.

The Daly-Virden area was a marked topographic "high" on the pre-Jurassic erosion surface, and Mississippian strata are overlain almost directly by Amaranth evaporites. In this area there is, consequently, a very thick weathered or altered zone which may extend to depths of 100 feet or more, especially along fractures. In areas such as Madeline, Wawanesa, and Hartney, which were very high topographically, but are overlain by post-Amaranth Jurassic shales, there is essentially no zone of anhydrite and dolomite alteration, although there is a brecciated, leached and weathered zone.

Economic Geology

Considerable information has been published concerning oil accumulation in Manitoba (Berg, 1956) and on related occurrences in adjacent parts of Saskatchewan and North Dakota (Edie, 1958; Fuller, 1956; Smith, 1956; Johnson, 1956; Vogt, 1956; Anderson and Nelson, 1956). The following will not be a detailed discussion of known oil occurrences in Manitoba, but will merely outline the general types of Mississippian oil traps in Manitoba and adjacent areas and indicate other possible favourable areas for Mississippian oil accumulation in Manitoba. Locations of the oil fields and oil occurrences are shown in Figure 27.

REGIONAL CONTROLS FOR OIL ACCUMULATION

The abundant oil accumulation in Mississippian strata of the Williston Basin area is due to unusually favorable stratigraphic and structure conditions in this area. The basinal (Lodgepole) facies of the Mississippian consists primarily of dark, somewhat argillaceous, bituminous-appearing limestones which would seem to constitute excellent petroleum source beds. Up the dip these basinal source beds grade to porous, fossiliferous-fragmental and algal-oolitic limestones which comprise excellent reservoir and migration beds. Perhaps of greatest importance, the porous rocks form a great variety of up-dip stratigraphic and to a lesser extent topographic and/or structural traps in which the oil could accumulate as it migrated up dip from the source beds. Thus, all three prerequisites for oil accumulation — namely source beds, reservoir rocks, and traps — are present within the Mississippian sequence. Because the oil-bearing Mississippian strata occur between tight, impermeable beds of the Bakken, Lyleton, Charles, or Amaranth formations, it does not seem probable that rocks other than Mississippian in age have contributed to the Mississippian oil accumulation in Manitoba or elsewhere in the northern part of the Williston Basin.

With one or two major exceptions, most of the Mississippian oil accumulation known to date occurs in stratigraphic traps on the northeastern flank of the basin, in southwestern Manitoba, southeastern Saskatchewan, and northern North Dakota. The main exceptions are the fields along the Nesson trend (Beaverlodge, Tioga, etc.) in northwestern North Dakota, and the Poplar field in northeastern Montana. The oil accumulation in these areas is controlled primarily by structure rather than stratigraphy and, because such structural traps are to a large degree unpredictable on the basis of regional stratigraphic study, they will not be considered further in this discussion.

There appear to be at least two main reasons for the abundance of oil accumulation on the northeastern flank of the basin and the apparent lack of oil elsewhere. Firstly, this area shows the greatest rate of lithologic or facies change; and secondly, the amount of pre-Jurassic uplift and erosion has been much more pronounced on the northeastern flank of the basin than elsewhere, and the erosion has truncated those more basinal facies showing the greatest degree of interbedding of reservoir rock and trap rock.

Lodgepole Oil Accumulation

To date the only known Lodgepole production in the Williston Basin area has been from Manitoba. The reason for this apparently restricted occurrence is somewhat obscure. The Lodgepole oil accumulation appears to result from conditions very similar to those controlling the better-known Mission Canyon-Charles accumulations of southeastern Saskatchewan. That is, a relatively basinal type of facies is developed in western Manitoba, and strata of this facies have been truncated by pre-Jurassic erosion. The localizing features, especially in the Daly area, are primarily structural and/or topographic, but regionally the basic controlling factor appears to be the truncation of the porous beds of the Virden and Whitewater Lake members. Most Lodgepole oil shows in Manitoba occur in a band roughly coinciding with, or parallel to, the subcrop belt of the Virden and Whitewater Lake units, and most oil production is obtained from these same beds or their stratigraphic equivalents. The producing interval in the Daly field is stratigraphically equivalent to the Virden-Whitewater Lake beds of the Virden area (Fig. 6).

The interbedded limestones and argillaceous limestones of the Upper Lodgepole probably formed a relatively impermeable cap rock which trapped the oil and caused migration to occur along the base of the unit, in the porous, oolitic and crinoidal beds of the Virden and Whitewater Lake units. Accumulation of oil apparently occurred where sufficient structure or topography was present, and/or near the pinchout edge of the Virden-Whitewater Lake beds. Local porosity variations were also important. It should be noted that the trend of the structure contours on the erosion surface, and the trend of the subcrop belt of the Virden-Whitewater Lake beds are somewhat discordant; the subcrop is seen to rise structurally to the northwest (Fig. 15). This would tend to cause any oil trapped at the truncated edge of the porous beds to migrate to the northwest, parallel to the edge of the subcrop belt; this might account for the more widespread production towards the north, in the Virden area, and the apparent lack of production or small production to the south.

The unique stratigraphic and structural relationships of the Lodgepole strata in Manitoba may explain the occurrence of abundant Lodgepole oil accumulation in Manitoba and the apparent lack elsewhere. The Lodgepole beds of Manitoba differ from those of Saskatchewan in that they contain abundant shaly material (a possible source of oil) and show good interbedding of permeable and impermeable beds, as in the Virden-Whitewater Lake sequence. In contrast, the Lodgepole beds of Saskatchewan are relatively uniform non-argillaceous cherty limestones which do not permit development of stratigraphic (truncation) traps as in Manitoba.

In North Dakota, Lodgepole beds show a facies similar to the producing facies in Manitoba, but pre-Jurassic uplift and erosion was much less pronounced and the favourable facies showing interbedding of cap and reservoir rock is not exposed at the pre-Jurassic erosion surface. In the area where Lodgepole strata are exposed at the erosion surface, the strata show a more uniform, shelf-like aspect and, consequently, provide a much less favourable locale for oil accumulation. In addition, the structural rise to the north of the subcrop belts would tend to cause a northward migration of oil into Manitoba.

Mission Canyon-Charles Oil Accumulation

Relatively little oil has been found in the Mission Canyon or Charles strata of Manitoba; however, almost all Mississippian fields in Saskatchewan and North Dakota produce from this interval. Most of the Saskatchewan and North Dakota production is from truncation traps formed where porous limestone units, interbedded with evaporites, are truncated by pre-Jurassic erosion and sealed by Amaranth (i.e. Watrous or Spearfish) strata. This has resulted in the formation of roughly linear trends or bands of pools associated with individual reservoir be (Fig. 15). Examples are the Midale trend, and the Alida-Nottingham trend Saskatchewan (Edie, 1958). Lateral closure on the truncation traps is due to loc structure and/or topography on the erosion surface. Since the rate of faci change to the northeast coincides approximately with the rate of truncation of tl Mississippian strata, an optimum number of truncation (stratigraphic) traps hav been formed.

Facies-type stratigraphic traps resulting from porosity variations within th reservoir beds recently have been found to be important in the more basinal area. (Lignite field, Mitchell and Petter, 1958).

There exists a possibility of both truncation and facies traps in the Charles and Mission Canyon beds of southwestern Manitoba, but extensive exploratory drilling has resulted in discovery of only two small fields (Pierson, and Tilston), and two other potential oil producing areas (Westover, and Waskada).

One possible explanation for the scarcity of Mission Canyon oil accumulation in Manitoba is the structural relationship of the subcrop belts. Whereas the subcrop of the porous Lodgepole beds rises structurally to the northwest, the opposite is true for the MC-3 subcrop belt, which rises structurally to the southeast; there is no barrier to prevent migration out of the map-area. The subcrop of the MC-1, however, maintains a relatively uniform structural elevation in southwestern Manitoba and actually shows slight structural closure. On this basis, the truncational edge of the MC-1 would appear to be a more favourable zone for oil accumulation than the edge of the MC-3. It should be noted, however, that any local structural or topographic features could form effective traps.

Relation of Saskatchewan Oil Fields to The Manitoba Section

Of the oil fields in Saskatchewan only those comprising the Alida-Nottingham trend are considered here; other Saskatchewan fields produce from beds stratigraphically higher than those Mississippian beds present in Manitoba. The Alida-Nottingham, and Ingoldsby fields produce from the MC-3 limestones (Frobisher-Alida beds) which also occur in Manitoba. However, although the Alida-Nottingham trend strikes directly towards the southwestern corner of the province, drilling carried out to date has resulted in only one Manitoba discovery in MC-3 strata, the Pierson field. Several explanations for this particular distribution of oil are possible.

(1) The topographic-structural "highs" which localize the oil in Saskatchewan apparently are not present in Manitoba.

(2) It can be seen from the subcrop map (Fig. 15) that the subcrop and lithofacies trends of the Mission Canyon and Charles strata are discordant. This is a result of the more pronounced pre-Jurassic uplift and erosion in southern Saskatchewan. Because of this, the facies or rock type of any given unit changes somewhat along the strike of the subcrop belt. Consequently, the MC-3 strata forming the reservoir rocks along the subcrop belt in Saskatchewan show a more basinal aspect than the MC-3 strata forming the subcrop belt in Manitoba. This difference in facies could, in part, account for the apparent lack of oil accumulation in the MC-3 beds of southwestern Manitoba.

(3) In Manitoba the subcrop edge of the MC-3 rises structurally to the southeast (Fig. 15); consequently, the chances of having local structural or topographic closure along the pinch-out of the porous MC-3 strata are somewhat reduced. The regional structural rise tends to "open" any local

structures. By contrast, in Saskatchewan, the subcrop edge of the MC maintains a relatively constant regional structural elevation, and ar minor "high" on the erosion surface forms a potential oil trap.

It seems probable that all three factors listed above were important in coı trolling the oil accumulation.

Relation of North Dakota Fields to the Manitoba Section

In the immediate vicinity of the Manitoba-North Dakota border, commercial oil occurrences are present in North Dakota but drilling so far has failed to result in discovery of commercial oil occurrences in the Manitoba portion of this area.

Smith (1956) presents detailed studies of several North Dakota fields, and Anderson and Nelson (1956) show a number of cross-sections, and isopach and structure contour maps for northern Bottineau County. The various North Dakota fields differ considerably in type of oil accumulation and, consequently, each field is discussed separately.

The North Westhope field (tp. 163 and 164, rge. 79 and 80W) is within ½ mile of the border and produces from porous limestone beds within the "Charles evaporites" (Fig. 15). Despite the proximity of the field to Manitoba, these porous Charles strata are not present at any place in the province; they have been removed by pre-Jurassic erosion. However, as stratigraphically lower Charles evaporites are present in the area of the Anglo Ex Dando 3-32-1-25 and Calstan Imperial Dalny 8-10-2-26 wells, it is possible that a porous limestone or dolomite bed similar to the Westhope "pay zone" occurs within the "Charles" in this area and could be a potential producing horizon. If present, such a unit is of very limited areal extent, and has not been penetrated in any wells drilled to date.

The Northeast Landa field (tp. 163 and 164, rge. 78 and 79W; Smith, 1956) is situated less than ½ mile south of the Manitoba boundary. Production is from the MC-3 limestone, and the trap is primarily structural in nature, with some minor associated topography. Oil occurs on an irregular dome-shaped "high" with a closure of about 100 feet. The field is situated close to the subcrop edge of the "Charles", and the cap rock in most areas consists of Charles evaporites but, locally, where the Charles beds are eroded from the top of the structure, Amaranth (Spearfish) red beds form the cap rock. The structure apparently developed prior to the period of pre-Jurassic erosion as shown by the partial truncation of the structure. A similar structure is found in the Waskada-Hernfield area of Manitoba, where an inlier of MC-2 is present, and another in the Westover area where an MC-3 inlier, or embayment, is present. Both areas have favourable oil shows, and some production has been obtained from both areas.

The North Souris field (Anderson and Nelson, 1956) is situated at the pinch-out of the MC-3, and is apparently a truncation trap. Some structure and/or topography are also effective in forming the trap. Similar occurences should be possible in Manitoba at the pinch-out of the MC-3 and also at the pinch-out of the MC-1, provided that some type of lateral closure is present to complete the trap.

In the Newberg field (tp. 161, rge. 79 W, North Dakota) oil is produced from the so-called "Spearfish" red beds, which are correlative with the Amaranth or Watrous red beds of Manitoba and Saskatchewan. Although these strata are not of Mississippian age, the oil accumulation is directly related to the underlying truncated Mississippian beds. Production is obtained from both the Spearfish and Charles formations, and the Charles oil is believed to have "leaked" into the overlying red beds (Harrison and Larson, 1958). The field is situated at the subcrop of porous oil-bearing Charles beds. The Spearfish beds in the producing area show local development of sand and silt and are relatively porous. Sand accumulation is relatively local and occurs in a small synclinal or basinal structure. The sands pinch out both laterally and up dip. Similar traps could also be present in Manitoba at the subcrop of porous Mission Canyon beds. Thin porous sandy zones are known to be present in the lower part of the Amaranth (Spearfish) in the extreme southwestern part of the province, but no oil shows have been reported from them to date.

Known and Potential Mississippian Oil Traps in Manitoba

All Mississippian oil production in Manitoba has been obtained from a zone near the pre-Jurassic erosion surface. The same is true for many oil occurrences in adjacent parts of Saskatchewan and North Dakota. The cap rock in most cases is the secondary dense tight anhydritic dolomitic zone developed immediately below the erosion surface; however, in some areas such as Lulu Lake the secondary zone is very thin and the overlying Amaranth or Watrous red beds form the cap rock. Leaching, porosity infilling, and replacement related to the period of pre-Jurassic erosion have, in most cases, been important factors in controlling the porosity and permeability within the reservoir (Berg, 1956).

The three types of traps found in Manitoba are structural, truncation, and "topographic." Controlling factors in any field may involve any or all of these types of traps.

Topographic Traps

The Mississippian erosion surface was, in general, very flat (Fig. 20); however, as shown by local thinning of the Amaranth red beds a few local topographic highs were present in Amaranth time. These topographic highs, in some cases, are related very closely to oil accumulation, as in the Whitewater Lake and Lulu Lake areas, where the red bed isopachs are seen to outline the producing area. In view of the rather pronounced post-Amaranth tilting which has tended to "open" any closed topographic highs on the erosion surface, it is surprising that an exact correspondence of red bed isopachs and oil accumulation exists. It is possible that porosity variations due to weathering were controlled in part by the pre-Amaranth topography and have increased the effective closure. The dip of the erosion surface is at present 25 to 30 feet per mile and, hence, any pre-Jurassic topographic "high" with closure less than this will now be completely "open." Assuming that oil accumulation took place prior to or during tilting, some reservoirs may have been partly emptied by the tilting.

The Lulu Lake (abandoned), Whitewater Lake, Pierson, and Tilston fields appear to be examples of this type of trap.

Any topographic "high," with up-dip closure greater than about 25 feet per mile, and coincident with a subcrop of porous Mississippian strata, would constitute a potential oil trap.

Structural Traps

Structure has been an important factor in the localization of oil in the four largest fields — Daly, North Virden-Scallion, Virden Roselea, and Routledge. However, in no instance is it the sole controlling factor; truncation, topography, and secondary porosity variation are also important contributing factors in these fields.

The structures, especially in the Virden area, appear to range in age from post-Mississippian and pre-Amaranth to post-Favel. Detailed structure sections through the fields show that much of the structure is pre-erosion in age and has been almost completely truncated at the pre-Jurassic erosion surface. Some local structures, however, show a coincidence of structural and topographic "highs," indicating that the structure originated for the most part subsequent to the period of erosion, and prior to, or contemporaneous with, deposition of the Amaranth beds.

There is also some relatively minor post-Amaranth structure, as well as regional tilting towards the Williston Basin.

The considerable range in time of origin, and the very local nature of many of the structures, especially in the Virden area, are rather unusual for a relatively stable cratonic area. It seems probable that solution of salt from the Devonian Prairie Evaporite, and subsequent collapse of the overlying strata may have been a factor contributing to the present structure. Also suggestive of salt collapse are local reversals of structure such as that indicated by the Horne 4-12-10-27 well (Fig. 6). As shown by the thin Amaranth section, this area was a topographic and structural high on the Mississippian erosion surface but is now approximately 100 feet structurally low on the "Second Specks." A number of structural features in Saskatchewan are known to have developed by salt collapse. Probably basement tectonics also have played a considerable part in the structural development, but there are not sufficient data available at present to determine the amount of basement structure.

Differential compaction probably contributed somewhat to the post-Amaranth structure. The lower Jurassic (Melita) beds, and also the Ashville formation, show rapid facies changes from sandstone to shale; these lithologic changes have resulted in slight differential compaction within these units and development of minor structures in the overlying beds. Variations in thickness of the Amaranth red beds may also have resulted in some differential compaction which would tend to reflect the Mississippian topography in the overlying strata.

Truncation Traps

The relatively rapid truncation of Mississippian strata to the northeast, combined with the presence of an impermeable seal at the erosion surface due to the weathered zone and the overlying Amaranth beds, has resulted in favourable conditions for oil accumulation where porous strata are truncated at the erosion surface. The five principal truncation traps are shown in Figure 24. These traps occur at or near the subcrop edges of the MC-3 (A, B), MC-1 (C), Virden-Whitewater Lake (D), Scallion (E), and middle Bakken beds (F). In addition to truncation, some structural or topographic high coincident with the truncation trap is necessary to localize oil accumulation.

Traps A, B, and C would seem to be good potential reservoirs, especially since down-dip production has been obtained from local structural highs (Waskada, Westover, and Hernfield); however, as noted previously, little oil has been discovered to date in Manitoba in such traps. The Pierson field, situated near the pinch-out of the MC-3, and the Tilston field, situated near the pinch-out of the MC-1, are the only producing areas with traps approximating types B and C, and both are somewhat down dip from the pinch-out of the porosity zones. In both fields the traps appear to be primarily topographic and/or structural rather than purely truncational. The unfavourable regional structural relationships of traps A, B and C have been discussed previously.

Production has been obtained from type D traps in the North Virden-Scallion, Virden-Roselea, Routledge, West Routledge, Whitewater Lake, and Lulu Lake areas at or near the subcrop belt of the Virden-Whitewater Lake beds. Accumulation appears to be localized by topography, structure, and/or porosity variations. It is possible that the difference in lithology and resistance to erosion between the oolitic-crinoidal and shaly units may have caused some differential erosion and resulted in favourable topographic traps. A comparison of the subcrop map (Fig. 15), and the isopach map of the Amaranth Red beds in the central part of the map area (Fig. 20), shows that a rather well-defined zone of thick red beds coincides with the subcrop of the less resistant shaly beds of the Lower Virden, whereas the subcrop belt of the more resistant upper Virden and Whitewater Lake beds shows a relatively thin red bed section. This indicates that a minor escarpment or cuesta formed along the subcrop belt of the Virden-Whitewater Lake units during the

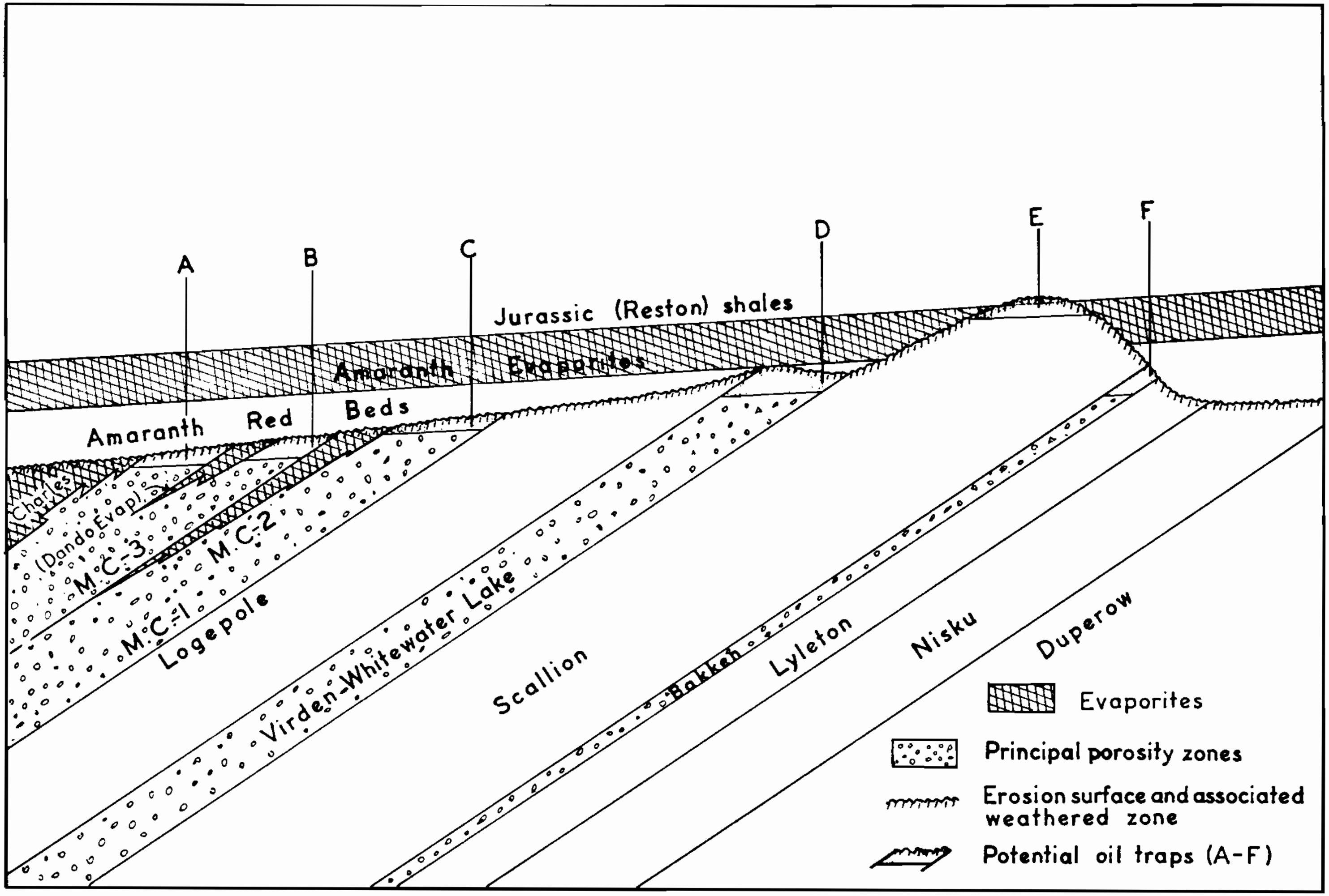


Figure 24. Diagrammatic east-west cross-section showing potential stratigraphic (truncation) traps in Mississippian strata of southwestern Manitoba. Vertical scale greatly exaggerated; average dip of Mississippian strata is 35 feet per mile, and of Jurassic strata, 19 feet per mile.

period of pre-Amaranth erosion. A similar but much less well-developed "cuesta" occurs at the erosional edge of the MC-1 beds.

Units correlative with the Virden-Whitewater Lake beds also produce in the Daly, Woodnorth, and Kirkella areas. The Daly and Woodnorth traps, however, are apparently primarily structural, although primary stratigraphic and secondary porosity variations related to the pre-Jurassic erosion surface are also important modifying factors in the oil distribution.

No evidence of oil accumulation is known at the pinch-out of the Scallion beds (trap E), although the situation would appear to be favourable. The pronounced topographic "high" in the Wawanesa area should be especially favourable, but no oil shows have been obtained to date. The erosional escarpment at the edge of the Scallion shows sufficient relief so that the dip on the erosion surface is reversed, and the trap would occur not at the exact edge of the Scallion, but somewhat to the southwest (Fig. 24). Although the Scallion beds are generally porous, the chalky nature of much of the unit suggests that the permeability is probably low, and possibly may have prevented oil migration through the unit. Nevertheless, some zones of excellent porosity and permeability (reefy?) are present locally in such areas as Boissevain and Birdtail.

Oil "shows" have been obtained from the middle Bakken sandstone and siltstone (trap F) to the north of the Daly area, and in adjacent areas of Saskatchewan (Rocanville). The middle Bakken appears to become progressively more sandy to the north with a resultant increase in porosity, and the subcrop belt of this unit appears to be a favourable area for oil accumulation. The middle Bakken also appears to be a porous, unconsolidated sand in or near the Wawanesa area (Dome Nesbitt 11-9-7-18 well) where it may form a potential truncation trap.

Facies Traps

Areas of rapid facies change in the Mississippian may be favourable locations for oil accumulation. The rapid, up-dip facies change from the porous Scallion limestone to the Routledge shale may constitute a favourable potential trap, at least in that area where erosion has cut sufficiently deep into Mississippian beds to encounter the Routledge shale and form a cap rock. The black Routledge shales probably are favourable source beds for petroleum.

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APPENDIX I

EVAPORITE DEPOSITION

Factors controlling evaporite deposition have been discussed in detail by many writers, including Usiglio (Pettijohn, 1949), King (1947), Sloss (1953), and Scruton (1953). In brief, evaporite deposits are formed where the rate of evaporation exceeds the rate of inflow of fresh water, and where some sort of barrier or restriction is present to inhibit marine circulation and confine the denser, more saline waters resulting from the excess evaporation. These denser waters tend to flow out of the basin because of the salinity (density) gradient, as shown by Scruton (1953).

There are two main types of restriction, physical (or static) and dynamic. In physical restriction, which is probably the more important type (Fig. 25), circulation is prevented or hindered by a physical barrier such as a tectonic or a topographic "sill," or by depositional sedimentary bodies such as sand bars, reefs, and algal-oolitic or crinoidal shoals. In most cases restriction is not complete, and the sill is low enough to permit some of the saline waters to escape from the evaporite basin, as in the case of the Mediterranean (Kuenen, 1950). The depth and width of the sill or barrier determines, to a large extent, the degree of restriction and the resultant salinity in the evaporite basin.

The second and probably less important type of restriction is dynamic restriction (Scruton, 1953), in which there is no physical barrier to circulation. The restriction is due to dynamic, frictional resistance between the inflowing and outflowing currents, and between the outflowing current and the sea bottom which hinders the outflowing marine current, as shown in Figure 25. Dynamic restriction is thus a factor in any evaporite basin where simultaneous inflow and outflow take place, but is most effective in very shallow and widespread seas where maximum development of frictional interface is attained.

If tectonic, physiographic, and climatic conditions become stabilized, dynamic equilibrium may be attained between inflow — consisting of rainfall, land-derived water, and normal marine sea water — and loss of water from the basin due to evaporation and outflow of saline water. As a result, salinity will be maintained at a relatively constant level, and the composition of the evaporites will remain constant also. Because of the relatively low concentration of $CaSO_4$ in sea water, significant thickness of relatively pure gypsum or anhydrite can be formed only under such conditions of equilibrium, and salinity must be maintained in the approximate range from 4 to 10 times normal. Below this range limestone rather than $CaSO_4$ is deposited, and above the range halite is precipitated in amounts greatly exceeding the $CaSO_4$.

The degree of restriction in an evaporite basin can be very high if the basin is relatively deep and if the depth of water above the "sill" is very shallow, so that only inflow of normal marine waters occurs. In this case salinity will rise continuously as long as restriction, inflow, and excess evaporation are maintained, until maximum salinity is reached at which point the brine is essentially saturated with respect to all constituents. Continuous precipitation of the more abundant and/or less soluble salts, especially NaCl, will take place during this time. The overall evaporite composition under such conditions of restriction will be the same as that of normal sea water, and so long as inflow into the basin is maintained there can be no great concentration of anhydrite or any of the rarer constituents such as potash salts. There would probably be some lateral differentiation in evaporite composition due to the horizontal salinity gradient, as indicated by Scruton (1953). The thickness of evaporite deposits formed under the above conditions of restriction is limited only by the amount of differential subsidence of the evaporite basin.

Complete restriction, in which no inflow or outflow takes place, can occur when the evaporite basin is completely isolated from the open sea. Under such conditions the composition of the evaporites will depend on the salinity in the evaporite basin at the time of complete restriction; if the salinity was sufficiently high, the very soluble but comparatively rare constituents such as potash can form a relatively high percentage of the late-stage evaporites of such deposits. Commercial concentrations of potash salts can occur only if conditions of virtually complete restriction and isolation are attained. The thickness of such hypersaline deposits is limited by the depth of water in the evaporite basin at the time of complete restriction.

In any evaporite basin the degree of restriction may vary greatly throughout the period of evaporite deposition. In general, however, maximum restriction of the basin seems to occur at or near the end of the period of evaporite deposition, and during the time of maximum tectonic differentiation of the basin.

MISSISSIPPIAN EVAPORITES

Mississippian, Mission Canyon seas were very shallow and widespread as shown by the extensive, sheet-like deposits of oolitic and bioclastic limestone such as the MC-1. Slight restriction, possibly dynamic in nature, was prevalent in the marginal areas; this is shown by the deposition of algal-oolitic limestones under penesaline conditions, probably very similar to the Bahama Bank type of environment described by Illing (1954). The periodic changes, from limestone to anhydrite precipitation, which are characteristic of the upper Mississippian evaporite cycles, were due to periodic increases in the degree of restriction, apparently resulting from periodic lowering of sea-level, or decrease in water depth. The relative drop in sea-level is indicated by the encroachment on the basin of terrestrial or shallow marine clastics, some of which contain plant fragments. The lowering of sea-level may have resulted in the formation of off-shore submarine bars of limestone sand, as in the case of present day emergent shorelines (Lobeck, 1939; pp. 346). Very shallow evaporite (anhydrite-dolomite) lagoons formed shoreward of the barrier bars, but restriction was not sufficient to cause precipitation of salt in these lagoons. On the shoals, conditions of relatively high wave energy and slightly higher than normal salinity apparently favoured algal, oolite, and calcarenite development, which played an important role in the Mission Canyon shoal buildup.

The variations in sea-level that gave rise to the cyclical Charles evaporites appear to have been basin-wide. It is possible that the sea-level fluctuations were caused by periodic tectonism, but the extremely widespread distribution and the cyclical repetition of the sediments make such a hypothesis rather doubtful. It seems more probable that eustatic variation in sea-level was the controlling factor.

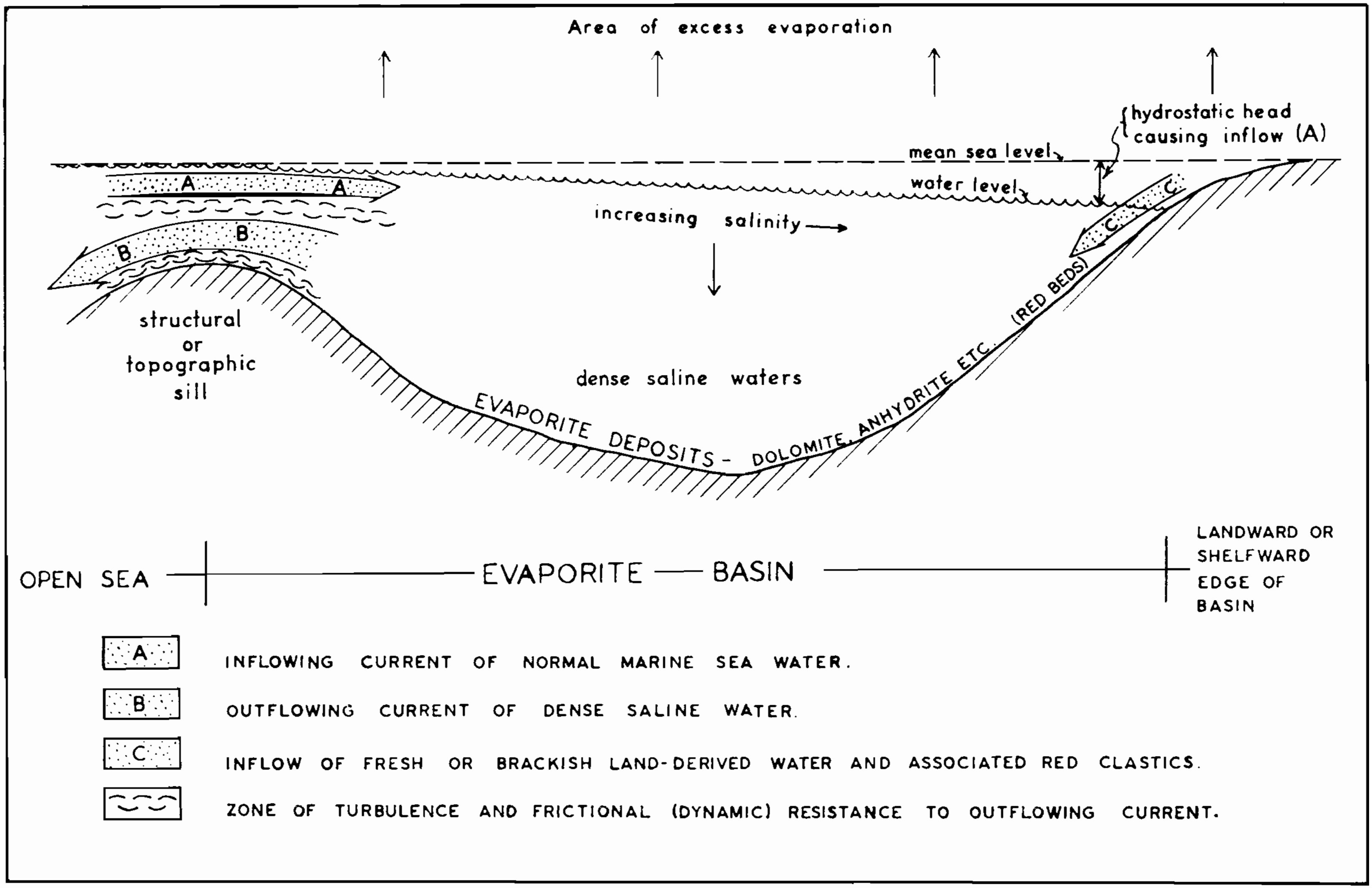
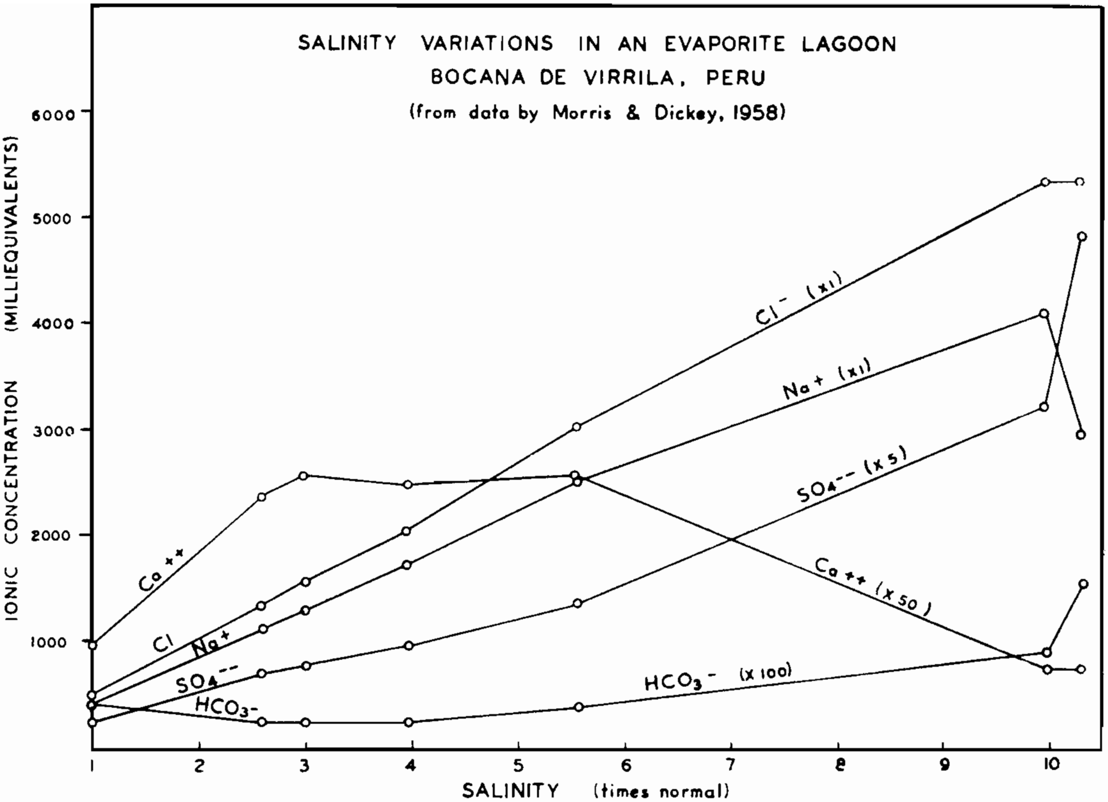


Figure 25. Diagrammatic cross-section of an evaporite basin showing both physical and dynamic restriction.



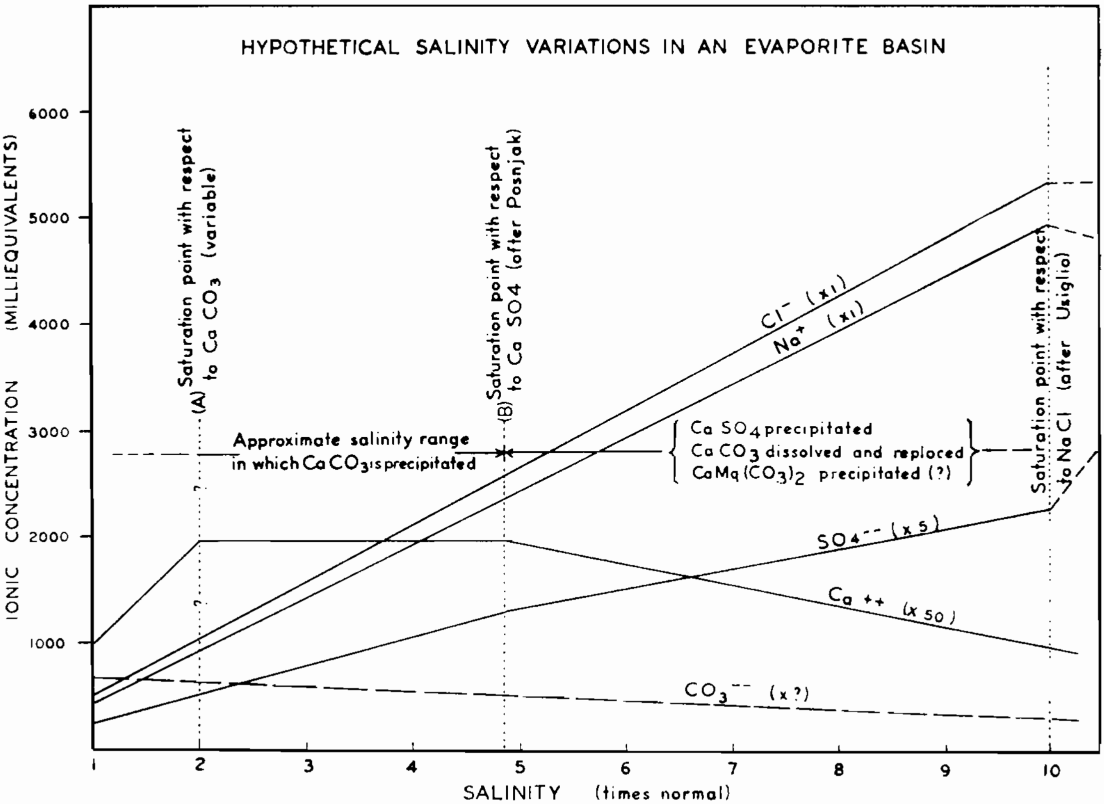


Figure 26. Salinity variations in an evaporite basin, showing both measured and hypothetical variations. Note that the vertical scale varies for the different ions, this was necessary because of the large differences in concentration of the ions involved.

Relatively minor changes in sea-level in the shallow Mississippian seas, probably as little as a few tens of feet, would have been sufficient to cause the evaporite cycles.

The eustatic (?) fluctuations in sea-level were superimposed on a continual, relatively uniform tectonic subsidence throughout the Williston Basin area, but the rate of subsidence generally decreased through Mission Canyon and Charles time so that the basin gradually filled up with sediments. As a result, there was a general regression of the seas, and the marginal evaporite lagoons, formed during periods of lowered sea-level, showed a progressive retreat towards the basin with each succeeding cycle. The MC-2 evaporite is an exception to this generalization, and apparently is the result of an unusually large drop in sea-level.

During deposition of the early Charles basin-margin evaporites, such as those that are found in Manitoba, salinity in most areas apparently did not rise above the 10 times normal limit necessary to precipitate halite. Later Charles deposits, as found in the central part of the Williston Basin, contain a high percentage of halite, indicating a much higher degree of restriction; however, no potash salts have been reported in the Charles evaporites, and it seems unlikely that complete restriction of the later Charles seas was attained.

Zone of Secondary Alteration

It has been shown that there is commonly a zone, immediately below anhydrite beds and anhydrite bearing red beds, where the underlying limestone has been strongly altered to dolomite and anhydrite. The occurrence of large secondary "porphyroblasts" of brown anhydrite in dolomite has been described by Fuller (1956, pp. 42). Similar porphyroblasts have been observed in Manitoba. Such replacements of carbonate, presumably originally calcite, by anhydrite normally would not be expected, as $CaCO_3$ is considerably less soluble than $CaSO_4$ and precipitates before anhydrite in the evaporite sequence. The genesis of the zone of anhydrite and dolomite replacement is discussed here briefly because of the important role this zone plays in forming the cap rock for all oil fields in Manitoba, as well as for many fields in Saskatchewan and North Dakota. However, a detailed physical-chemical discussion of the solubility relationships is beyond the scope of this report.

The principal factors controlling replacement of limestone by anhydrite appear to be twofold:

(1) the relative concentration of Ca, SO_4 and CO_3 ions in sea water, and

(2) the variation in concentrations of these ions with increasing salinity.

The sequence in which minerals are precipitated during evaporite deposition is controlled by the activity products (K@) which take into consideration not only the concentration of the ions forming the minerals being precipitated, but also the effect of all other ions in solution. A compound or mineral is precipitated when, as a result of evaporation, its activity product is reached:

eg. K@ for $CaCO_3$ = @Ca × @CO_3

and K@ for $CaSO_4$ = @Ca × @SO_4

Continued evaporation after the activity product of a particular mineral is reached will result in precipitation of that mineral in order to maintain K@ constant. The variation in concentration of the ions forming the precipitate will depend on the relative concentration of these ions in the solution. In sea water, the ions forming the precipitate (eg. Ca and SO_4) are not present in stoichiometric proportions; consequently, with continued evaporation and precipitation, the concentration of the more abundant ion forming the precipitate will continue to rise, although at a reduced rate, and that of the less abundant ion will decrease in order to maintain K@ constant.

This is especially important in the case of $CaSO_4$ precipation because the concentration of SO_4 in normal sea water is almost three times that of Ca. Consequently, as salinity increases above the 4 times normal limit necessary to start precipitation of $CaSO_4$, the SO_4 concentration will continue to increase whereas the concentration of Ca will decrease, or be suppressed, as shown in Figure 26, in order to maintain K@.

The second important factor is the variation of the CO_3 ion content relative to salinity during the evaporite deposition. The concentrations of all ions except CO_3 are essentially direct functions of salinity. It is generally agreed that the CO_3 ion concentration is controlled primarily by the CO_2 content of the atmosphere (Rankama and Sahama, 1950, pp. 465), and is therefore relatively constant and more or less independent of salinity. Salinity does affect the CO_3 concentration, but only to a limited extent over the range of salinity affecting the $CaCO_3$ and $CaSO_4$ deposition, and these effects can be largely disregarded. Krumbein and Garrels (1952) indicate that the CO_3 ion concentration actually decreases with increasing salinity, rather than increasing as does the concentrations of the other ions.

On the basis of the above discussion, the idealized sequence of events taking place in a marine evaporite basin can be reconstructed. The effective concentration, or activity, of all ions in solution, except CO_3, will rise until the water becomes saturated with respect to $CaCO_3$, which is the first significant precipitate to form (Fig. 26, point A). Once $CaCO_3$ starts to precipitate, the concentration of both Ca and CO_3 will remain relatively constant at the appropriate K@ value, and the concentration of all other ions will increase with continued evaporation until the @SO_4 is sufficiently high so that the K@ for $CaSO_4$ is reached (Fig. 26, point B). (The Ca remains constant between points A and B because the CO_3 is constant). At this salinity, approximately 4 times normal, both the $CaCO_3$ and $CaSO_4$ will tend to precipitate together from solution. However, with continued evaporation, the SO_4 concentration will continue to rise because SO_4 is more abundant than Ca in sea water, especially as some of the Ca already has been precipitated as $CaCO_3$. This will result in a corresponding decrease in Ca concentration in order to maintain the K@ for $CaSO_4$, which will lower the Ca concentration below that necessary for precipitation of $CaCO_3$. Consequently, once salinity exceeds approximately four times normal, $CaCO_3$ can no longer be precipitated. In fact, continued evaporation will result in further increase in SO_4 concentration with corresponding further suppression of the Ca concentration which will cause any calcite in contact with the saline waters to tend to dissolve. As $CaSO_4$ is being precipitated at the same time, the resultant conditions are ideal for metasommatic replacement of calcite by anhydrite (or gypsum). The foregoing postulated salinity variations are supported by the measured salinities in an evaporite lagoon (Morris and Dickey, 1957).

Although, when $CaSO_4$ begins to precipitate, the Ca concentrations is lowered below that necessary to precipitate $CaCO_3$, the Mg concentration is apparently sufficiently high to precipitate dolomite; consequently, dolomite is the only carbonate that can be precipitated contemporaneously with anhydrite (or gypsum). In addition, since the Mg concentration in sea water exceeds that of SO_4, it is probable that dolomite is stable throughout the range of precipitation of anhydrite. This is supported by sample evidence which shows dolomite interbedded with halite and anhydrite in the uppermost Charles evaporites of the central Williston Basin area.

The pronounced dolomitization associated with the anhydrite replacement probably is related to the increased concentration of Mg in the saline waters, although factors controlling dolomite formation are little understood at the present time. However, the fact that calcite becomes unstable under conditions of increased salinity would favour replacement of calcite by dolomite if there was any tendency at all for dolomite to form under those conditions. According to Kramer (1958) dolomite becomes the stable carbonate mineral in sea water if salinity exceeds 95 parts per thousand (approximately 3 times normal).

APPENDIX II

DESCRIPTIONS OF SELECTED LITHOLOGIC SECTIONS

Cleary Calstan Prov 6-21-1-19

WELL NO. 1

JURASSIC

Amaranth Red Beds

Depth in Feet	
3055—3069	Siltstone to very fine sandstone; dark brick red to mottled light grey towards base; several bands very sandy with abundant coarse rounded frosted sand grains; patchy anhydrite; sharp contact with:

MISSISSIPPIAN

Lodgepole Formation

SCALLION MEMBER

3069—3071	Limestone, dolomitic; few patches of anhydrite.
3071—3112.8	Limestone, white, finely crystalline granular to chalky, scattered crinoid fragments; good intergranular porosity, slight pinpoint to fine vuggy porosity associated in part with fossil solution cavities; sparsely fossiliferous with corals, bryozoa, and brachipods; faint relict calcarenite texture; several dense beds; somewhat dolomitic in part.

ROUTLEDGE SHALE

3112.8—3114.8	Dolomite, argillaceous, medium grey to reddish, earthy, silty.
3114.8—3115.2	Limestone, finely crystalline, tight; abundant spines or spicules.
3115.2—3116.2	Limestone, light buff to reddish grey, slightly argillaceous, extremely fossiliferous, dense to slightly granular, silty to fine sandy.
3116.2—3117.2	Dolomite, argillaceous, medium grey to reddish, as above.
3117.2—3117.8	Shale, dark silvery grey to black, massive, blocky.
3117.8—3120.3	Reddish grey silty argillaceous dolomite grading to medium dark grey dolomitic shale at the base; fossiliferous.
3120.3—3123.3	Limestone, light buff, finely crystalline, moderately granular, scattered crinoid fragments.
3123.3—3123.5	Shale, dark grey.
3123.5—3125	Dolomite, argillaceous, silty, medium grey, very fossiliferous towards base; few patches of red hematite (fossil replacement).
3125—3196	Not cored.
3196—3211	Shale, dark grey to black; massive to very slightly fissile in part with conchoidal fracture; slightly pyritic.

Bakken Formation

3211—3229	Note: Incomplete recovery. The black shale section probably includes the Routledge-Bakken contact, but no lithologic change is noticeable. Recovery is as follows: 5.0′ Black shale, as above. 3.2′ Dolomite, silty, medium grey, slightly argillaceous. 1.3′ Shale, medium dark grey, very finely banded, moderately fissile. 0.5′ Shale, medium light grey, massive. 0.5′ Dolomite, fine-grained, silty, medium grey, massive. 4.0′ Sandstone, fine-grained, dolomitic; mottled in shades of grey to reddish and purplish grey.
3229—3234	Sandstone, fine-grained, mostly very finely banded, moderately fissile, dolomitic; light grey to dark greyish red with red coloration prominent towards base; several interbeds light greenish grey silty, slightly argillaceous dolomite.

DEVONIAN

Lyleton Formation

3234—3249	Shale, dolomitic; light grey to greenish grey, slightly silty and pyritic, massive.

Royalite Triad et al Max Lake No. 1 (4-36-1-21)

MISSISSIPPIAN

Lodgepole Formation

LOWER WHITEWATER LAKE

3279—3279.1	Shale, calcareous, medium light grey.
3279.1—3280.5	Dolomite, light grey, massive; fine to coarse calcarenite or oolite texture; becomes calcareous towards the base.
3280.5—3282.1	Limestone, medium to coarse fragmental; oolitic towards base; tight.
3282.1—3284.4	Argillaceous dolomite or dolomitic shale, reddish and purplish grey, streaked and mottled; few small anhydrite inclusions; few thin beds light grey dense argillaceous dolomite near base.
3284.4—3289	Limestone, medium brown, oil-stained in part, medium crinoidal to finely crystalline; tight to slightly porous; several thin bands of purplish grey argillaceous limestone.
3289—3293	Limestone, very argillaceous, mottled and streaked in shades of purplish and reddish grey; scattered crinoid and other fossil fragments.
3293—3296.5	Limestone, reddish grey, argillaceous, moderately fossiliferous fragmental throughout; several tight oolitic beds. Towards the base some of the oolites appear to be hematite.

UPPER VIRDEN

3296.5—3303	Oolitic limestone, light buff to medium dark grey, very tight; few stylolitic partings. Several bands and partings of red and light purplish grey dense argillaceous limestone. Prominent open vertical fracture shows strong oil stain and druzy pyrite coating. Fracture shows offsetting of about ¼".
3303—3308	Limestone, predominantly crinoidal, fossiliferous fragmental, light grey, tight, oolitic in part. Bands of light grey, dense, argillaceous limestone are common in the upper part.
3308—3310	Oolitic limestone; few thin beds of light grey dense slightly argillaceous limestone.
3310—3311.2	Oolitic limestone, coarser grained, partly crinoidal; shows good, patchy, interfragmental porosity with associated oil staining.
3311.2—3313	Limestone, fine grained, oolitic to crinoidal; slight patchy oil stain near base.
3313—3318	Limestone, predominantly finely crystalline or fine fragmental, uniform, non-argillaceous; some medium grained crinoidal limestone showing slight patchy oil stain; scattered oolites in bottom 6 inches; good porosity.
3318—3325	Limestone, light buff, finely crystalline granular to saccharoidal; few thin grey shaly bands near the top, becomes argillaceous towards base; nodules and bands of soft white earthy tripolitized chert are common.
3325—3328	Limestone, medium grey, dense, argillaceous, fossiliferous; few patches crinoidal limestone.
3328—3339	Limestone, light grey to brown, finely crystalline granular with scattered to abundant crinoid fragments; few thin bands of oolitic limestone; fairly good intergranular porosity towards the base; some strong vertical fracturing, tight to open; some dense, grey argillaceous limestone in bottom 3 inches.
3339—3590	Not Cored.

Bakken Formation

3590—3609	Shale, black, fissile at the top, becoming dark grey towards base; some conodonts; may include some Routledge shale; grades sharply to:
3609—3630	Coarse siltstone to very fine grained sandstone, medium light grey, argillaceous, dolomitic, and slightly pyritic. Grain size increases towards the base, and some beds of medium-grained sandstone are present. Fine dark hair-like markings are common. Some bands are finely laminated. Grades sharply, and with no apparent break to:

DEVONIAN

Lyleton Formation

3630—3643	Shale, slightly dolomitic, light grey to greenish, massive, slightly mottled and streaked; abundant pyrite along fractures. Grades to:
3643—3645	Red shale, slightly dolomitic; some breccia fragments of dolomite.
3645—3645.5	Shale, light grey.
3645.5—3649.5	Red shale, slightly dolomitic, massive; some fine breccia fragments of dolomite near base; passes sharply but conformably to:

Nisku Formation

3649.5—3651	Dolomite, light grey, dense, argillaceous; scattered patches of anhydrite.
3651—3655	Dolomite, buff, fossiliferous fragmental.

WELL NO. 9

Souris Valley et al Meggison 10-14-1-25

JURASSIC

Amaranth Red Beds

2950—2965.5	Siltstone, medium dark reddish brown, argilaceous, dolomite; scattered anhydrite inclusions; coarse rounded frosted sand grains abundant towards base.

MISSISSIPPIAN

Mission Canyon Formation

MC-2 MEMBER

2965.5—2968.5	Anhydrite; somewhat brecciated appearance due to fine irregular veinlets of reddish grey dolomite.
2968.5—2969.8	Dolomite, finely crystalline; patchy oil stain; anhydrite inclusions.
2969.8—2972	Dolomitized calcarenite, finely crystalline.
2972—2979	Anhydrite and argillaceous dolomite, mottled grey and reddish grey.
2979—2985	Dolomitic anhydrite and anhydritic dolomite, very finely crystalline to "lithographic" appearance; medium to light brown and reddish brown; more anhydritic towards base; grades to:
2985—2989	Anhydrite, clear crystalline, massive.
2989—2990.3	Dolomite with veinlets and inclusions of anhydrite.
29990.3—2998	Anhydrite.

MC-1 MEMBER

2998—3017	Dolomite, finely crystalline to dense; some vertical fractures filled by anhydrite; few anhydrite inclusions.
3017—3019.5	Limestone, dolomitic, light buff, finely crystalline, granular; few anhydrite inclusions.
3019.5—3021	Dolomite, mottled grey to purplish, very finely crystalline.
3021—3022	Limestone, light buff, finely crystalline granular, calcarenite.
3022—3026.5	Dolomite, microcrystalline to microsaccharoidal; some good pinpoint porosity.
3026.5—3037	Limestone, very light buff, fine oolite or calcarenite, finely crystalline, granular.

WELL NO. 11

Anglo Ex Dando 3-32-1-25

JURASSIC

Amaranth Red Beds

2982—3002	Siltstone, argillaceous, micaceous, medium reddish brown to grey, irregularly bedded; small anhydrite inclusions; rounded frosted sand grains abundant towards base. Grades to sandstone in part, showing fine crossbedding.

MISSISSIPPIAN

Charles Formation

3002—3008.5	Predominantly anhydrite, clear crystalline to light brownish grey, lithographic, probably dolomitic; few bands light buff dense dolomite.
3008.5—3009.5	Limestone and dolomite, finely crystalline to saccharoidal, oil-stained.
3009.5—3009.8	Anhydrite.
3009.8—3011.4	Dolomite, light buff, finely crystalline; large brown crystals of secondary anhydrite scattered throughout.
3011.4—3018.9	Anhydrite and dolomite; coarse breccia appearance with large patches and stringers of microcrystalline granular dolomite; slight oil staining near base.

Mission Canyon Formation

MC-3 MEMBER

3018.9—3050	Limestone, light buff, earthy appearing; faint relict fragmental and algal texture; considerable intergranular anhydrite near top.

WELL NO. 12

Anglo Ex Souris Valley Smart 4-1-1-26

JURASSIC

Amaranth Red Beds

3047—3078	Siltstone, micaceous, argillaceous, dolomitic, some sandy patches, medium grey and reddish brown; rounded frosted sand grains abundant in lower 7 feet; sharp contact with:

MISSISSIPPIAN

Charles Formation

3078—3081.5	Sandstone, fine grained, pale grey, massive, tight (could possibly be Amaranth).
3081.5—3082.5	Dolomite, argillaceous, dense; banded purplish red, grey, and reddish brown.
3082.5—3083.8	Anhydrite, dolomitic, massive, brownish to reddish grey, dense to lithographic.
3083.8—3089.7	Shale, dolomitic, massive, mottled and banded as above; in part silty
3089.7—3094.6	Anhydrite, massive, finely crystalline, partly dolomitic, light yellowish brown to grey.
3094.6—3096	Dolomite, buff, massive, finely crystalline; anhydrite inclusions up to 3 inches (15%).
3096—3098.2	Dolomitic shale, dusky red and reddish brown, massive.
3098.2—3100.8	Anhydrite, fine to medium crystalline; numerous red shale partings; several bands grey argillaceous dolomite.
3100.8—3101.5	Dolomitic shale, reddish brown, massive.
3101.5—3102	Anhydrite, medium grey, dolomitic, slightly argillaceous, lithographic.
3102—3102.7	Argillaceous dolomite, mottled greyish red to reddish brown.
3102.7—3104.4	Anhydrite, very dolomitic and argillaceous, moderate red to brownish red; interbanded with argillaceous dolomite; breccia appearance.
3104.4—3105.3	Anhydrite, finely crystalline.
3105.3—3105.7	Argillaceous dolomite, finely crystalline, pale to moderate red.
3105.7—3109.9	Anhydrite, clear, massive, fine to medium crystalline; slightly brecciated at base.
3109.9—3112.7	Sandstone to sandy dolomite, pale grey to reddish grey, good patchy fine vuggy porosity; patchy oil stain in upper 14 inches; anhydrite fragments or inclusions common in lower 6 inches; bottom 3 inches are shale with anhydrite inclusions.
3112.7—3117.7	Anhydrite — upper part brecciated with stringers of yellowish grey dolomite; lower part massive, dolomitic; grades to:

Mission Canyon Formation

MC-3 MEMBER

3117.7—3124	Dolomite, slightly calcareous, pale yellowish grey, massive, finely crystalline to slightly granular; many anhydrite inclusions; fair to excellent vuggy porosity; 5 inch band near base shows good oil stain.
3124—3124.9	Dolomitic limestone, massive; good vuggy porosity as above.
3124.9—3132.4	Limestone, buff, very finely crystalline to slightly earthy, fair patchy vuggy porosity; euhedral, lathlike, randomly oriented crystals of brown anhydrite are common; faint brecciated appearance.
3132.4—3134.9	Limestone, slightly dolomitic; pale greenish grey, massive, microcrystalline, tight; irregular patches brown crystalline anhydrite; several thin oolite bands; stylolites near base.
3134.9—3139	Limestone, finely crystalline, fair vuggy porosity; white blade-like anhydrite crystals common in upper part; oolitic at base.

WELL NO. 13

Calstan Waskada 9-13-1-26

Mission Canyon Formation

MC-2 MEMBER

3022—3025	Dolomite, pale yellowish grey, massive, calcarenite or oolite texture; grades to 6-inch bed of dolomitic anhydrite in middle of unit. Lower part of unit contains patches of anhydrite; shows good fine vuggy porosity and oil stain.
3025—3027	Dolomite, pale greenish grey, slightly calcareous; texture varies from microcrystalline to oolitic; some anhydrite as fracture fillings. Lower part of unit consists of interbedded dolomite and anhydrite showing breccia-like appearance in part; ¼-inch bed of dolomitic sandstone at base of unit.

MC-1 MEMBER

3027—3030	Dolomite, slightly calcareous, finely crystalline to oolitic, massive; argillaceous in upper 3 inches; oil stained at base.
3030—3032.5	Dolomitic limestone, pale yellowish grey, slightly oil stained, massive, dense, argillaceous; fair fine vuggy porosity; trace anhydrite.
3032.5—3034	Dolomite, massive, calcarenite or oolite, fair fine vuggy porosity, stylolitic.
3034—3046.9	Limestone, dolomitic, argillaceous, earthy, yellowish grey; trace anhydrite as porosity and fracture filling.
3046.9—3101	Interbedded limestone and dolomitic limestone, light grey to moderate yellowish brown, mostly finely crystalline to earthy appearing, in part calcarenite: good to patchy oil stain throughout; scattered fine vuggy porosity; few thin bands of fossiliferous fragmental limestone; few grey to greenish grey shaly beds; trace anhydrite as vein fillings; trace nodular white chert.

WELL NO. 21

Souris Valley McKague 2-27-1-27

MISSISSIPPIAN

Charles Formation

3146—3187	Interbedded red beds (approximately 65% of unit), and massive anhydrite (35% of unit); beds range in thickness from a few inches up to 5 feet. The red beds vary from dense or lithographic argillaceous dolomite to sandy dolomite, possibly anhydritic, and dolomitic shale. Several beds approach a sandstone in composition. Beds are slightly fractured, and fractures are filled with anhydrite; one fracture shows differential movement with different rock types bounding the fracture; numerous thin beds have a brecciated appearance. Locally the red beds show pale grey to greenish reduction patches, especially adjacent to fractures. The anhydrite is pale yellowish grey to brown, extremely fine grained, dolomitic and slightly argillaceous. It occurs as irregular patches or fragments, and in bands up to 2 feet thick. Base of red bed unit of Charles: 3187′.
3187—3207	Interbedded anhydrite and argillaceous dolomite or dolomitic shale; as above, but little or no red coloration; mostly shades of greenish to yellowish grey. Several of the anhydrite beds have a pronounced brecciated appearance, with abundant patches and stringers of dolomite and argillaceous dolomite.
3207—3209	Sandstone, grading to sandy argillaceous dolomitic limestone, medium light grey; sand grains show fair to moderate rounding; abundant breccia fragments of anhydrite up to 1 inch in diameter.
3209—3216.2	Anhydrite and dolomitic anhydrite, dense; abundant stringers and patches of dolomite in upper 2 feet.
3216.2—3217.2	Limestone, slightly argillaceous, becoming dolomitic towards base, pale yellowish grey.
3217.2—3222.5	Dolomitic anhydrite, argillaceous, dense, massive; sharp contact with:

Mission Canyon Formation

MC-3 MEMBER

3222.5—3230	Limestone, oolitic and calcarenitic, coarse-grained, pale yellowish grey, excellent intergranular porosity, no oil stain; some anhydrite infilling of porosity near base of unit.

WELL NO. 23

Cleary Souris Valley Moore 11-13-1-28

JURASSIC

Amaranth Red Beds

3220—3236.3	Siltstone to very fine sandstone, medium reddish brown, argillaceous, dolomitic, slightly micaceous; large rounded frosted sand grains are abundant; irregular inclusions of anhydrite.

MISSISSIPPIAN

Charles Formation

3236.3—3236.5	Shale, massive, dolomitic, dark brownish red with green mottling, sandy (could be Amaranth).
3236.5—3238.5	Breccia-fragments of medium reddish brown dense dolomitic anhydrite in matrix of sandy siltstone.

3238.5—3240	Shale, dolomitic, sandy, dark red to green, banded and mottled; grades to grey dense dolomitic anhydrite in the middle of the unit.
3240—3243	Anhydrite, slightly dolomitic and argillaceous, dense or lithographic; grades from medium brown to light grey.
3243—3244.5	Dolomite, anhydritic, argillaceous; few red and green shaly bands.
3244.5—3258.5	Anhydrite, pure, dense to finely crystalline; several thin beds of dense dolomite.
3258.5—3260.6	Anhydrite, dark brown to reddish, dolomitic, argillaceous.
3260.6—3263.6	Anhydrite, light grey, dense.
3263.6—3264.6	Anhydritic dolomite, medium dark reddish brown, argillaceous.
3264.6—3268.6	Anhydrite, pure, crystalline.
3268.6—3270.6	Dolomite, light grey, slightly calcareous, microcrystalline to microsaccharoidal, partly oil-stained.
3270.6—3271	Anhydrite.
3271—3272.5	Sandstone, and very sandy argillaceous dolomite, medium to light grey; irregular inclusions of anhydrite.
3272.5—3277.6	Anhydrite breccia. Irregular fragments of anhydrite in a matrix of light grey-buff, very finely crystalline dolomite. Grades to "lithographic" anhydrite in lower part. Sharp contact with:

Mission Canyon Formation

MC-3 MEMBER

3277.6—3280	Limestone, predominantly finely crystalline, tight to slightly granular; calcarenite in part, but original texture is in general poorly preserved; good medium vuggy porosity partly infilled by anhydrite.
3280—3305	Limestone, very light buff, algal-oolitic to calcarenitic; rather dense textured for the most part; some dense beds show only faint relict calcarenite texture; patchy, good to excellent, fine to medium vuggy porosity; slightly fossiliferous.
3305—3320	Limestone, light buff to white, earthy-appearing, uniform fine oolite or calcarenite; good intergranular porosity; abundant scattered "eyes" of brown crystalline dolomite.

WELL NO. 39

Rio Prado Souris Hill 16-9 (16-9-2-28)

JURASSIC

Amaranth Red Beds

3230—3240.5	Siltstone, medium reddish brown, micaceous, argillaceous, anhydritic and sandy. Grades to:

MISSISSIPPIAN

Charles Formation

3240.5—3244.3	Dolomitic shale, dark dusky red, massive. Shows pronounced light greenish grey mottling in upper 3"; contains a few scattered inclusions of anhydrite.
3244.3—3247	Anhydrite, pure, crystalline; 2-inch red shale band near the top; becomes buff, dolomitic towards base.

Mission Canyon Formation

MC-3 MEMBER

3247—3248	Dolomite, finely crystalline granular to saccharoidal, oil-stained.
3248—3249.5	Dolomite, as above, light grey, unstained.
3249.5—3252	Anhydrite breccia; large irregular anhydrite inclusions in light grey finely saccharoidal dolomite. Medium to fine subrounded sand grains are also abundant.
3252—3273	Dolomite, light grey-buff, mostly finely crystalline tight to moderately granular; few bands show medium calcarenite and algal-oolitic texture; much anhydrite as irregular bands and fracture fillings; 4-inch band of oil staining near base.
3273—3275	Dolomitic limestone, calcarenite or micro-breccia; fine-grained, light grey, angular limestone grains in brown dolomite matrix.
3275—3276	Dolomite, as above, finely crystalline, tight.
3276—3289	Fragmental limestone, partly dolomitic, light grey buff; irregular to rounded fragments of dense to microgranular or earthy limestone in fine granular dolomitic matrix; few scattered crinoid fragments, horn corals common; few small patches of anhydrite.
3289—3297	Limestone, light grey, earthy; appears fine fragmental when wet.
3297—3302.5	Dolomite, calcareous, light grey, slightly argillaceous, microgranular to microsaccharoidal; increasingly calcareous towards base.
3302.5—3309	Limestone, light grey, finely crystalline granular, fossiliferous.
3309—3316	Limestone, light grey, dense to slightly granular; good medium vuggy porosity in upper part; some stylolites; patchy anhydrite.
3316—3319	Limestone, light grey, dolomitic; microgranular to microsaccharoidal.
3319—3321	Limestone, very light buff to white, dense; few patches of anhydrite; slightly fractured, with brown dolomite infilling or alteration.

WELL NO. 42

Baysel Calstan Boissevain 3-20-3-19

MISSISSIPPIAN

Lodgepole Formation

SCALLION MEMBER

2478—2515	Limestone, predominantly finely crystalline; abundant chert nodules. Section varies from light buff to faintly mottled greenish grey/purplish limestone, to dark brownish red argillaceous limestone; crinoid fragments are scattered throughout; numerous bands and irregular lenses of "clean" fragmental limestone occur in the shalier beds; stylolitic partings common throughout. Grades to:
2515—2523.5	Limestone, massive, tight; some fine irregular banding; shades of pale grey to red; reddish beds moderately argillaceous; few scattered crinoid fragments; stylolitic partings common towards base.
2523.5—2524	Shale, grey, slightly calcareous, massive; fair thin irregular banding; faint brecciated appearance.
2524—2536	Limestone, extremely fossiliferous, "reefy" appearance; abundant brachiopods and bryozoa, and some corals. Fossils are not comminuted and appear to be, at least in part, in growth positions; extremely good porosity in fossiliferous beds (D.S.T. 1665' salt water). Towards the base fossil content decreases and unit becomes tight and slightly argillaceous; grades to:
2536—2541	Limestone, light grey, microgranular, slightly argillaceous; few to abundant scattered crinoid fragments; tight.

Note: the bottom of this core is at the base of the Scallion limestone, and is underlain by 10-20 feet of Routledge shale. It is possible that the 6-inch shale bed is related to the Routledge shale, and the "reefy" limestone may be genetically related to the formation of the Routledge shale.

WELL NO. 53

Rio Prado Souris Gibson 2-14 (2-14-3-28)

JURASSIC

Amaranth Red Beds

3130—42	Red beds, siltstone, dark reddish brown, argillaceous, dolomitic, micaceous; scattered inclusions of anhydrite; abundant rounded frosted sand grains towards the base.

MISSISSIPPIAN

Mission Canyon Formation

MC-3 MEMBER

3142—3159.5	Dolomite, medium light yellowish brown, fine to medium crystalline, tight; shot with abundant bands and stringers of white crystalline anhydrite.
3159.5—3161	Dolomite, light yellowish grey, microgranular to microsaccharoidal; scattered light brown crystals of anhydrite are common; good oil stain in upper 2 inches.
3161—3163	Dolomite, fine to medium crystalline, light yellowish brown.
3163—3166.2	Anhydrite (80%) and red argillaceous dolomite; brecciated appearance with the dolomite as interstitial material between large irregular inclusions or fragments of anhydrite.
3166.2—3167.7	Dolomite, medium light grey buff, earthy to dense, slightly argillaceous.
3167.7—3172.1	Anhydrite breccia with red argillaceous dolomite matrix as above.
3172.1—3173.6	Limestone, light grey, fine-grained calcarenite; some brown secondary crystals of anhydrite.
3173.6—3179	Dolomite, finely crystalline, tight; large irregular inclusions or fragments of clear crystalline anhydrite are abundant in the lower part of the unit.
3179—3180.6	Dolomite, light grey, microcrystalline to microsaccharoidal; scattered patches of anhydrite.
3180.6—3181.2	Limestone, medium to fine-grained oolite or calcarenite.
3181.2—3182.1	Dolomite, light grey, microsaccharoidal; good intergranular to fine vuggy porosity.
3182.1—3189	Limestone, algal-oolitic, light buff; fairly tight to extremely porous in lower part, in part dense with no remnant oolite texture; some patchy anhydrite.

WELL NO. 66

Souris Valley et al McInnes 8-20-4-25

MISSISSIPPIAN

Mission Canyon Formation

MC-1 MEMBER

2640—2645	Dolomite, pale yellowish brown, finely crystalline, faint relict fragmental texture; few patches and veinlets of anhydrite; few chert nodules.

Lodgepole Formation

2645—2655	Dolomite; some chert and anhydrite (secondary); several bands greenish grey dense argillaceous limestone with irregular reddish mottling.
2655—2658.5	Limestone, pale greenish grey with reddish motting, dense to microgranular; some patches of anhydrite.
2658.5—2720	Limestone, variable, few dense beds of dolomite near the top; consists of interbedded dense argillaceous limestone grading to calcareous shale in part, and medium-to coarse-grained crinoidal fossiliferous limestone. Bright red hematitic partings are common separating the different lithologic types. The argillaceous limestones, which comprise about 70% of the unit are medium grey to purplish and reddish grey, mottled in part. The crinoidal limestones are pale yellowish grey to brown, mostly tight to some slight intergranular porosity, partly silicified. Several bands of calcareous chert are present. Crinoidal beds are up to 4 inches thick.
2720—2729	Predominantly fine fragmental limestone, grading to coarse fragmental in part; some mottled argillaceous limestone as above.
2729—2731	Coarse crinoidal limestone.
2731—2764	Limestone, predominantly medium-to fine-grained, crinoidal, fossiliferous; few thin beds dense argillaceous limestone as above; few red shale partings; few bands of chert and silicified limestone; minor anhydrite as fracture fillings (2745—50).
2764—2774	Limestone, as above, but purplish to reddish grey mottled argillaceous limestone predominant.
2774—2795	Limestone, mostly fine fragmental, pale grey to yellowish brown; considerable medium to coarse crinoidal limestone; few thin mottled argillaceous bands.
2795—2805	Limestone predominantly medium to coarse crinoidal; few shaly beds; several prominent vertical fractures sealed with anhydrite; trace chert; fair vuggy porosity.
2805—2820	Limestone, fine fragmental to finely crystalline granular, slightly argillaceous.

WELL NO. 157

Cruickshank 14-4 (14-4-10-28)

MISSISSIPPIAN

Lodgepole Formation

2380—2405	Breccia zone. Brecciated dolomite, medium to light yellowish brown, finely crystalline to granular; patchy oil stain, becoming more prominent towards the base; abundant anhydrite, coarsely crystalline. Matrix is reddish brown dolomitic shale containing few coarse rounded frosted sand grains. Matrix and anhydrite are related to overlying Amaranth Red Beds, and breccia zone could be included in basal part of the Amaranth. Grades to
2405—2436	Dolomite, pale yellowish-brown, oil-stained, finely crystalline to microgranular, massive; much anhydrite in bands up to 6 inches wide, and as fracture fillings; much white to brownish grey chert; several thin beds of greenish-grey and purplish red mottled, slightly argillaceous limestone, and a few red shale partings; slight pinpoint and intergranular porosity; few scattered crinoid and brachiopod fragments in upper part.
2436—2436.7	Dolomite, fossiliferous fragmental (crinoidal), highly silicified, light purplish red.
2436.7—2437	Anhydrite.

UPPER DALY MEMBER

2437—2444	Dolomite, argillaceous, pale greenish to reddish grey with dark reddish mottling; fairly well banded and slightly fissile, red shale partings common; very finely crystalline to earthy; sparsely fossiliferous; minor anhydrite and yellowish brown dolomite as above.
2444—2450.5	Limestone, mostly reddish grey with some green and purplish red mottling, and a few red shaly partings; slight patchy oil stain especially along fractures; fine to medium crystalline; minor white chert.
2450.5—2452.2	Limestone, oil-stained, finely crystalline to saccharoidal; abundant worm-like markings.
2452.2—2457	Limestone, slightly argillaceous, reddish grey to slightly greenish mottled, finely crystalline; much pinkish calcareous chert in bands up to 4 inches thick.
2457—2463.5	Limestone, mostly oil-stained, finely saccharoidal to microgranular, scattered chert nodules, slightly fossiliferous.

MIDDLE DALY MEMBER (FIRST CRINOIDAL MARKER)

2463.5—2468.5	Limestone, crinoidal, fossiliferous; grades to finely saccharoidal in part; slight patchy oil stain; some silicified limestone and fossil fragments; some mottled limestone as above.
2468.5—2481	Limestone, good oil stain, finely saccharoidal with a few scattered crinoid fragments, good intergranular porosity, abundant chert nodules; few thin red shaly bands near the top, and few thin bands of anhydrite.

LOWER DALY MEMBER

2481—2488	Dolomitic limestone similar to above; anhydrite common as bands up to several inches wide; some red shaly partings and minor chert.

CRUICKSHANK SHALE FACIES

2488—2496	Dolomitic limestone, crinoidal, yellowish brown to reddish grey, patchy oil stain; several bands of anhydrite. Beds of mottled purplish and greenish grey argillaceous limestone are common, and contain abundant bryozoan fragments; less dolomitic towards base.
2496—2506	Dolomitic limestone, slightly argillaceous, mottled and streaked purplish red and greenish grey, finely saccharoidal to microgranular; abundant bryozoa and crinoid fragments; numerous thin bands and patches of anhydrite; several patches coarsely recrystallized limestone.

CRUICKSHANK CRINOIDAL FACIES

2506—2512	Limestone, coarse crinoidal, strongly oil-stained, fair intergranular porosity.
2512—2518.5	Limestone, slightly dolomitic, light to medium yellowish brown, patchy oil stain, finely saccharoidal to microgranular; numerous beds of silicified limestone; few small stringers of anhydrite; fair vuggy porosity.
2518.5—2526.5	Crinoidal limestone, oil-stained; crinoid fragments in finely crystalline to saccharoidal matrix; grades to fine saccharoidal limestone in part; several thin beds of chert and silicified limestone.
2526.5—2534	Limestone, fine saccharoidal to crystalline; scattered crinoid and brachiopod fragments; oil-stained.
2534—2548	Crinoidal limestone, coarse-grained, good intergranular porosity, heavily oil-stained.
2548—2589	Interbedded finely crystalline to saccharoidal limestone and crinoidal limestone, as above; mostly oil-stained; few thin shaly beds; some chert nodules and silicified limestone.

CROMER SHALE FACIES

2589—2620	Limestone, slightly argillaceous, mottled shades of purplish red and greenish grey, microgranular to earthy; slight vuggy porosity in a few bands but no oil stain; several thin beds of finely crystalline yellowish brown limestone and crinoidal limestone; few cherty bands.
2620—2656	Limestone, very argillaceous, shades of medium greyish red, mottled in part; scattered crinoid fragments; chert bands and nodules common.

BASAL LIMESTONE FACIES

2620—2696	Cherty limestone, mostly coarsely mottled purplish-red and greenish-grey, slightly argillaceous; abundant chert as white and grey nodules; few thin beds of silicified limestone; few thin beds crinoidal to finely crystalline limestone; scattered crinoid fragments.

Bakken Formation

2696—2701	Shale, medium dark grey to brownish, slightly fissile to subconchoidal fracture, abundant conodants (Recovery 1'). Note: Intervals estimated from electric logs, 9 feet of core missing in interval 2695—2727.
2701—2703.5	Dolomite, argillaceous, slightly calcareous, massive, dense to microgranular; pale to medium greyish red with irregular greenish grey reduction patches; abundant fine black thread-like markings; slightly silty.
2703.5—2704.8	Dolomite, calcareous, argillaceous, pale greenish grey, massive, finely saccharoidal to microgranular.
2704.8—2708.2	Dolomite, silty, argillaceous, grading to dolomitic siltstone in part, finely laminated; pale yellowish grey and brown at top grading downward to reddish and purplish grey, and light grey at base.

DEVONIAN

Lyleton Formation

2708.2—2710.4	Shale, dolomitic, purplish to reddish grey, irregular fine banding, fissile at top.
2710.4—2711.4	Thinly interbedded pale yellowish brown finely saccharoidal dolomitic limestone, and smooth green shale; slightly silty.
2711.4—2727	Shale, slightly dolomitic; predominantly greyish red to purplish with some round greenish grey reduction patches; few interbeds of green dolomitic shale and reddish brown dolomitic limestone.

WELL NO. 169

Calstan Scallion Prov. 5-11-11-126

MISSISSIPPIAN

Lodgepole Formation

LOWER WHITEWATER LAKE

1965—1972	Limestone, medium to dark greyish red, argillaceous, fine granular to saccharoidal; several beds fossiliferous fragmental, crinoidal limestone up to 4 inches thick. Grades to:

UPPER VIRDEN

1972—1984.8	Limestone, crinoidal, pale yellowish brown, oil-stained, good fine intergranular porosity, few stylolites, few green shaly partings, fossiliferous. Grades to finely crystalline in some beds. Much white to grey chert in lower part of unit, as bands up to 4 inches thick; some partly silicified limestone; trace anhydrite. Grades to:
1984.8—1986.8	Limestone, greenish grey to slightly mottled purplish; fine fragmental at top grading to finely crystalline with few scattered crinoid fragments; green shaly partings common.
1986.8—1989	Oolitic limestone, pale yellowish brown, oil-stained; fair intergranular porosity grading to tight in part.

LOWER VIRDEN

1989—1991	Limestone, argillaceous, massive, tight; greenish grey with purplish mottling at top, grading to reddish grey; finely granular; fossiliferous.
1991—1995.4	Limestone, argillaceous, purplish red to greenish grey banded and mottled; abundant patches and bands of fragmental limestone towards base; minor chert.
1995.4—2000	Limestone, massive, pale yellowish brown, slightly oil-stained; finely crystalline at top grading to fragmental crinoidal limestone at base; trace white chert.
2000—2003.1	Oolitic limestone, oil-stained; good intergranular porosity except in upper 6 inches; somewhat crinoidal towards base.
2003.1—2005	Limestone, argillaceous, light grey to reddish, mottled in part, finely crystalline.
2005—2005.8	Limestone, light grey, fine fragmental, tight, red and grey shaly partings common.
2005.8—2009.8	Oolitic limestone, oil-stained, fair intergranular porosity, grading to predominantly crinoidal at base.
2009.8—2010.4	Limestone, argillaceous, light grey to reddish, finely crystalline.
2010.4—2013.7	Oolitic limestone, crinoidal in upper part, fair porosity.
2013.7—2014.6	Limestone, somewhat argillaceous, pale grey to reddish mottled, finely crystalline, scattered crinoid fragments; several red shaly partings.
2014.6—2015	Oolitic limestone (out of place?).
2015—2019	Limestone; interbedded light grey to reddish mottled finely crystalline limestone and greyish red argillaceous limestone, moderately fissile; fossiliferous with fossils partly silicified.
2019—2024	Limestone, pale yellowish brown, oil-stained, finely crystalline with scattered crinoid fragments, somewhat granular; trace pinpoint to vuggy porosity; several stylolites.
2024—2026.5	Limestone, coarse crinoidal, oil-stained, fair vuggy to intergranular porosity.
2026.5—2028	Limestone, pale grey, finely crystalline to partly fragmental, slight reddish mottling, numerous shaly partings, tight.

SCALLION MEMBER

2028—2036	Limestone, oil-stained, finely crystalline to fragmental, few irregular white chert nodules, patchy oil stain.
2036—2041	Limestone, mottled purplish red to greenish grey, finely crystalline with scattered crinoid fragments; fossiliferous with fossils partly silicified; trace oil stain.
2041—2081	Limestone, pale yellowish brown, patchy oil stain decreasing towards base, finely crystalline granular to subsaccharoidal, scattered crinoid fragments; several bands of greenish grey to purplish mottled limestone, slightly argillaceous; few irregular chert nodules, becoming common towards base; considerable vertical fracturing sealed by anhydrite. Base of oil staining—2081.
2081—2228	Limestone with abundant nodular chert forming up to 30 per cent of the unit. Limestone is predominantly fine grained crystalline to somewhat granular or earthy; scattered crinoid fragments and few thin beds of crinoidal limestone. Colour is variable, mostly light grey-buff and reddish to purplish grey, mottled. Darker beds are slightly to moderately argillaceous. No definite lithologic units.

Bakken Formation

2228—2239	Shale, black to dark silvery grey, massive, smooth conchoidal fracture, fossiliferous (conodonts and brachiopods). (May include some Routledge shale equivalent.)
2239—2249	Siltstone, dolomitic, argillaceous, massive, pale to medium grey and reddish grey; black hair-like markings abundant in the upper part.
2249—2253	Siltstone to fine sandstone, slightly coarser grained than above, light greenish grey, dolomitic; several beds of light green, dense, argillaceous dolomite.
2253—2262	Siltstone to fine sandstone, dark grey to red, finely laminated, argillaceous, dolomitic.

DEVONIAN

Lyleton Formation

2262—2267	Shale, dark grey to slightly purplish, massive; could be lower Bakken?
2267—2271	Dolomite, highly argillaceous, medium grey to reddish; some green shaly beds; massive to slightly brecciated in appearance.
2271—2275	Breccia fragments of light grey dolomite in dark grey shale matrix; some bright green shale; slickensides; pyrite.
2275—2276	Dolomite, light to medium grey containing many small fragments of dark grey shale; grades to breccia at base.
2276—2280	Shale, dark grey to reddish grey, massive, non-calcareous, greenish "reduction" patches near the top; thin breccia zone in middle of unit consists of dolomite and dark grey and green shale, as above. Grades to:
2280—2294	Shale, bright red, dolomitic, grading to argillaceous dolomite in part. Structure varies from massive to very finely contorted or brecciated in appearance; several thin beds of grey dolomite, and several green shale partings; a few beds show fine lamination; several patches of anhydrite at the base.

Nisku Formation

2294—	Limestone, white to buff, massive, dense; several bands of anhydrite. Note: It is possible that some of the core from the Scallion 5-11 was mixed up prior to examination. The writer did not attempt to reorganize the core. The reported tops, which are probably accurate, are as follows:

Mississippian	1900
1st shale	1967
2nd shale	1991
1st oolite	2001
2nd oolite	2008.5
3rd oolite	2013
4th oolite	2022
Bakken	2228

WELL NO. 205

Homestead Birdtail 10-8 (10-8-15-27)

MISSISSIPPIAN

Lodgepole Formation

1564—1566	Dolomite, finely crystalline to dense, medium light grey to reddish in part; patchy vuggy porosity; somewhat brecciated appearance.
1566—1574	Dolomite, argillaceous, very fine earthy to dense texture, massive, few reddish patches, becoming less argillaceous towards the base; few calcareous bands; very siliceous.
1574—1579	Dolomite, light grey to slightly reddish, very siliceous; several thin beds crinoidal limestone; slight pinpoint porosity.
1579—1584	Dolomite, light grey, argillaceous, siliceous (possibly silty), massive.
1584—1589	Limestone, light grey-buff, medium crystalline, crinoidal, tight.
1589—1594	Limestone medium crinoidal, tight, few white cherty nodules; one thin bed silicified crinoidal limestone.
1594—1604	No core recovery.
1604—1609	Dolomite and chert, mottled white to light brownish grey. Dolomite is very saccharoidal, extremely porous (50%), with vuggy and intergranular porosity. Chert is white, soft, earthy and porous.
1609—1614	Dolomite and chert, porosity decreasing; much dolomite is finely crystalline to dense, tight; becomes calcareous towards base; abundant crinoid fragments.
1614—1616	Dolomite, finely crystalline to dense; patches coarse crinoidal limestone; very good fine vuggy porosity; much white earthy chert.
1616—1623	Limestone, light grey-buff, medium crinoidal, somewhat granular; several white cherty beds; mostly tight with few bands good fine vuggy porosity.
1623—1646	Dolomite, medium grey, finely crystalline to dense with scattered medium, crystalline "eyes"; very abundant white earthy chert in bottom 10 feet; excellent fine to medium vuggy porosity throughout (+ 50% in some beds).

Bakken Formation

1786—1789	Shale, medium grey (red streak), massive; trace red to yellowish mottling.
1789—1791	Dolomitic shale, medium red, massive, hard, dolomitic.
1791—1793	Dolomite, argillaceous, silty, medium greyish red to purplish grey.
1793—1801	Siltstone, dolomitic, argillaceous, becoming coarser grained and grading to fine sandstone towards base; mostly thin bedded and colour banded, fissile in part; variegated, shades of yellowish, reddish, and purplish grey.

DEVONIAN

Lyleton Formation

1801—1806	Argillaceous dolomite grading to dolomitic shale at base; predominantly red at top becoming mustard yellow and variegated towards base; irregular brecciated appearance; very slightly silty.

WELL NO. 213

Dome Birtle 16-17-17-27

MISSISSIPPIAN

Lodgepole Formation

1727—1752	Limestone and dolomitic limestone, very cherty (20-30%), slightly argillaceous, highly fossiliferous; porosity varies from slight to excellent; medium to coarse vuggy porosity due mainly to leaching of fossil fragments. The more porous beds are very dolomitic, and the less porous beds are calcareous with a few greenish grey shaly partings; 10 feet of core missing.

Bakken Formation

1811—1813	Sandstone and siltstone, fine-grained, dolomitic, slightly argillaceous, pale yellow to pale grey and reddish grey, massive; abundant hair-like veinlets, dark red, fringed with yellow; fossils replaced by hematite are common; grades to:
1813—1819.5	Fine sandstone and siltstone, medium reddish grey, faintly mottled and irregularly banded. Grain size increases towards base, grading to fine and medium sandstone in basal 8 inches; friable, poorly cemented.
1819.5—1821.5	Dolomite, argillaceous, silty, sandy, mottled reddish and yellowish grey; massive to slightly fine-bedded and banded near base; trace crossbedding; 2-inch breccia bed at base.

DEVONIAN

Lyleton Formation

1821.5—1836	Argillaceous dolomite grading to dolomitic shale at base, slightly silty; several thin breccia beds and few scattered breccia fragments; variegated, predominantly dusky reddish to purplish grey with some patches of yellowish and greenish grey, mottled; much colour leaching or reduction along fractures. Fine crossbedding is present in the uppermost part of the unit, in the more dolomitic beds.

WELL NO. 217

S.A.M. Victor No. 1 (6-29-17-29)

MISSISSIPPIAN

Lodgepole Formation

1617—1617.2	Limestone, finely crystalline, pale reddish grey mottled.
1617.2—1618.5	Shale, calcareous, mottled shades of greyish to purplish red.
1618.5—1618.7	Breccia light grey, earthy, argillaceous limestone fragments in red calcareous shale matrix.
1618.7—1619.5	Limestone, light grey, earthy, argillaceous, irregular brecciated appearance, glauconitic; abundant horn corals.
1619.5—1638	Limestone, pale grey to slightly pinkish and greenish; finely crystalline with abundant scattered crinoid fragments; grades to crinoidal limestone in part. Thin, irregular greenish shaly partings are common throughout and give nodular, mottled appearance. Slight patchy coarse vuggy porosity; no oil stain. Few white chert inclusions. Pyrite inclusions common in basal 1 foot. Sharp contact with:

Bakken Formation

1638—1638.5	Shale, pale greenish grey, massive, non-calcareous, grades to:
1638.5—1642.5	Shale, medium grey, slight purplish and reddish grey mottling and fine banding.
1642.5—1647.5	Shale, slightly calcareous, medium dark grey to brownish grey, shows fine banding in part, massive; fossiliferous-conodonts, plant fragments, brachiopod fragments; few irregular hematite inclusions; grades to:
1647.5—1672	Siltstone, grading to fine sandstone towards base, pale greenish grey, massive, irregular fine banding, argillaceous, dolomitic, friable and poorly cemented; strong oil stain in thin, coarse-grained beds up to 1 inch thick (approx. 5% of unit); considerable pyrite as fine disseminated nodules and veinlets.

Appendix III

WELL DATA

1. Sections in Canada are numbered 1 to 36 beginning in the southeast corner of a township. Legal subdivisions are numbered 1 to 16 beginning in the southeast corner of a section. In the present report all locations, unless otherwise specified, are west of the principal meridian. Legal subdivision 1, section 21, township 1, range 19, for example, is designated 6-21-1-19.
2. K. B. refers to the elevation of the Kelly bushing; the tops of the lithologic units are given as depths below K. B. Tops have been chosen from electric logs and samples or core where these were available.
3. Blank spaces in the list of tops indicate that, due to pre-Jurassic erosion, the units are missing; dashes indicate that the well did not penetrate deep enough to intersect the particular units.

Well No.	WELL NAME	Location	K.B.	Red Beds	Charles	MC-3	MC-2	MC-1	Upper Lodgepole	Lower Lodgepole	Bakken	Lyleton (?)
1	CLEARY CALSTAN PROV. 6-21	6-21-1-19	2154	2932	—	—	(Routledge 3118)		—	3070	3205	3236
2	AMERADA TURTLE MTN. PROV. "M-A" 16-4-1-20	16-4-1-20	2211	3097	—	—	(Routledge 3412)		—	3217	3507	3544
3	HOMESTEAD et al TURTLE MOUNTAIN No. 1	10-26-1-20	2247	3075	—	—	(Routledge 3330)		—	3200	3420	3448
4	CITIES SERVICE EAST MAX LAKE No. 1	14-29-1-20	2233	3097	—	—	(Routledge 3400)		—	3220	3480	3520
5	ROYALITE TRIAD et al LULU LAKE No. 1	16-14-1-21	2296	3210	—	—	—	—	3296	3338	3658	3683
6	ROYALITE TRIAD et al MAX LAKE No. 1	4-36-1-21	2287	3170	—	—	—	—	3273	3283	3600	3630
7	BAYSEL CALSTAN SHARPE LAKE 3-27-1-22	3-27-1-22	2183	3210	—	—	—	—	3300	3460	3790	—
8	CLEARY FLOSSIE LAKE 10-21	10-21-1-23	2151	3266	—	—	—	3353	3392	3639	3963	3985
9	SOURIS VALLEY et al MEGGISON 10-14-1-25	10-14-1-25	1566	2840	—	—	2964	2997	3155	—	—	—
10	IMPERIAL CALSTAN HERNEFIELD 1-30-1-25	1-30-1-25	1551	2890	—	—	—	3004	3110	3389	3670	3730
11	ANGLO EX DANDO 3-32-1-25	3-32-1-25	1554	2887	3000	3019	3053	3086	3243	3518	3807	3834
12	ANGLO EX SOURIS VALLEY SMART 4-1-1-26	4-1-1-26	1527	2953	3078	3119	3236	3280	3408	—	—	—
13	CALSTAN WASKADA 9-13-1-26	9-13-1-26	1534	2915	—	—	3020	3029	3175	3457	3755	3818
14	CALSTAN WASKADA 16-13-1-26	16-13-1-26	1543	2902	—	—	—	3013	3164	3441	3728	3785
15	SOURIS VALLEY et al PROV. 16-18-1-26	16-18-1-26	1428	2910	3044	3068	3165	3182	3330	—	—	—
16	TEXACO McCOLL COULTERVALE A3-2	3-2-1-27	1488	3050	3198	3302	3403	3432	—	—	—	—
17	E. DONNLEY 1-3	1-3-1-27	1495	3100	3250	3375	3485	3515	—	—	—	—
18	SOURIS VALLEY DOWNEY 11-9-1-27	11-9-1-27	1496	3100	3214	3236	3342	3386	3529	3836	4100	4116
19	GLCC et al COULTER PROV. 16-16-1-27	16-16-1-27	1497	3066	—	3195	3305	3345 (?)	3484	3775	4055	4070
20	SOURIS VALLEY MOORE 5-20-1-27	5-20-1-27	1491	3075	3202	3218	3331	3388	3512	3814	4073	4087
21	SOURIS VALLEY McKAGUE 2-27-1-27	2-27-1-27	1497	3020	3129	3222	3332	—	—	—	—	—
22	KODIAK DUNNING No. 1	16-28-1-27	1498	3045	3160	3178	3275	3320	3444	3742	—	—
23	CLEARY SOURIS VALLEY MOORE 11-13	11-13-1-28	1481	3100	3228	3260	3375	3410 (?)	3547	3853	4124	4145
24	SOURIS VALLEY WHITE 5-14-1-28	5-14-1-28	1494	3180	3304	3355	3459	3520	3630	3952	4212	4240
25	RIO PRADO SOURIS FENTON 5-17	5-17-1-28	1519	3246	3384	3408	3545	3557 (?)	3718	—	—	—
26	CLEARY SOURIS VALLEY HALLAM 15-5	15-5-1-29	1574	3393	3524	3640	3750	3764 (?)	3937	—	—	—
27	POPLAR GAS EX ADMIRAL ANTLER No. 1	8-15-1-29	1538	3328	3463	3494	3644	3653	—	—	—	—
28	IMPERIAL COPLEY 11-18-1-29	11-16-1-29	1574	3400	3560	3630	3750	3762	—	—	—	—
29	CLEARY SOURIS VALLEY WHITE 5-34	5-34-1-29	1590	3274	—	3427	3560	3577	3745	—	—	—
30	DOME HOLMFIELD 13-5-2-15	13-5-2-15	1581	1853	—	—	—	—	—	1862	1975	1995
31	JUMPING POUND-PROSPECT-HIGH CREST et al HORTON 8-15	8-15-2-20	1914	2702	—	—	—	—	—	2798	3012	3030
32	OWEN No. 1	8-11-2-22	2124	3078	—	—	—	—	3180	3231	3582	—
33	CALSTAN DELORAINE 10-31-2-23	10-31-2-23	1646	2640	—	—	—	2700	2753	—	—	—
34	CALSTAN IMPERIAL DALNY 8-10-2-26	8-10-2-26	1533	2895	3026	3093	3128	3169	3294	—	—	—
35	J. P. OWEN NORTH COULTER 5-32	5-32-2-26	1490	2883	—	—	2995	3018	3167	3450	3700	—
36	ANGLO EX GOULD 3-14-2-27	3-14-2-27	1494	2968	—	3080	3116	3140	3298	—	—	—
37	SOURIS VALLEY et al SHARP 2-18-2-27	2-16-2-27	1502	3034	—	3162	3245	3255	3428	3714	3970	—
38	CALSTAN IMPERIAL SOUTH ELVA 13-30-2-27	13-30-2-27	1499	3000	—	3128	3172	3185	3345	—	—	—
39	RIO PRADO SOURIS HILL 16-9	16-9-2-28	1514	3110	3241	3252	3355	3372	3540	—	—	—
40	SOURIS VALLEY et al SHANNON 1-22-2-28	1-22-2-28	1506	3065	—	3198	3305	3320	3486	—	—	—
41	CALSTAN PIERSON PROV. 2-29-2-29	2-29-2-29	1578	3268	—	3365	3471	3488 (?)	3656	3995	4196	4220
42	BAYSEL CALSTAN BOISSEVAIN 3-20-3-19	3-20-3-19	1689	2346	—	(Routledge 2538)		—	—	2384	2560	2575
43	DOME NACO SOUTH WHITEWATER 2-2-3-21	2-2-3-21	1778	2592	—	—	—	—	2676	2688	2934	—
44	CALSTAN WHITEWATER 11-16-3-21	11-16-3-21	1661	2456	—	—	—	—	2510	2560	2868	2890
45	J. P. OWEN ELLIS 3-10-3-22	3-10-3-22	1849	2560	—	—	—	—	2648	2726	3053	3071

Well No.	WELL NAME	Location	K.B.	Red Beds	Charles	MC-3	MC-2	MC-1	Upper Lodgepole	Lower Lodgepole	Bakken	Lyleton (?)
46	CALSTAN WHITEWATER 15-36-3-22	15-36-3-22	1638	2440	—	—	—	—	2494	2522	2843	2866
47	CALSTAN IMPERIAL NORTH GOODLANDS 16-9-3-24	16-9-3-24	1554	2660	—	—	—	2758	2816	—	—	—
48	DAKOTA CASSAN 5-23	5-23-3-24	1592	2611	—	—	—	2692	2716	2980	3290	3313
49	SOURIS VALLEY et al McKEE 1-15-3-25	1-15-3-25	1554	2696	—	—	—	2792	2875	—	—	—
50	CLEARY McCALLUM 4-32	4-32-3-26	1455	2705	—	—	—	2823	2943	3220	3475	(?)
51	ANGLO EX SKELTON 14-4-3-27	14-4-3-27	1486	2930	—	3048	3080	3094	3250	—	—	—
52	CLEARY SOURIS VALLEY INNES 4-17	4-17-3-27	1526	2959	—	3073	3080	3101	3262	—	—	—
53	RIO PRADO SOURIS GIBSON 2-14	2-14-3-28	1529	3023	—	3142	3163	3182	3346	—	—	—
54	IMPERIAL EDWARD 4-16-3-28	4-16-3-28	1544	3070	—	3192	3252	3266	—	—	—	—
55	TEXACO McCOLL GRAHAM CREEK A4-29	4-29-3-28	1553	3068	—	3183	3208	3224	—	—	—	—
56	IMPERIAL PIERSON 13-2-3-29	13-2-3-29	1562	3160	—	3285	3348	3362	3540	—	—	—
57	SOURIS VALLEY et al WICKS 1-8-3-29	1-8-3-29	1588	3218	—	3350	3428	3443	3612	—	—	—
58	IMPERIAL CANADIAN SUPERIOR PIERSON 8-26-3-29	8-26-3-29	1567	3094	—	3214	3245	3254	3413	—	—	—
59	CEGO CAYUGA 13-31-3-29	13-31-3-29	1635	3210	—	3326	3348	3358	3548	—	—	—
60	OROCO BOISSEVAIN 3-1	3-1-4-19	1659	2208 (?)	—	—	—	—	—	2210	2350	2358
61	WESTERN ORTHEZ 13-36	13-36-4-19	1628	2056	—	—	—	—	—	2070	2241	2270
62	CALSTAN SOUTH REGENT 6-7-4-21	6-7-4-21	1647	2426	—	—	—	—	2472	2478	2797	2810
63	B.A. UNION CROLL 4-13-4-21	4-13-4-21	1646	2353	—	—	—	—	—	2440	2646	2660
64	DOME COX WHITEWATER LAKE 4-4-4-22	4-4-4-22	3060	2510	—	—	—	—	2598	2640	2957	2973
65	CALSTAN IMPERIAL NAPINKA 2-7-4-25	2-7-4-25	1483	2605	—	—	—	2717	2768	—	—	—
66	SOURIS VALLEY et al McINNES 8-20-4-25	8-20-4-25	1471	2525	—	—	—	2634	2650	2920 (?)	3182	3205
67	IMPERIAL WEST BRENDA 13-17-4-26	13-17-4-26	1489	2682	—	—	—	2804	2930	3202	3452	3475
68	ANGLO EX COATES 13-20-4-27	13-20-4-27	1505	2822	—	—	—	2920	3042	—	—	—
69	J. P. OWEN BRODIE 1-11-4-29	1-11-4-29	1576	3037	—	—	—	3161	3318	3635	3849	3860
70	IMPERIAL CALSTAN EUNOLA 4-28-4-29	4-28-4-29	1616	3098	—	—	—	3222	3358	3709	3878	3897
71	U.S. SMELTING 3-30 DRAPER	3-30-5-21	1563	2191	—	—	—	—	—	2202	2502	2515
72	IMPERIAL UNDERHILL 4-8-5-22	4-8-5-22	1633	2395	—	—	—	—	2443	2470	2772	2788
73	SOURIS VALLEY WARNEZ 5-13-5-22	5-13-5-22	1635	2320	—	—	—	—	2334	2347	2654	2671
74	IMPERIAL CANADIAN SUPERIOR ARGUE 15-13-5-23	15-13-5-23	1589	2350	—	—	—	—	2390	2428	2723	2735
75	IMPERIAL CANADIAN SUPERIOR ARGUE 5-33-5-23	5-33-5-23	1456	2193	—	—	—	—	2272	2395	2688	2711
76	MADISON LAUDER 1-19	1-19-5-24	1444	Missing	—	—	—	—	2077 (?)	(?)	2625 (?)	2645
77	ROYALITE TRIAD et al EAST HARTNEY No. 1	7-27-5-24	1453	2012	—	—	—	—	2070	2170	2478	2496
78	CALSTAN HARTNEY 16-33-5-24	16-33-5-24	1420	(?)	—		(Mississippian Missing)		—	—	—	—
79	CALSTAN LAUDER 9-14-5-25	9-14-5-25	1444	2280	—	—	—	—	2373	2617	2893	2918
80	SAPPHIRE BERNICE No. 1	10-18-5-25	1439	2432	—	—	—	—	2530	2750	3012	—
81	CALSTAN IMPERIAL RUTH 1-17-5-26	1-17-5-26	1454	2572	—	—	—	2694	2717	—	—	—
82	DOME COX NORTH BROOMHILL 5-31-5-27	5-31-5-27	1528	2730	—	—	—	2840	2890	3163	3400	3420
83	WIDNEY CAN. SUP. BROOMHILL No. 1	3-3-5-28	1544	2840	—	—	—	2940	3084	3384	3613	3635
84	CLEARY WILSON 15-22	15-22-5-28	1531	2795	—	—	—	2877	2970	—	—	—
85	TILSTON A No. 1	5-12-5-29	1585	2952	—	—	—	3052	3174	3478	3695	3705
86	CLEARY ROWBOTTOM et al 3-19	3-19-5-29	1667	3073	—	—	—	3148	3202	3570	3720	3744
87	McCARTY & COLEMAN DOBSON 6-4	6-4-6-20	1570	2078	—	—	—	—	—	2110	2252	2275
88	McCARTY & COLEMAN SANDS 2-13	2-13-6-20	1543	1946	—	—	—	—	—	1953	2112	2140
89	McCARTY & COLEMAN MOFFAT 16-3	16-3-6-21	1529	2092	—	—	—	—	—	2143	2302	2318

Well No.	WELL NAME	Location	K.B.	Red Beds	Charles	MC-3	MC-2	MC-1	Upper Lodgepole	Lower Lodgepole	Bakken	Lyleton (?)
90	McCARTY & COLEMAN FORBES 1-31	1-31-6-22	1442	2018	—	—	—	—	2027	2035	2320	2345
91	McCARTY & COLEMAN MORRICE 12-28	12-28-6-23	1420	2072	—	—	—	—	2088	2128	2418	2430
92	U.S. SMELTING 1-35 ALSTON	1-35-6-23	1430	2022	—	—	—	—	2029	2055	2342	2370
93	SAPPHIRE EAST GRANDE CLAIRIERE No. 1	14-16-6-24	1429	2207	—	—	—	—	2268	2362	2646	2668
94	REALITY DOMINION MINERALS SUPERIOR PIPESTONE No. 1	6-16-6-25	1426	2293	—	—	—	—	2385	2582	2848	2870
95	AMERADA CLAIRIERE PROV. "M-B" 15-27-6-25	15-27-6-25	1434	2234	—	—	—	2311	2326	2572	2853	2870
96	SAPPHIRE SOUTH PIPESTONE No. 1	12-24-6-26	1431	2347	—	—	—	—	2408	2638	2890	2905
97	CALSTAN RESTON 7-27-6-27	7-27-6-27	1483	2540	—	—	—	—	2642	2850	3082	3108
98	SHELL RESTON 14-29-6-27	14-29-6-27	1527	2610	—	—	—	—	2723	—	—	—
99	PERRY FULK 6-36-6-27	6-36-6-27	1486	2472	—	—	—	—	2576	2778	3014	3040
100	SOURIS VALLEY et al STONEY CREEK 2-17-6-28	2-17-6-28	1564	2820	—	—	—	2932	2965	3235	—	—
101	CALSTAN NORTH TILSTON 4-3-6-29	4-3-6-29	1645	2946	—	—	—	3068	3152	3473	3652	3682
102	DOME COX NORTH TILSTON 7-15-6-29	7-15-6-29	1628	2898	—	—	—	3017	3047	3350	3533	—
103	DOME NESBITT 11-19-7-18	11-19-7-18	1462	Missing	—	—	—	—	—	1640	1710	1738
104	McCARTY & COLEMAN JANZ 16-20	16-20-7-21	1438	1877	—	—	—	—	—	1890	2058	2080
105	SHELL CALSTAN DENBOW 12-29-7-22	12-29-7-22	1430	1963	—	—	—	—	—	2026	2183	2210
106	SOUTH DELEAU 2-11	2-11-7-24	1439	2088	—	—	—	—	2100	2188	2473	2492
107	DOME NACO PLUM LAKE 16-34-7-24	16-34-7-24	1428	1974	—	—	—	—	1981	2046	2322	2350
108	CALSTAN FINDLAY 9-26-7-25	9-26-7-25	1421	2140	—	—	—	—	2208	2285	2562	2578
109	NORTHERN RUSTIN 2-16	2-16-7-27	1511	2538	—	—	—	—	2633	2855	3072	3090
110	CALSTAN LINKLATER 10-21-7-28	10-21-7-28	1629	2662	—	—	—	—	2717	2872	3062	3084
111	NORTHERN WEST SINCLAIR 2-28	2-28-7-29	1724	2857	—	—	—	—	2932	3130	3290	3310
112	CAN. SUP. ROUNTHWAITE 10-17-8-17	10-17-6-17	1278	1430			Mississippian eroded....Devonian Duperow 1478					
113	CALSTAN WAWANESA 3-1-8-18	3-1-8-18	1364	Missing	—	—	—	—	—	1334	1446	1450
114	DOME HAYFIELD 12-22-8-20	12-22-8-20	1459	Missing	—	—	—	—	—	1680	1783	1810
115	SHELL CALSTAN DELEAU 8-19-8-23	8-19-8-23	1426	1980	—	—	—	—	—	2067	2194	2212
116	CALSTAN SOUTH RALSTON 5-34-8-23	5-34-8-23	1430	1926	—	—	—	—	—	2018	2078	2100
117	CALSTAN EAST OAK LAKE PROV. 11-28-8-24	11-28-8-24	1421	1895	—	—	—	—	1906	1930	2225	2245
118	AMERADA OAK LAKE PROV. "M-C" 2-12-8-25	2-12-8-25	1419	2072	—	—	—	—	2115	2190	2442	2460
119	CAN. DEV. OAK LAKE CPR 4-35-8-25	4-35-8-25	1420	2007	—	(Routledge 2358 (?))		—	2020	2077	2375 (?)	2394
120	DOME COX BELLEVIEW 16-1-8-26	16-1-8-26	1432	2280	—	—	—	—	2366	2428	2702	—
121	ROYALITE TRIAD et al SCARTH No. 1	14-19-8-26	1482	2300	—	—	—	—	2393	2495	2750	—
122	AGNEW 13-27	13-27-8-26	1426	2160	—	—	—	—	2223	2328	2592	2610
123	WEST AGNEW 14-1	14-1-8-27	1497	2365	—	—	—	—	2463	2560	2813	2830
124	B.A. UNION WOODNORTH SWD 9A-28-8-27	9-28-8-27	1544	2356	—	—	—	—	2422	2520	2755	2790
125	B.A. CDN. SUP. WOODNORTH 3-33-8-27	3-33-8-27	1550	2358	—	—	—	—	2418	2499	2748	2765
126	CALSTAN EWART PROV. 4-14-8-28	4-14-8-28	1611	2510	—	—	—	—	2532	2870 (?)	2884	2915
127	CALSTAN CROMER 8-27-8-28	8-27-8-28	1547	2435	—	—	—	—	2450	2570	2790	2812
128	CLEARY SCHMELTZ 6-36	6-36-8-28	1560	2402	—	—	—	—	2418	2555	2770	2792
129	DOME COX WEST EWART 12-15-8-29	12-15-8-29	1723	2748	—	—	—	—	2782	2950 (?)	3135	3160
130	DOME BRANDON 3-5-9-19	3-5-9-19	1374	1382	—	—	—	—	—	1389	1531	1565
131	McCARTY & COLEMAN OAK LAKE 13-6	13-6-9-24	1431	2000	—	(Routledge 2202)		—	—	2060	2276	2300
132	McCARTY & COLEMAN PLAISIER 4-24	4-24-9-25	1435	1965	—	(Routledge 2270)		—	1994	2055	2342	2370
133	CALSTAN ROUTLEDGE PROV. 13-29-9-25	13-29-9-25	1434	1976	—	(Routledge 2230)		—	1989	2033	2308	2335
134	McCARTY & COLEMAN DeGALLEY 12-35	12-35-9-25	1411	1962	—	(Routledge 2220)		—	2010	2014	2290	2317

Well No.	WELL NAME	Location	K.B.	Red Beds	Charles	MC-3	MC-2	MC-1	Upper Lodgepole	Lower Lodgepole	Bakken	Lyleton (?)
135	SOURIS VALLEY et al JEFFREY 1-22-9-26	1-22-9-26	1446	2046	—	(Routledge 2366)		—	2077	2186	2428	2450
136	B.A. HB SOUTH MAPLES 7-26-9-26	7-26-9-26	1447	2042	—	(Routledge 2338)		—	2082	2144	2402	2420
137	CALSTAN WOODNORTH PROV. 5-18-9-27	5-18-9-27	1598	2320	—	—	—	—	2330	2435	2652	2660
138	CAN DEV MITCHELL EAST DALY 10-32-9-27	10-32-9-27	1595	2312	—	—	—	—	2370	2522	2758	2770
139	CALSTAN EAST CROMER PROV. 13-14-9-28	13-14-9-28	1631	2409	—	—	—	—	2415	2505	2731	2752
140	CALSTAN DALY 1-30-9-28	1-30-9-28	1691	2520	—	—	—	—	2538	2670	2855	2876
141	MADISON EBOR 11-12	11-12-9-29	1704	2588	—	—	—	—	2597	2780	2952	2968
142	DOME COX HB EBOR 7-26-9-29	7-26-9-29	1696	2560	—	—	—	—	2570	2730	2898	2920
143	CALSTAN WEST BUTLER 1-31-9-29	1-31-9-29	1784	2659	—	—	—	—	2667	2830	2988	3010
144	PEACOCK EXPLORATION KEMNAY No. 1	13-4-10-20	1395	Missing	—	—	—	—	—	1490	1533	1550
145	DOME COX NORTH ROUTLEDGE 3-13-10-25	3-13-10-25	1215	1700	—	(Routledge 1856)		—	—	1746	1924	—
146	WELCH 12-18	12-18-10-25	1441	1955	—	(Routledge 2212)		—	1962	2018	2290	2308
147	IMPERIAL MAPLES SWD 2-8-10-26	2-8-10-26	1468	2038	—	—	—	—	2050	2168	2430	2448
148	CALSTAN SOUTH VIRDEN 1-12-10-26	1-12-10-26	1442	1959	—	(Routledge 2217)		—	1970	2118	2295	2310
149	WILLIAMS 12-14	12-14-10-26	1435	1929	—	(Routledge 2270)		—	1937	2007	2280	2295
150	CALSTAN VIRDEN 2-26-10-26	2-26-10-26	1451	1918	—	—	—	—	1922	1998	2258	2305
151	SKINNER 6-28	6-28-10-26	1486	2015	—	—	—	—	2042	2110	2384	2409
152	IMPERIAL COMPTON 5-3-10-27	5-3-10-27	1578	2265	—	—	—	—	2320	2507	2744	2760
153	BAY CANADIAN SUPERIOR HORN 4-12	4-12-10-27	1523	2169	—	—	—	—	2174	2237	2483	2500
154	CALSTAN DALY 15-18-10-27	15-18-10-27	1614	Missing	—	—	—	—	2190	2280	2505	2515
155	CALSTAN DALY 16-20-10-27	16-20-10-27	1601	2315	—	—	—	—	2353	2440 (?)	2648	2662
156	SOURIS VALLEY et al STUDER 1-24-10-27	1-24-10-27	1503	2105	—	—	—	—	2120	2220	2474	2490
157	CRUICKSHANK 14-4	14-4-10-28	1660	2377	—	—	—	—	2387	2488	2696	2711
158	SKELTON 1-10	1-10-10-28	1653	2345	—	—	—	—	2355	2420	2660	—
159	CALSTAN DALY 10-12-10-28	10-12-10-28	1629	2240	—	—	—	—	2257	2318	2550	2570
160	CALSTAN DALY 8-14-10-28	8-14-10-28	1636	2294	—	—	—	—	2305	2372 (?)	2594	2608
161	MADISON 4-31	4-31-10-26	1704	2412	—	—	—	—	2423	2527	2716	—
162	CALSTAN NORTH BUTLER PROV. 8-11-10-29	8-11-10-29	1718	2480	—	—	—	—	2500	2637 (?)	2802	2830
163	SAPPHIRE NORTH WEST BUTLER No. 1	4-16-10-29	1759	2565	—	—	—	—	2612	2745 (?)	2920	2950
164	HENDERSON BLUE CROWN CARPENTER No. 1	13-27-10-29	1741	2488	—	—	—	—	2495	2595 (?)	2772	—
165	CALSTAN IMPERIAL LENORE 2-20-11-24	2-20-11-24	1503	1887	—	(Routledge 1997 (?))		—	—	1992	2010	2040
166	BAYSEL HB ROSELEA 10-8-11-25	10-8-11-25	1343	Missing	—	(Routledge 1968)		—	1710	1730	—	—
167	SHELL LENORE 14-15-11-25	14-15-11-25	1473	1858	—	(Routledge 2112)		—	1867	1925	2192	2212
168	DOME COX WEST LENORE 2A-32-11-25	2-32-11-25	1469	1835	—	(Routledge 2110)		—	1840	1850	2130	—
169	CALSTAN SCALLION PROV. 5-11-11-26	5-11-11-26	1489	Missing	—	—	—	—	1900	1960	2228	2262
170	CALSTAN SOUTH HARMSWORTH 6-25-11-26	6-25-11-26	1486	Missing	—	(Routledge 2142 (?)		—	1830	1858	2150	2171
171	CAN. SUP. DOME et al WHITEFORD 8-28	8-28-11-26	1522	Missing	—	—	—	—	1884	1940	2218	2244
172	CALSTAN HARGRAVE 15-12-11-27	15-12-11-27	1561	Missing	—	—	—	—	2093	2155	2402	2418
173	BAYSEL CALSTAN HARGRAVE PROV. 15-16-11-27	15-18-11-27	1611	Missing	—	—	—	—	2120	2180	2408	2425
174	WEST CDN MILL CITY HARGRAVE 6-18-11-27	6-18-11-27	1638	2309	—	—	—	—	2330	2406	2628	—
175	McCARTY & COLEMAN FOSTER 3-24	3-24-11-27	1568	2072	—	—	—	—	2082	2154	2402	2420
176	SAPPHIRE NORTH DALY No. 1	11-2-11-28	1661	2360	—	—	—	—	2436	2530	2736	—
177	SAPPHIRE NORTH WEST DALY No. 1	9-5-11-28	1704	2417	—	—	—	—	2442	2553	2747	—
178	SAPPHIRE REAPER No. 1	12-36-11-28	1648	2220	—	—	—	—	2235	2355	2564	2588
179	CLEARY WOOD 16-3	16-3-11-29	1754	2483	—	—	—	—	2527	2633 (?)	2816	2843
180	CALSTAN ELKHORN 7A-8-11-29	7-8-11-29	1783	2393	—	—	—	—	2504	2588	2774	2810

Well No.	WELL NAME	Location	K.B.	Red Beds	Charles	MC-3	MC-2	MC-1	Upper Lodgepole	Lower Lodgepole	Bakken	Lyleton (?)
181	IMPERIAL BLOSSOM 3-17-12-24	3-17-12-24	1550	1852	—	(Routledge 1942 (?))		—	—	1930 (?)	1955	1982
182	SAPPHIRE WEST BLOSSOM No. 1	16-20-12-25	1515	1888	—	(Routledge 1967)		—	—	1902	1988	2002
183	EAST HARMSWORTH 5-1	5-1-12-26	1488	1820	—	—	—	—	1832	1894	2168	2192
184	DOME COX HARMSWORTH 1-10-12-26	1-10-12-26	1497	1833 (?)	—	—	—	—	1847	1888	2172	2194
185	DOME NACO TWO CREEKS 1-19-12-26	1-19-12-26	1546	Missing	—	—	—	—	1890	1957	2205	2318
186	CALSTAN HARMSWORTH PROV. 6A-24-12-26	6-24-12-26	1594	1785	—	—	—	—	1790	1822	2080	2107
187	DOME COX TWO CREEKS 4-32-12-26	4-32-12-26	1527	Missing	—	—	—	—	1850	1925	2192	2218
188	DOME COX SOUTH TWO CREEKS 4-12-12-27	4-12-12-27	1566	Missing	—	—	—	—	1920	1970	2223	2240
189	CALSTAN TWO CREEKS 9-22-12-27	9-22-12-27	1572	1786 (?)	—	—	—	—	1824	(?)	2114	2130
190	BASCO KANAGE 13-21	13-21-12-28	1639	2086	—	—	—	—	2091	2157	2350	2375
191	CALSTAN KIRKELLA 16-5-12-29	16-5-12-29	1745	2384	—	—	—	—	2394	2520	2703	—
192	SAPPHIRE KIRKELLA 14-12	14-12-12-29	1684	2258	—	—	—	—	2280	2395 (?)	2572	2607
193	CALSTAN KIRKELLA 5-21-12-29	5-21-12-29	1729	2283	—	—	—	—	2298	2382 (?)	2614	2660
194	PEACOCK EXPLORATION ARROW No. 1	15-20-13-25	1573	Missing	—	—	—	—	—	1794	1879	1913
195	DOME COX MINIOTA 12-28-13-26	12-28-13-26	1487	Missing	—	—	—	—	—	1788	1882	1893
196	ROYALITE TRIAD et al TWO CREEKS No. 1	2-3-13-27	1562	Missing	—	—	—	—	1800	1850	2090	—
197	SAPPHIRE WEST MINIOTA No. 1	4-20-13-27	1565	Missing	—	—	—	—	1757	1797	2009	2025
198	PEACOCK EXPLORATION WEST BURBANK 11-2	11-2-13-29	1663	Missing	—	—	—	—	2108	2195	2363	2400
199	MANSON TOWN SAPPHIRE HENDERSON No. 1	3-28-13-29	1673	Missing	—	—	—	—	2024	2100	2270	2298
200	DOME ARROW RIVER 12-10-14-25	12-10-14-25	1643	Missing	—	—	—	—	—	1830	1858	1865
201	CANADIAN OIL & GAS RESERVE et al UNO No. 1	15-10-14-27	1293	Missing	—	—	—	—	—	1433	1610	1622
202	J. P. OWEN POOLE MANSON 14-5-14-29	14-5-14-29	1678	Missing	—	—	—	—	2012	2067	2248	2272
203	SAPPHIRE WEST WILLEN No. 1	9-11-14-29	1631	Missing	—	—	—	—	1900	1922	2118	2138
204	PATHFINDER & ASSOC. MILNE 29-4	4-29-15-26	1637	Missing	—	—	—	—	—	1803	1848	1865
205	HOMESTEAD BIRDTAIL 10-8	10-8-15-27	1535	Missing	—	—	—	—	—	1556	1782	1805
206	HOMESTEAD LONG ISLAND BIRDTAIL No. 1	9-21-15-27	1540	Missing	—	—	—	—	—	1532	1698	1715
207	CALSTAN TREAT PROV. 15-29-15-28	15-29-15-28	1547	Missing	—	—	—	—	1572	1600	1795	1816
208	J. P. OWEN McAULEY 12-2	12-2-15-29	1604	Missing	—	—	—	—	1793	1822	2012	2046
209	J. P. OWEN ROSS V.L.A. 3-33	3-33-15-29	1588	Missing	—	—	—	—	1652	1707	1895	1917
210	DOME BIRTLE 14-35-16-27	14-35-16-27	1710	Missing	—	—	—	—	—	1705	1798	1822
211	DUPONT 14-25	14-25-16-28	1573	Missing	—	—	—	—	—	1532	1665	1687
212	DOME NACO LAZARE 12-34-16-29	12-34-16-29	1576	Missing	—	—	—	—	—	1480 (?)	1700 (?)	(?)
213	DOME BIRTLE 16-17-17-27	16-17-17-27	1712	Missing	—	—	—	—	—	1654	1800	1822
214	IMPERIAL MADELINE 16-18-18-29	16-18-16-29	1597	Missing	—	—	—	—	1370	1400 (?)	1605	1640
215	IMPERIAL FOXWARREN 16-32-19-27	16-32-19-27	1821	Missing	—	—	—	—	—	1536	1624	1660
216	SOCONY WOODLEY SOUTHERN GAINSBOROUGH No. 1 (SASK.)	16-29-1-30	1618	3487	3592	3730	3873	3878	4050	4395	4600	4630
217	S.A.M. VICTOR No. 1	6-29-17-29	1582	Missing	—	—	—	—	1395	1445 (?)	1639	1676