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MANITOBA

DEPARTMENT OF MINES, RESOURCES AND ENVIRONMENTAL MANAGEMENT
MINERAL RESOURCES DIVISION

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RESERVOIR POTENTIAL OF THE DEADWOOD AND WINNIPEG FORMATIONS SOUTHWESTERN MANITOBA

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Abstract

Southwestern Manitoba comprises the northeastern corner of the Williston Basin — a major Paleozoic and Mesozoic depositional basin centered near the town of Williston, North Dakota, and containing in excess of 15 000 feet (4600 m) of sedimentary fill. The Winnipeg Formation of Middle or Upper Ordovician age comprises a complex sequence of interbedded sands and shales which form the initial sedimentary deposits in this basin framework. In Manitoba, the sands and shales of the Winnipeg Formation form the basal Phanerozoic deposits and lie directly on deeply eroded and highly weathered Precambrian basement, except for a small area in extreme southwestern Manitoba where a thin wedge of Cambrian clastics of the Deadwood Formation is present.

A brief review of the limited data available for the Deadwood Formation is presented because of the current interest in a significant new oil discovery in this formation, only 30 miles (48 km) southwest of the southwestern corner of the province. Data for only three holes indicate that an erosionally truncated wedge of Deadwood strata, up to possibly 175 feet (53 m) thick, underlies an area of approximately 20 townships in the extreme southwestern corner of the province.

In order to evaluate as closely as possible the potential for oil and gas accumulation in the sands of the Winnipeg Formation, detailed lithofacies studies of the formation were undertaken. These show a complex facies pattern with a thin northern shelf facies consisting almost entirely of sand, grading southward to a transitional sequence of interbedded sands and shales, which in turn passes southward into a deeper basinal shale facies. Despite the complexity of sand distribution, the lithofacies data indicate several areas where possible up-dip sand pinchouts may form potential stratigraphic traps for oil accumulation. These potential traps are examined in some detail. The possibility of structural entrapment is also discussed, and, although no direct evidence of structural traps has been found, indirect evidence, particularly geophysical evidence, is used to outline several prospective areas.

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RESERVOIR POTENTIAL OF THE DEADWOOD AND WINNIPEG FORMATIONS, SOUTHWESTERN MANITOBA

by H. R. McCabe

INTRODUCTION

The purpose of this study, as initially conceived, was to determine the lithofacies pattern of the basal Ordovician Winnipeg Formation, with the primary objective of outlining areas of possible sand pinchout favourable for oil and gas exploration.

The report has essentially been compiled in two separate stages. The initial stage was completed in 1972, when all available data for the Winnipeg Formation were compiled. When the report was nearing completion, a 25-hole deep test program was undertaken by Asamera Oil Corp., with all holes to be drilled to Precambrian basement and hence to intersect a complete section of the Winnipeg Formation. Electric and gamma ray logs were to be run for all holes. Because this large amount of new data (an increase of more than 25 per cent in the available data base) would not be completed and available for release for several years, it was decided to set aside the study until such time as all the new data could be compiled and integrated into the study. The total available data base now amounts to 123 test holes in the 70 000 square mile (180 000 sq. km) area underlain by Winnipeg-Deadwood strata.

The new data provided a valuable check on the validity of the initial study, in particular, the degree of predictability of the Winnipeg lithofacies pattern. It was found that addition of the supplementary data necessitated very little change in the isopach or structure contour maps of the Winnipeg, Red River or Precambrian formations (Figs. 5, 8, 9), but considerable change was required with respect to the lithofacies maps (Figs. 12, 14). The lithofacies changes, however, were in detail only, and almost no change in overall pattern or interpretation was necessary.

When the second stage of compilation of the Winnipeg report was nearing completion, a highly significant new oil discovery was made in the Cambrian Deadwood Formation in North Dakota, only 30 miles (48 km) southwest of the southwestern corner of the Province. This discovery has stimulated a great deal of exploration activity in nearby areas, including southwestern Manitoba, to evaluate the potential for further Cambrian oil accumulation, since the North Dakota discovery is the first known oil occurrence in Cambrian strata of the Williston Basin.

At the time of initial compilation of the Winnipeg Formation report, only one questionable occurrence of Cambrian Deadwood strata was known in southwestern Manitoba, in the 16-16-1-27* well. However, two subsequent holes, one an Asamera deep test and the second a deep test drilled by Manitoba Mineral Resources Limited both intersected Cambrian strata. Because of the newly discovered oil potential of the Cambrian strata, and the newly available stratigraphic data relating to the distribution of Cambrian strata in southwestern Manitoba, it was decided to expand the earlier study to include not only the Winnipeg Formation but also all data relating to the Deadwood Formation, although such data are admittedly sparse.

This report is not intended to be a comprehensive study of the Winnipeg Formation, inasmuch as detailed lithological studies have not been carried out. The reason for this is that the sand beds in the Winnipeg Formation are for the most part poorly consolidated to unconsolidated, and sample recovery for most sand intervals is poor. Lithologic studies of the Winnipeg Formation would thus have supplied little useful data regarding *quantitative* sand distribution and reservoir potential. Consequently, this study has been based primarily on interpretation of mechanical logs. Where specific areas of potential sand pinchout have been noted, or where mechanical log interpretation is uncertain, well cuttings have been checked to obtain all available information regarding reservoir quality. In addition, the principal cored sections, including those reportedly showing oil stain, are described in Appendix I, along with photographs of selected lithologies. For more detailed discussions of the lithology of the Winnipeg Formation, the reader is referred to the list of selected references, especially those by Baillie (1952), Paterson (1971), and Vigrass (1971).

* For this report, all wells are referred to by location only, using the standard location system used in western Canada. For example, 16-16-1-27 refers to the well located in l.s.d. (legal survey division) 16, section 16, township 1, range 27. All range designations are west of the principal meridian unless specifically noted otherwise.

Composite geophysical maps showing all available gravity and magnetic coverage for southwestern Manitoba are also presented. The geophysical anomaly patterns can be related, in some degree, to structural instability and hence to possible variation in the pattern of sand distribution in the Winnipeg Formation. These maps consequently provide useful data for any attempt to define specific exploration targets.

Presentation of Metric Data

Although all government reports are now presented in metric rather than British units, the present report posed a difficult problem inasmuch as the entire data base for the study consists of electric and gamma ray logs all scaled in feet. It would have been possible to convert all data, including scales of the electric and gamma logs, to metric, but any attempt by the reader to compare data from this report with the existing data base would have been difficult indeed. Therefore, in order to present the data in as useful a form as possible, it was decided to present all maps, sections and data tables in both metric and British units, so that problems of comparison of data would be minimized.

All data were recorded initially in British units, and the elevations and thicknesses were contoured using British rather than metric units. The resultant metric intervals are thus irrational (e.g. 50 feet = 15.2 m). For some maps (Figs. 5, 8, 9) the base used consisted of a modification of a previously prepared map, so it was not possible to metricate all data. To aid in distinguishing between British and metric values, all metric values have been listed in parentheses (Table II etc.). In most cases, the metric conversion figures are recorded only to the nearest metre. In the case of drill stem test data (Table III), metrication has not yet been undertaken by the industry, so the pressure readings have been shown only in pounds per square inch.

DEADWOOD FORMATION

Definition

The Deadwood Formation is commonly defined as that sequence of predominantly clastic beds, characteristically glauconite-bearing, of Cambrian or Cambro-Ordovician age unconformably overlying eroded Precambrian basement, and overlain unconformably by the sandstones and shales of the Middle or Upper Ordovician Winnipeg Formation (Table 1). The type section of the Deadwood Formation is in the Black Hills area of South Dakota, but the unit has been correlated in the subsurface throughout much of western North Dakota, eastern Montana and southern Saskatchewan.

Distribution

Regionally, the Deadwood strata comprise a thick wedge of clastic sediments occurring throughout most of the Williston Basin area. Deposition of these strata, however, was not controlled by subsidence of the Williston Basin, since differential thickening of Deadwood strata is not specifically related to the Williston Basin depocenter. The northeastward thinning of Deadwood strata towards Manitoba appears to be primarily the result of regional truncation at the pre-Winnipeg unconformity. Studies by Porter and Fuller (1959) suggested the presence of a thin erosional wedge of Deadwood strata in the extreme southwestern corner of the Province, but at the time, the only test hole providing somewhat questionable evidence of Deadwood strata was the 16-16-1-27 well which intersected approximately 40 feet (12 m) of dark grey to black bituminous appearing shale below the basal sandstone of the Winnipeg Formation (Figs. 1, 4). This hole was not drilled deep enough to reach Precambrian basement, and glauconitic sandstone and siltstone generally considered diagnostic of Deadwood strata were not intersected. Identification of these shale beds as Cambrian Deadwood Formation was thus open to question.

The presence of Deadwood strata in southwestern Manitoba was, however, essentially confirmed in 1975 when MMR Waskada 11-29-1-25 intersected and partially cored a sequence of glauconitic sandy strata beneath the massive, clean, basal sandstone of the Winnipeg Formation, and above Precambrian basement. Descriptions of the Deadwood core are included in the Appendix.

Lithology and Thickness

The following discussion of the lithology of the Deadwood Formation is based almost entirely on core for the Waskada well, which intersected the basal 54 feet (16.5 m) of the Winnipeg Formation, including the entire thickness of the basal sandstone unit, as well as the uppermost 6 feet (1.8 m) of the Deadwood Formation. The basal 2 foot (0.6 m) section of the Winnipeg Formation consists of a highly pyritic sandstone breccia with abundant irregular to nodular pyrite inclusions and, in one zone, clasts up to ½ inch (1 cm) of quartzite. Glauconite grains, apparently derived from the underlying Deadwood beds occur sparsely in the basal portion of the breccia zone but are absent in the overlying sandstone of the Winnipeg Formation.

The basal breccia bed of the Winnipeg Formation passes sharply (unconformably) (Plate IIIc) into dark greenish-grey, highly glauconitic argillaceous siltstone to fine sandstone of the Deadwood Formation. Although the contact is sharp and somewhat irregular, there is almost no visible evidence that the contact marks a major unconformity. Except for the minor occurrence of detrital glauconite, the presence of quartzite clasts (which actually occur about 2 feet (0.6 m) above the contact and could possibly be derived from Precambrian basement), and possibly some of the pyrite inclusions, there is little evidence of any significant incorporation of material derived from the Deadwood Formation in the basal sands of the overlying Winnipeg Formation.

The upper 5 feet (1.5 m) of the Deadwood Formation shows intervals of very fine uniform lamination, in places faintly crossbedded, interspersed with intervals where the laminated sands and silts are highly disrupted and fragmented (Plate Ia,b). Minor diastemic breaks are in evidence throughout. This texture does not appear to result from organic reworking, although some bioturbation is possible. This texture, incidentally, closely resembles the fragmented textures seen in the argillaceous sandstone intervals of the overlying Winnipeg Formation (Plate II). Nodular pyrite is common in a 2 foot (0.6 m) zone immediately below and at the

	Baillie, 1952 Manitoba	Genik, 1954 Manitoba	Andrichuk, 1959 Manitoba	Sproule, 1964 Manitoba	Carlson and Anderson, 1965 North Dakota	Porter and Fuller, 1965 Williston Basin	Paterson, 1971 Saskatchewan	Vigrass, 1971 Sask., Man.	McCabe This paper Manitoba
MIDDLE OR UPPER ORDOVICIAN	WINNIPEG FORMATION	WINNIPEG FORMATION	WINNIPEG FORMATION	WINNIPEG FORMATION	WINNIPEG GROUP	WINNIPEG GROUP — WINNIPEG FORMATION	WINNIPEG FORMATION	WINNIPEG FORMATION	WINNIPEG FORMATION
	Upper Unit (Sandstone and shale)	Deer Island Member	Upper * (100' slice)	No.1 Sand *	Roughlock Formation	Upper Member		Upper Unit	Upper Unit * (50% slice)
				No.2 Sand *	Icebox Formation		Icebox Member	marker interval	
	Basal sandstone unit	Black Island Member	Lower * (remaining slice)	No.3 Sand *	Black Island Formation	Lower Member (Burgen)	Black Island Member	Lower Unit	Lower Unit * (50% slice)
CAMBRIAN OR CAMBRO-ORDOVICIAN			Cambrian		Deadwood Formation	Deadwood Formation	Deadwood Formation	Deadwood Formation	Deadwood

* Informal, operational units only

Table 1 Stratigraphic subdivisions and nomenclature Cambrian Deadwood, and Ordovician Winnipeg Formations contact with the Winnipeg Formation. Fine irregular stringers of medium grey shale occur scattered throughout, and the glauconite content of this interval approaches 50% in places.

The highly glauconitic beds pass downward gradationally into a section of irregularly interbedded light buff, relative clean siltstones to very fine sandstones and medium greenish-grey shale (Plate Ic). The siltstones are finely laminated to slightly crossbedded, and only slightly glauconitic; the contacts between the siltstone and shale bands are sharp but irregular. The siltstone beds range from about ¼ inch (0.5 cm) to 1 inch (2.5 cm) in thickness, and the shaly interbeds from fine partings up to about ½ inch (1 cm). The sharp irregular contacts are indicative of numerous diastemic breaks in sedimentation, and minor soft-sediment deformation features are evident. Irregular to lensoid and spherical inclusions (fragments ?) of siltstone are common in the shale bands. A few pyrite nodules up to ¼ inch (0.5 cm) in diameter occur in the siltstone bands, and the bedding plane exposed in one section of core shows a network of fine shale-filled fractures suggestive of desiccation cracks, although the cracks are so fine and of such limited vertical extent that they are almost invisible in a cross-section of the core.

Only about 1 foot (0.3 m) of interbedded siltstone-shale sequence was cored in the Waskada well, but the hole was subsequently drilled to Precambrian basement, intersecting a total thickness of 58 feet (17.7 m) of Deadwood beds. Well cuttings from the basal 52 feet (15.8 m) of this interval indicate a relatively clean section of siltstone to fine sandstone, slightly glauconitic, and probably including some shale interbeds towards the top. The mechanical log response (Fig. 4) indicates that the section becomes progressively cleaner towards the base. Fine intergranular porosity is fairly good, as there is little or no cementing material. No sign of oil staining was noted in either core or samples, and no evidence of gas was recorded by the "sniffer" that was used throughout the drilling of this hole. Good samples of granitic rock were recovered from the Precambrian basement almost immediately below the Deadwood beds, indicating a zone of basement weathering probably less than 5 feet (2 m) in thickness.

The Asamera Sinclair Prov. 16-34-6-29 well, drilled in 1974, is believed to have intersected a complete section of 57 feet (17.4 m) of Deadwood strata, although no core was taken from this well, and sample quality was extremely poor. Traces in the well cuttings of glauconitic sandstone and black shale similar to that noted for the 16-16-1-27 well attest to the presence of Deadwood strata, but other than this, the only evidence is in the mechanical log interpretation (Fig. 4). These logs show the presence of an interbedded sand (?) and shale sequence below what appears to be the basal sandstone unit of the Winnipeg Formation. The presence of a reported 77 foot (23.5 m) section of Deadwood strata in the nearby 12-28-7-30 well in Saskatchewan, approximately 10 miles northwest of the Asamera Sinclair well, offers supporting evidence that the basal section in the Asamera Sinclair well is in fact Deadwood.

A comparison of the mechanical logs for the Coulter and Waskada wells (Fig. 4) indicates marked differences in lithology in the basal part of the Deadwood Formation. In the Waskada well, the basal 40 feet (12.2 m) of the Deadwood consist of a relatively clean siltstone to fine sandstone, whereas in the Sinclair well, the Deadwood (on the basis of log interpretation) consists of 20 feet (6.1 m) of shale underlain by 15 feet (4.6 m) of clean highly resistive material, which in turn is underlain by appoximately 20 feet (6.1 m) of shale. The nature of the clean, highly resistive interval in the Sinclair well is uncertain; a tight carbonate or a tight (cemented) siltstone or sandstone could give rise to this response. Traces of tight siltstone along with traces of black shale were noted in the well cuttings. Assuming that the lower portions of the Deadwood Formation in these two holes are correlative, the foregoing suggests that marked lithofacies changes occur within the Deadwood; such changes will have considerable significance for any program attempting to evaluate the petroleum prospects of the Deadwood Formation in southwestern Manitoba.

As noted previously, the only other hole to have intersected Deadwood strata in Manitoba is the Coulter 16-16-1-27 well. This hole intersected a 40 foot (12.2 m) section of shaly beds below the basal Winnipeg sandstone unit. Well cuttings only are available for this interval, and these are of only fair quality. The samples consist dominantly of medium grey to olive-grey, splintery shales, not too different from the overlying Winnipeg shales. However, some intervals consist of a very dark grey to black, bituminous appearing shale. Traces of fine siltstone, possibly slightly glauconitic, also were seen. Although the lithology of these samples does not directly indicate that they are Deadwood strata, correlation with the Waskada well leaves little doubt that the 40 foot (12.2 m) shaly section in the 16-16-1-27 well is Deadwood. The hole was not drilled deep enough to intersect Precambrian basement.

No definite evidence of any Deadwood type lithology was seen in any of the wells drilled to the northeast of the three above-mentioned wells, so the effective erosional edge of Cambrian-Deadwood strata can be assumed to lie immediately northeast of a line drawn through the 16-34-6-29 and 11-29-1-25 wells (Figs. 5, 13). Thin remnants of Deadwood could possibly occur northeast of this indicated limit, but would be almost impossible to identify. The erosional edge thus roughly parallels the trend of the structural contours. Extrapolation of the limited data available suggests that Deadwood strata are thinning to the northeast at a rate of about 4 feet per mile (0.75 m per km), so that a maximum thickness of 175 to 200 feet (53 to 61 m) of Deadwood strata can be expected in the extreme southwestern corner of the Province, in Township 1, Range 29.

Cambrian oil discovery

The Cambrian Deadwood Formation discovery well drilled in October, 1977, is located approximately 30 miles (48 km) west and 3 miles (4.8 km) south of the southwestern corner of the Province (NE, SW 9-163N-87W, Renville County, North Dakota). Although details as to the type of accumulation are not yet available, the following information has been released to date. Approximately 300 feet (91 m) of Deadwood Formation was intersected at a depth of about 9 600 feet (2 926 m). A drill stem test of the interval 9 577 to 9 696 feet (2 913 to 2 955 m) yielded, in a 2 hour test, 32° API oil at a projected flow rate of 2 800 barrels per day. The pay zone is described as an approximate 50 foot (15 m) thick sandstone zone at the base of the formation, capped by a limestone bed within the formation. The hole was drilled on an indicated seismic structural high, and entrapment is believed to be structural, although there has been no indication of the size or extent of the accumulation.

Inasmuch as the North Dakota producing zone comprises the basal part of the Deadwood Formation, it is thought likely that these beds extend into Manitoba, and possibly are equivalent to the 40 foot (12 m) section of basal sandstone intersected in the Waskada 11-29-1-25 well. However, overstep of basal Cambrian beds to the northeast could have occurred, so precise correlation of the North Dakota producing zone with the Manitoba section will have to await acquisition of further data. The possibility of facies changes within the Deadwood reservoir beds, as noted previously, will also have to be considered. Entrapment at the truncated edge of the Deadwood reservoir beds (i.e. subcrop) in Manitoba, is thus a possibility, but the basal sandy breccia zone of the overlying Winnipeg Formation, as cored in the Waskada well, does not appear to be sufficently impermeable to provide an effective cap rock for a subcrop trap. This raises the interesting possibility of leakage of Cambrian oil from the truncated Deadwood reservoir beds into the suprajacent porous and permeable reservoir beds of the Winnipeg Formation.

The best prospects for Deadwood oil accumulation in Manitoba would appear to be in a structural trap, presumably comparable to that forming the trap in the discovery area. To date available data do not show any evidence of significant structures in the area of Deadwood occurrence in Manitoba, either on the basis of well data or reported regional seismic surveys, although several minor seismic structures, with questionable closure, have been outlined. The possibility of such traps, however, cannot be ruled out, and extensive detailed seismic studies have been carried out since the discovery to determine the detailed structural pattern. If seismic studies prove favourable, exploratory drilling in Manitoba is anticipated in 1978.

WINNIPEG FORMATION

Definition

The Winnipeg Formation, in Manitoba, consists of a complex sequence of interbedded sands and shales, ranging in composition from more than 90 per cent shale to more than 90 per cent sand. Thickness of the formation ranges from 0 in the north to 196 feet (60 m) in the south (Fig. 5). It overlies unconformably the deeply weathered and eroded, but for the most part extremely flat and highly peneplained Precambrian basement, except for the previously discussed area in the extreme southwestern corner of the Province, where a thin wedge of Cambrian Deadwood Formation occurs unconformably below the Winnipeg Formation.

The Winnipeg Formation is overlain with apparent conformity by limestones of the Upper Ordovician Red River Formation. The basal Red River strata contain argillaceous interbeds of Winnipeg-type lithology, and represent a transitional zone between the two formations. These transition beds have been referred to as the Hecla Beds by Fuller (1961). The top of the Winnipeg Formation is placed at the base of the first limestone bed — the base of the transitional zone. This corresponds to the base of the resistive response on the mechanical logs (Figs. 1, 2, 3).

Considerable difference of opinion has been voiced as to the exact age of the sparsely fossiliferous Winnipeg Formation. It is either Middle or Upper Ordovician, and is overlain by the Upper Ordovician Red River Formation (Oberg, 1966; Vigrass, 1971). Throughout the southern part of the map-area, the Winnipeg-Red River contact appears to maintain a constant stratigraphic position. To the north, however, both the Winnipeg and Red River formations thin markedly, and the basal dolomites of the Red River Formation become sandy. The "Winnipeg" sands in this northern area may represent a somewhat transgressive or diachronous facies, possibly equivalent to the basal portion of the Red River beds to the south.

Previous Work

The report by A. D. Baillie (1952) on Ordovician Stratigraphy of Lake Winnipeg and Adjacent Areas, provides the only comprehensive study of the outcrop geology of the Winnipeg Formation in Manitoba. Baillie presented a detailed review of previous work, lithologic descriptions, and faunal studies. He informally subdivided the Winnipeg Formation into an upper unit of interbedded sand and shale and a lower, basal sandstone unit. Supplementary laboratory studies and regional lithofacies analysis were presented by Genik (1952) in a Master's thesis based on field work carried out with Baillie. However, since only limited subsurface data were available at that time, interpretation of the regional depositional framework was possible only in the most generalized terms. Subsequently, Genik formally proposed subdivision of the Winnipeg Formation into a lower Black Island Member, and an upper, Deer Island Member (Genik, 1954) (Table 1).

Subsequent to Baillie's work, a large amount of subsurface data has become available, and a number of subsurface studies have been carried out covering Manitoba and adjacent parts of the general Williston Basin area. The following discussion outlines briefly some of the more pertinent studies. The reader is referred to the selected references for a more complete list.

An excellent regional analysis of the Lower Paleozoic formations, including the Winnipeg Formation, was outlined by Porter and Fuller (1959), but the first comprehensive subsurface study of the Winnipeg Formation in southwestern Manitoba (tp. 1-18, rge. 7E-29W) was by Andrichuk (1959). He presented a detailed review of previous work, generalized lithologic descriptions, stratigraphic and electric log cross-sections, and isopach and lithofacies maps. The upper and lower parts of the Winnipeg Formation were discussed separately but he did not suggest a formal stratigraphic subdivision. Andrichuk was the first worker to outline the large, bar-like sand body south of Winnipeg (Figs. 3, 14). He informally referred to it as the "Carman sand body", and suggested that it resulted from tectonic subsidence of the Precambrian basement. He also presented a reconstructed isopach map of the Winnipeg Formation, in which he attempted to define more accurately the true depositional framework of the unit by removing the effects of differential compaction.

In a regional review of oil and gas prospects of the Pre-Mississippian sedimentary rocks of southwestern Manitoba, Sproule (1964) presented a detailed study of sand distribution in the Winnipeg Formation, utilizing all data available at that time, including isopach and structure contour maps. He indicated the presence of three principal sand zones in the Winnipeg Formation (Table 1). Zone 3 corresponds with the basal sandstone (Black Island Member); Zone 2 corresponds approximately with the upper part of the "Lower Winnipeg" (as defined later in this report); and Zone 1 corresponds to the "Carman sand" and other equivalent upper Winnipeg sands. Sand thicknesses, depositional edges, and drill stem tests were noted, and several areas of potential oil entrapment were outlined. Some of these potential areas are still valid prospects and are outlined in more detail in the present study.

In a regional context, the sands and shales of the Winnipeg Formation were deposited in the Williston Basin, a major intra-cratonic basin which controlled the depositional pattern in Manitoba, Saskatchewan, North Dakota and Montana throughout most of Paleozoic and Mesozoic time. Manitoba comprises only a small segment on the northeastern flank of this basin, so an understanding of depositional conditions in Manitoba requires close integration with data for the adjoining areas of Saskatchewan and North Dakota. The following reports present such regional data.

Carlson (1960) presented detailed lithologic descriptions along with isopach and lithofacies maps for North Dakota and adjacent areas. He also included data from paleontologic studies, some of which were based on samples obtained from the Manitoba outcrop section. Carlson proposed subdivision of the Winnipeg Formation into three members: a basal Black Island Member (sandstone) (Genik, 1954), a middle, Icebox Member (shale) (McCoy, 1952), and an upper Roughlock Member (calcareous sandstone, sandstone, calcareous shale) (McCoy, 1952). According to Carlson's map, the Roughlock Member pinches out along the Manitoba-North Dakota border, with a maximum possible thickness of only about 10 feet (3 m) in extreme southern Manitoba. Carlson shows a maximum sand development in the central part of the Williston Basin. As will be shown later, this differs considerably from the writer's and Vigrass's findings for Manitoba and Saskatchewan, where sands generally are best developed in the fringing, shelf area, and sand content decreases basinward. This apparent contradiction probably results because of the rapid thickening of the basal sandstone (Black Island Member) in the central part of the basin.

Paterson (1971) presented detailed descriptions of all available cored holes in Saskatchewan, as well as a comprehensive review of the regional lithofacies pattern, isopach and structure contour maps, and stratigraphic cross-sections. No attempt was made, however, to quantify the pattern of sand distribution within the Winnipeg Formation. Paterson extended Carlson's (1960) North Dakota correlations and nomenclature to Saskatchewan and subdivided the Winnipeg Formation into a lower, Black Island Member and an upper, Icebox Member.

The most recent regional subsurface study is by Vigrass (1971), who presented a lithofacies study of the Winnipeg Formation in Manitoba and Saskatchewan, along with lithologic descriptions and a review of the postulated paleogeography and environment of deposition. He also suggests several general areas for oil entrapment. In his study Vigrass attempted to subdivide the Winnipeg Formation into Upper and Lower members utilizing detailed electric log and sample correlation of marker beds near the middle of the unit. It is interesting to note the difference in interpretation between Vigrass and Paterson (op. cit., Table 1) for the Saskatchewan area. Vigrass postulated a marked transgressive overlap of Upper Winnipeg beds, with the Upper Winnipeg reflecting the maximum period of marine transgression. Paterson, on the other hand, indicates just the opposite; that the lower Winnipeg (Black Island Member) extends farther to the northwest than the upper Winnipeg, and that there is a hiatus or disconformity between the lower Winnipeg and the overlying Red River Formation. This difference in opinion points out the difficulty in attempting to establish detailed correlation of units within the Winnipeg Formation, especially in the high-sand facies to the north and west.

A review of the above regional data for Saskatchewan and North Dakota indicates that facies changes in the Winnipeg Formation are more pronounced and more irregular in Manitoba than in adjacent areas of Saskatchewan and North Dakota. Because of this, the writer considers it difficult, if not impossible, to establish a widely applicable stratigraphic subdivision of the Winnipeg Formation in Manitoba; consequently, the Black Island-Icebox-Roughlock subdivision used elsewhere is not extended into Manitoba, although such a subdivision undoubtedly could be applied in some areas.

Method of Study

All available mechanical logs were examined for those wells drilled deep enough to intersect the Winnipeg Formation (Fig. 5). Sand intervals were determined on the basis of the mechanical log response. In most cases, both the S.P. (Spontaneous Potential) and gamma (radiation) curves serve to delimit accurately the sand and shale intervals. Where present, the sands are commonly highly porous and permeable (i.e. excellent potential reservoir beds), and show a relatively clean separation from the shales. Because of this, the S.P. and gamma responses generally are sharp and well defined. In some wells, however, mechanical log responses are "vague" and lithologic estimates consequently uncertain.

"Vague" log response can result from a number of factors such as poor mud conditions in the hole, unusual salinity in the formation fluids, and mechanical problems during logging. Mixed lithologies such as sandy shales and argillaceous sandstones also produce "vague" mechanical log responses that are difficult to interpret quantitatively. Typical examples of log interpretation are shown in the stratigraphic cross-sections (Figs. 1, 2, 3).

For the purposes of this report, the writer has attempted to determine the number and thickness of "discrete sands". The term "discrete" sand is used in this report to designate a separate or individual sand bed which has the potential of forming a reservoir unit. Determination if a sand "break" on a mechanical log is a discrete sand or not is sometimes a rather subjective decision, depending on the quality of the log response. In general, a reasonably strong S.P. or gamma ray response was required, along with a thickness in excess of about two feet (1 m). Where the sand appeared to be less than two feet (1 m) thick it was ignored, and where shale breaks less than two feet (1 m) thick occurred within a larger sand interval, these were ignored. On the number of sands maps (Figs. 12, 14), (+) or (−) signs have been noted beside some wells where there is some uncertainty in log interpretation as to how many discrete sands are present. Table II presents a summary of all well data.

Where possible, well cuttings were checked to clarify questionable mechanical log interpretations. Features checked include the top of the Precambrian (to differentiate between Winnipeg sands and shales and weathered basement), highly radioactive intervals (black shale), and resistive intervals (cemented or silty sands).

Correlation

A preliminary study of mechanical logs indicated that accurate correlation of marker beds within the Winnipeg Formation would not be possible — at least not throughout the entire map-area. Local correlation of markers is possible, however, especially in the southern portion of the map-area. Also apparent, is a general break between the upper and lower portions of the Winnipeg, with sands present in the upper or lower parts of the formation but shaly beds more common in the middle. In order to present a clearer, more detailed picture of sand distribution within the Winnipeg Formation it was decided to arbitrarily subdivide the formation into two operational units, Lower and Upper Winnipeg, at the calculated mid-point of the unit. This provides slice maps of the upper and lower 50 percentile portions of the unit. As the study progressed, it became evident that the shaly marker beds near the middle of the unit could be correlated, albeit with considerable uncertainty, throughout much of the southern portion of the map-area (see Figs. 1, 2, 3). In this area, the markers maintain a relatively constant position close to the middle of the unit. They appear to approximate time stratigraphic markers, and their relatively constant stratigraphic position near the middle of the unit suggests that the slice maps probably also approximate true facies maps. There is little evidence of any time transgression or diachroneity of sand unit *within* the Winnipeg Formation. The basal sandstone, or Black Island Member, however, is almost certainly diachronous in a regional sense, at least in the northern areas.

Where sands occur straddling the middle of the unit, a decision was made as to which portion of the Winnipeg Formation the sand bed was most closely associated, and the sand then included in either the Upper or Lower unit. For example, the "Carman Sand" (Fig. 14) thickens to almost 100 feet (30 m) and straddles the middle of the Winnipeg Formation along its axis of thickest development. Nevertheless, this sand bed is definitely associated with the Upper Winnipeg, as shown by stratigraphic cross-section C-C' (Fig. 3).

In order to show as clearly as possible the complex nature of sand distribution, a "lithologic" map of the Winnipeg Formation was prepared showing strip logs of sand distribution in all wells in the southwestern portion of the study area (Fig. 13). This covers the area of prime interest for oil and gas exploration. Areas of possible up-dip sand pinchout are noted. East-west cross-sections A-A' and B-B' (Figs. 1, 2), which approximate structural dip sections, were drawn so as to include several areas of possible sand pinchout. It should be noted, however, that these sections are subparallel to the isopach or facies trend of the Winnipeg Formation (Fig. 5). Cross-section C-C' (Fig. 3) shows the configuration of the "Carman sand body."

GENERAL STRATIGRAPHY AND STRUCTURE

The isopach-structure contour map of the Winnipeg Formation (Fig. 5), along with the Upper and Lower Winnipeg lithofacies maps (Figs. 12, 14), can be interpreted directly to show the regional tectonic and sedimentational setting, but only with considerable caution. The principal factor "distorting" the true depositional isopach pattern is differential compaction. Sharp lateral lithologic changes from sand to shale (Figs. 1, 2, 3) result in isopach and, to a lesser extent, structural anomalies due to preferential or differential compaction of the shale beds. The sand beds, by contrast, are essentially unconsolidated and uncompacted. The effects of differential compaction are most obvious in the area of the "Carman Sand" (Figs. 3, 5 and 14), where an area of pronounced thickening (up to 70 feet) (21 m) is seen to coincide with an area of thick, local sand development (up to 100 feet) (30 m). The overlying Ordovician strata show a comparable amount of thinning (Fig. 8), so that the total Ordovician section (Fig. 7) shows only a gradual, more or less uniform southward thickening.

Restored Isopach

In order to define more accurately the depositional pattern of the Winnipeg Formation, and especially to outline any possible pre-Winnipeg topographic features on the Precambrian erosion surface, an attempt was made to compile a "restored isopach" by removing the effects of differential compaction. Andrichuk (1959) presented a restored isopach map for the southern part of the map-area using all data available at that time, and utilizing a compaction factor of 40 per cent. This factor appears to be reasonable, but a strong residual anomaly is still evident in the area of the "Carman Sand" (Andrichuk, op.cit., Fig. 11). Apparently because of the presence of this residual anomaly, Andrichuk postulated that the "Carman Sand" had been deposited along a local, tectonically negative basin area or hinge line, during a minor erosional break or hiatus. According to this interpretation, however, there should be little or no differential compaction associated with the "Carman Sand", at least along the northern, structurally controlled edge, since the sand would have, for the most part, filled the tectonically subsiding basin, and no laterally equivalent shales would have been deposited. The overall uniformity of the total Ordovician isopach (Fig. 7), with no evidence of appreciable local isopach thickening, is a strong argument against Andrichuk's hypothesis.

Because of the uniform southward thickening shown by the total Ordovician section, the writer expected that the isopach anomaly associated with the "Carman Sand" was due entirely to differential compaction and would be removed by restoring the original shale thickness. A restored isopach was prepared, using all presently available data, and utilizing a somewhat higher compaction factor of 50 per cent (Fig. 6). The 50 per cent factor is believed to be the maximum possible compaction factor for a shale bed with an initial thickness of 100 feet (30 m) (Gretener and Labute, 1969). Despite the use of the higher compaction factor, the resulting restored isopach still shows a strong residual thickness anomaly in the area of the "Carman Sand", although the thin area north of the "Carman Sand" has been largely removed. An examination of two closely spaced anomalous wells on the flanks of the "Carman Sand" (16-22-7-10 and 13-7-8-9) shows that the total shale thickness is almost equal in the two wells (only 11 feet (3.4 m) difference), so that the added 46 feet (14 m) of section in the 16-22-7-10 well could not possibly be explained by any conceivable compaction factor, assuming that the lithologic estimates are accurate. Obviously, some factor other than just differential compaction has also been effective; this will be discussed later.

Aside from the anomaly in the area of the "Carman Sand", the restored isopach (Fig. 6) shows a more or less uniform southward thickening, comparable to that shown by the total Ordovician isopach. This is believed to be more representative of the regional pattern of subsidence than is the normal isopach. A number of anomalous features are evident along a north-trending belt in the vicinity of range 25W; this is coincident with the Birdtail-Waskada Axis, a structural feature described in a later section. No other significant anomalous features are indicated, and there is no evidence of any appreciable relief on the Precambrian surface.

On the basis of the restored isopach map, and the total Ordovician isopach, and considering the data for specific wells, it appears that the "Carman Sand" represents an area of true isopach or depositional thickening, but with little or no tectonic subsidence. At first this may appear contradictory, but several factors or combination of factors could explain this thickening.

i) Errors in interpretation of mechanical logs. Sandy and silty shales will have been included

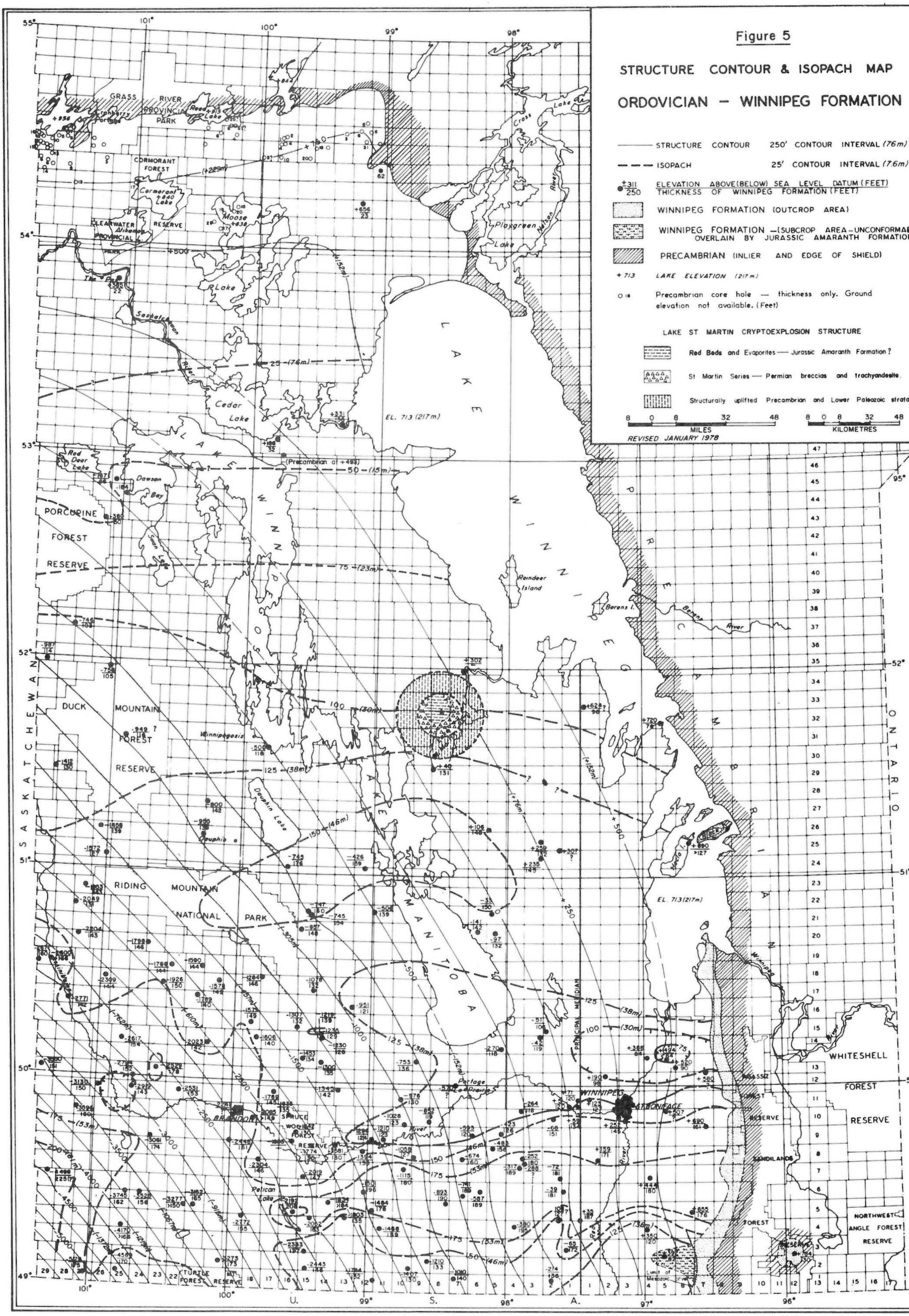

Figure 5
STRUCTURE CONTOUR & ISOPACH MAP
ORDOVICIAN – WINNIPEG FORMATION
STRUCTURE CONTOUR 250' CONTOUR INTERVAL (76m)
ISOPACH 25' CONTOUR INTERVAL (7.6m)
+311 / 250 ELEVATION ABOVE (BELOW) SEA LEVEL DATUM (FEET) / THICKNESS OF WINNIPEG FORMATION (FEET)
WINNIPEG FORMATION (OUTCROP AREA)
WINNIPEG FORMATION – (SUBCROP AREA – UNCONFORMABLY OVERLAIN BY JURASSIC AMARANTH FORMATION)
PRECAMBRIAN (INLIER AND EDGE OF SHIELD)
+ 713 LAKE ELEVATION (217 m)
Precambrian core hole — thickness only. Ground elevation not available. (Feet)
LAKE ST MARTIN CRYPTOEXPLOSION STRUCTURE
Red Beds and Evaporites — Jurassic Amaranth Formation?
St Martin Series — Permian breccias and trachyandesite.
Structurally uplifted Precambrian and Lower Paleozoic strata
MILES
KILOMETRES
REVISED JANUARY 1978
LAKE WINNIPEG
LAKE WINNIPEGOSIS
LAKE MANITOBA
PRECAMBRIAN
SASKATCHEWAN
ONTARIO
WINNIPEG
BRANDON
U. S. A.

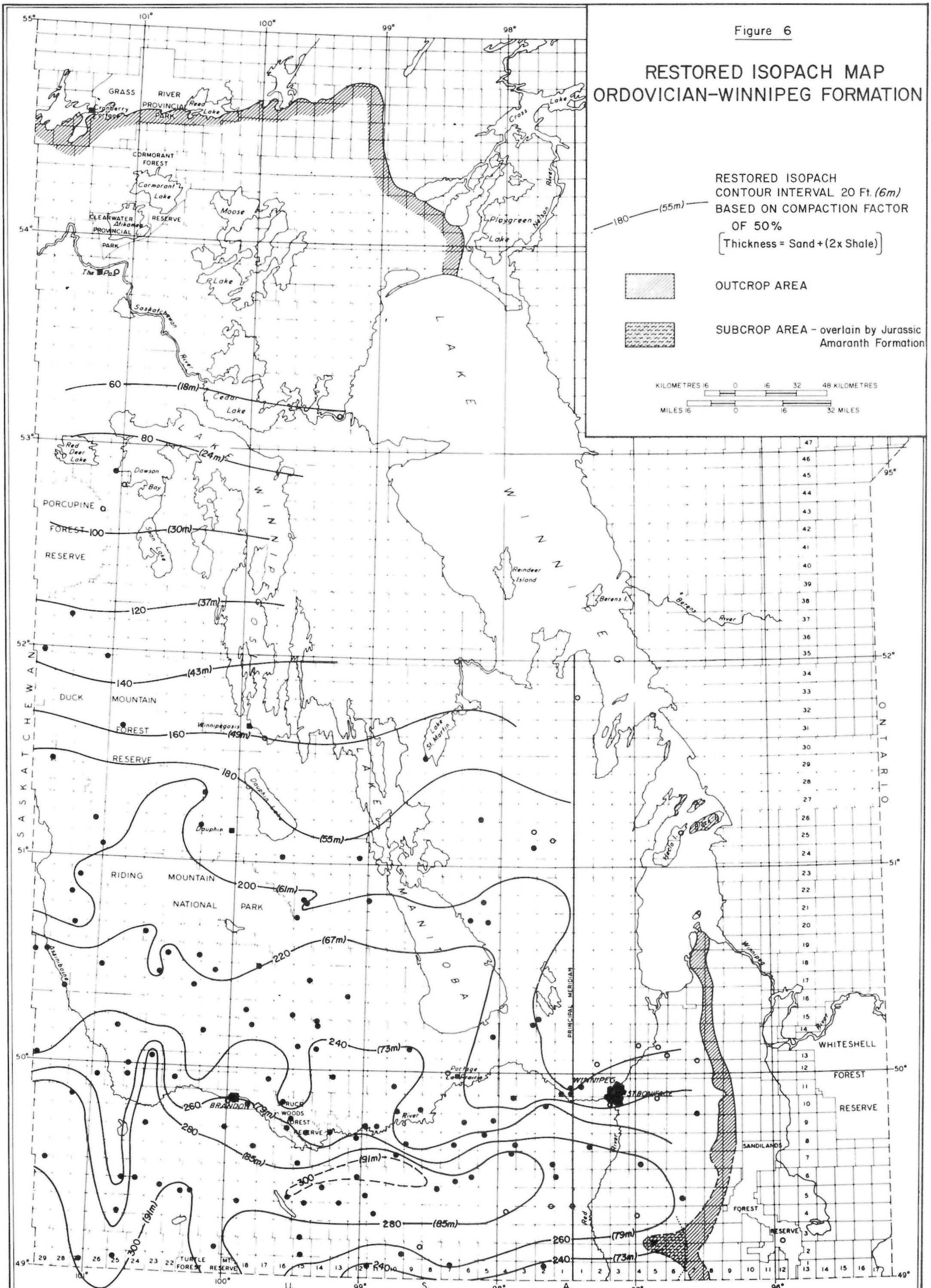

Figure 6
RESTORED ISOPACH MAP
ORDOVICIAN-WINNIPEG FORMATION
RESTORED ISOPACH
CONTOUR INTERVAL 20 Ft. (6m)
BASED ON COMPACTION FACTOR
OF 50%
[Thickness = Sand + (2x Shale)]
180 (55m)
OUTCROP AREA
SUBCROP AREA - overlain by Jurassic Amaranth Formation
KILOMETRES 16 0 16 32 48 KILOMETRES
MILES 16 0 16 32 MILES
LAKE WINNIPEG
LAKE WINNIPEGOSIS
LAKE MANITOBA
SASKATCHEWAN
ONTARIO
U. S. A.
PRINCIPAL MERIDIAN
GRASS RIVER PROVINCIAL PARK
CORMORANT FOREST RESERVE
CLEARWATER PROVINCIAL PARK
PORCUPINE FOREST RESERVE
DUCK MOUNTAIN FOREST RESERVE
RIDING MOUNTAIN NATIONAL PARK
TURTLE MT. FOREST RESERVE
SPRUCE WOODS FOREST RESERVE
WHITESHELL FOREST RESERVE
SANDILANDS FOREST RESERVE
WINNIPEG
ST. BONIFACE
BRANDON
Portage la Prairie
Dauphin
Winnipegosis
The Pas
Cranberry Portage

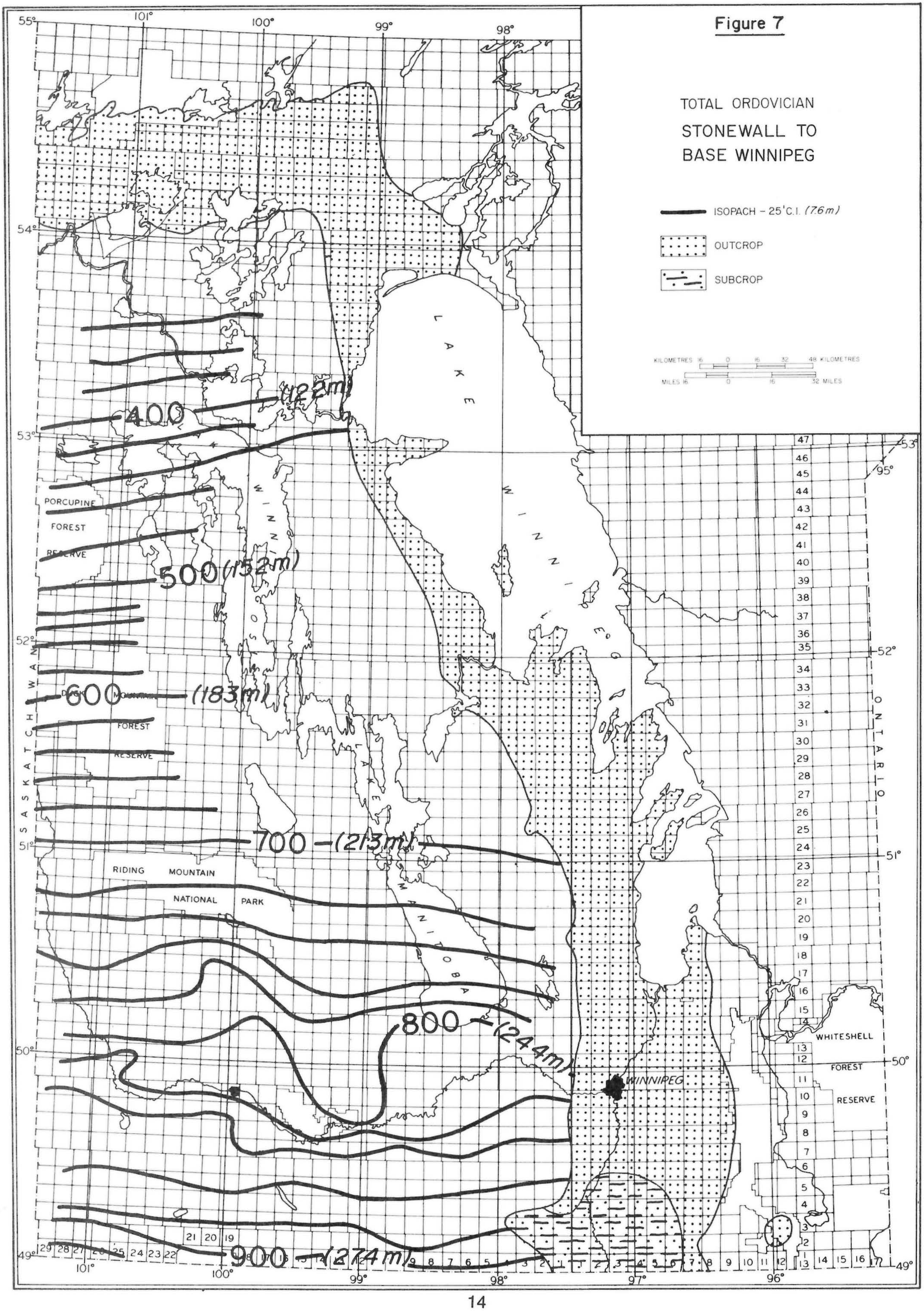
Figure 7
TOTAL ORDOVICIAN
STONEWALL TO
BASE WINNIPEG
ISOPACH - 25' C.I. (7.6 m)
OUTCROP
SUBCROP
KILOMETRES 16 0 16 32 48 KILOMETRES
MILES 16 0 16 32 MILES
400 (122m)
500 (152m)
600 (183m)
700 (213m)
800 (244m)
900 (274m)
LAKE WINNIPEG
LAKE WINNIPEGOSIS
LAKE MANITOBA
PORCUPINE FOREST RESERVE
DUCK MOUNTAIN FOREST RESERVE
RIDING MOUNTAIN NATIONAL PARK
WHITESHELL FOREST RESERVE
WINNIPEG
SASKATCHEWAN
ONTARIO
55°
54°
53°
52°
51°
50°
49°
101°
100°
99°
98°
97°
96°
95°

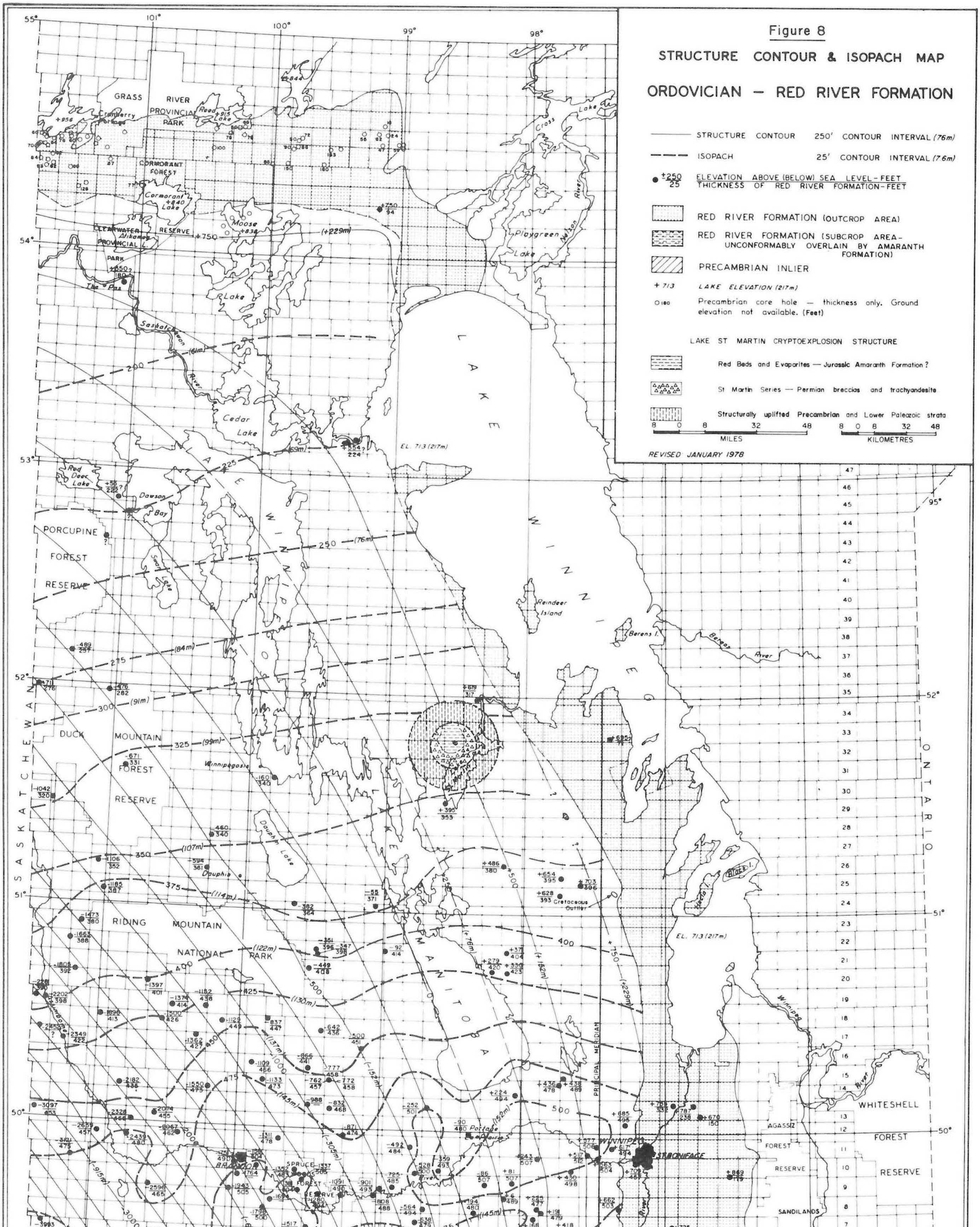
Figure 8
STRUCTURE CONTOUR & ISOPACH MAP
ORDOVICIAN — RED RIVER FORMATION
STRUCTURE CONTOUR 250' CONTOUR INTERVAL (76m)
ISOPACH 25' CONTOUR INTERVAL (7.6m)
+250 / 25 ELEVATION ABOVE (BELOW) SEA LEVEL - FEET / THICKNESS OF RED RIVER FORMATION - FEET
RED RIVER FORMATION (OUTCROP AREA)
RED RIVER FORMATION (SUBCROP AREA - UNCONFORMABLY OVERLAIN BY AMARANTH FORMATION)
PRECAMBRIAN INLIER
+713 LAKE ELEVATION (217m)
Precambrian core hole — thickness only. Ground elevation not available. (Feet)
LAKE ST MARTIN CRYPTOEXPLOSION STRUCTURE
Red Beds and Evaporites — Jurassic Amaranth Formation?
St Martin Series — Permian breccias and trachyandesite
Structurally uplifted Precambrian and Lower Paleozoic strata
MILES
KILOMETRES
REVISED JANUARY 1978
GRASS RIVER PROVINCIAL PARK
CORMORANT FOREST
CLEARWATER PROVINCIAL PARK
The Pas
LAKE WINNIPEG
Cedar Lake
EL. 713 (217m)
PORCUPINE FOREST RESERVE
DUCK MOUNTAIN FOREST RESERVE
RIDING MOUNTAIN NATIONAL PARK
LAKE WINNIPEGOSIS
LAKE MANITOBA
Dauphin Lake
Reindeer Island
Berens I.
Cretaceous Outlier
PRINCIPAL MERIDIAN
WINNIPEG
ST BONIFACE
BRANDON
Portage
SPRUCE WOODS FOREST RESERVE
Pelican Lake
TURTLE MT. FOREST RESERVE
WHITESHELL FOREST RESERVE
AGASSIZ FOREST RESERVE
SANDILANDS FOREST RESERVE
NORTHWEST ANGLE FOREST RESERVE
Limit of Mesozoic cover
SASKATCHEWAN
ONTARIO
U. S. A.

with clean shales in the writer's log interpretations, because of comparable log response. This will have tended to reduce the effective compaction factor. However, if the shales above or below the sand beds are more sandy than laterally equivalent shales, this will have tended to exaggerate the apparent thickness in the sandy areas, in the restored isopach map (i.e. the effective compaction factor will be lower in the area of sandy shale than in the area of "clean" shale).

ii) Tectonism. To explain the apparent thickening in the area of the "Carman sand" solely by tectonism would require subsidence during deposition of the "Carman Sand", and subsequent (Ordovician) uplift by an equivalent amount to provide the indicated uniform southward thickening of the total Ordovician section (Fig. 7). This seems highly unlikely. The slight structrual nosing on the southern edge of the "Carman Sand" (Fig. 5) probably reflects primarily the effects of differential compaction, but the slight nosing shown by the Precambrian structure contour map (Fig. 9) suggests that some slight tectonic movement may have been effective in the localization of the "Carman Sand", although not a prime factor as suggested by Andrichuk (1959).

iii) Depositional topography. The "Carman Sand" may have formed a prominent topographic high on the depositional surface (e.g. offshore bar) with adjacent areas of deeper water shale deposition. If the bar was then drowned during later Winnipeg and Red River subsidence, the topographic relief of the sand body would have resulted in a gradual, progressive depositional thinning of the later sediments over this topographically high area (Figs. 3, 8). The lower, deeper-water areas flanking the sand bar would then have been filled gradually by the later Winnipeg and Red River sediments, so that by the end of Ordovician time, the depositional surface was once again essentially flat. In the writer's opinion, this appears to be the most plausible explanation for the origin of the "Carman Sand" and its associated isopach anomalies, although tectonism may also have had some modifying or localizing effect.

The configuration of the "Carman Sand" could be significant in interpreting the mode of origin. If, as suggested above, the "Carman Sand" is an offshore bar, the top of the sand bar should be prominently convex upward. The problem in ascertaining the configuration is the selection of a suitable datum horizon from which to hang the section, or to set the section on, so as to reconstruct the original shape of the body. As shown in Figure 3, the sand appears to be almost flat on top, with the base convex downwards. This configuration is due in large part to the effects of differential compaction and/or topographic relief on the top of Winnipeg datum used to hang the section. A more accurate presentation probably would have been either to sit the section on Precambrian basement or to hang it from the top of the Ordovician, a horizon presumably above most of the effects of either differential compaction or bottom topography. Both of these latter reconstructions give rise to a convex upward configuration for the sand body — a configuration compatible with a bar-type origin.

Structure

The preceding section has dealt with "superficial" isopach and structure anomalies related to differential compaction or depositional relief. In addition, several true, tectonically derived structural features have affected the Winnipeg Formation. The principal structure is the Moose Lake Syncline (McCabe, 1967) (Figs. 5 and 9), a broad synclinal flexure trending roughly northeast through Moose Lake (vicinity tp. 56, rge. 16W). The northeastward continuation of this trend is seen to be coincident with a major Precambrian feature — the Churchill-Superior boundary zone and its associated "nickel belt". The expression of this Precambrian feature where it extends beneath the Paleozoic cover is evidenced by the pattern of associated gravity anomalies, especially the "Nelson River High". This geophysical anomaly trend can be traced to the southwest where it is seen to coincide approximately with the Birdtail-Waskada Axis (McCabe, 1967; Bell, 1971). The latter is a zone of complex Paleozoic and Mesozoic structural and stratigraphic anomalies, in part related to solution of Devonian evaporite beds and collapse of overlying strata. The writer (McCabe, op.cit.) has suggested that these Paleozoic and younger features may reflect recurrent minor basement tectonism along this zone.

The east-west depositional trends of the Ordovician strata (Figs. 5, 7, 8) are highly anomalous relative to the expected regional Williston Basin framework, which, in Manitoba, trends northwest, roughly parallel to the present structure contours. This suggests that the portion of the Williston Basin east of the Churchill-Superior boundary zone (Birdtail-Waskada Axis) may have undergone a relatively greater degree of subsidence than the area west of the

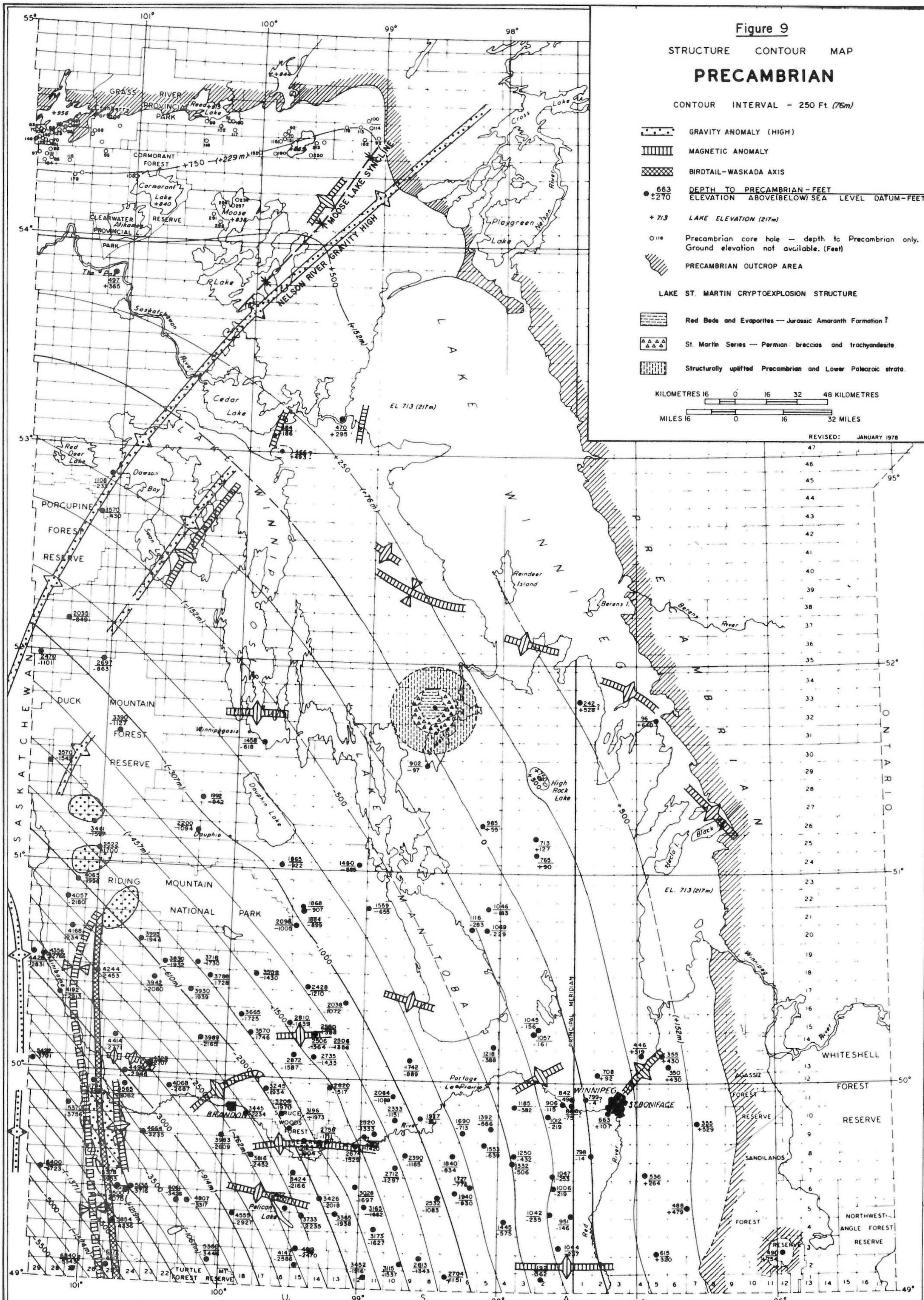

Figure 9
STRUCTURE CONTOUR MAP
PRECAMBRIAN

boundary zone. The east-west trend of the Ordovician strata is also seen to parallel the east-west trend of magnetic anomalies in the Precambrian basement. As will be pointed out later, facies trends in the Winnipeg Formation may have been modified in the area of the Birdtail-Waskada Axis. Although no definite structural anomalies affecting the Winnipeg Formation, can be delineated along this axis (Fig. 5) well control is extremely sparse, and the possibility of such structures cannot be ruled out. In general, a considerable degree of correlation appears to exist between Precambrian basement tectonic elements and the depositional framework of Ordovician strata.

The prominent structural anomaly in the Lake St. Martin area (vicinity tp. 32, rge. 8W) is a crypto-explosion crater of approximate Permian age (McCabe and Bannatyne, 1970). Beds of the Winnipeg Formation have been uplifted by as much as 700 feet (212 m) around the rim of this structure, and occur at or near outcrop just south of the narrows on Lake St. Martin. The sands are thus open to surface, with little chance of oil entrapment on the flanks of the structure. Conceivably, if deformation occurred as a series of step faults, conditions for entrapment could obtain on the flanks of the crater, but this seems doubtful, especially in view of the pervasive fracturing evident in Paleozoic rocks on the flanks of the crater.

The smaller Precambrian inlier in the Highrock Lake area (vicinity tp. 29, rge. 2W) (Fig. 5) may represent either a Precambrian monadnock or a second crypto-explosion structure. If it represents a monadnock (erosional high) on the Precambrian surface, entrapment of oil or gas in sand pinchouts on the flank of the structure would be possible, although the sedimentary cover in this area is thin. If the feature represents a second crypto-explosion crater, and this is believed to be the case, the possibilities of oil accumulation would be slight, for the reasons previously noted for the Lake St. Martin structure.

The only other structural anomaly of any magnitude known to affect the Winnipeg Formation, occurs in the 1-29-5-24 well. This feature does not show in Figure 5 because the 1-29 well was not drilled deep enough to intersect the Winnipeg Formation. It was, however, drilled to a point well below the expected depth of the top of the Winnipeg, and in fact was drilled to a point about 100 feet (30 m) below the expected depth of Precambrian basement. It bottomed in what appears to be an abnormally thick sequence of Ordovician Red River carbonates — 788 feet (240 m) as compared to a "normal" thickness of 500 feet (152 m) (Fig. 8). The cause of this structural/stratigraphic anomaly is unknown, but it most likely relates to faulting associated with the nearby Hartney Structure, which may possibly be another crypto-explosion (meteorite impact ?) crater (McCabe, 1971; Sawatsky, 1975) although its origin is very much open to question. The Winnipeg Formation must also have been involved in this structural deformation, and oil entrapment is possible, depending on the configuration of the structure. However, no specific prospective area can be outlined with the limited data presently available.

The slight suggestion of an anticlinal flexure along the southern edge of the "Carman Sand" has already been mentioned in connection with the effects of differential compaction. This feature is also evident on the Precambrian surface (Fig. 9), and probably results from minor tectonic movement as well as differential compaction.

Although the above-noted anomalies are the only structures known to affect Winnipeg strata, the sparsity of well control leaves considerable room for as yet undiscovered structures. It should be noted that the structure contour maps on both the Precambrian and Winnipeg Formation (Figs. 5, 9) have been drawn on a regional basis, that is, assuming a regional gradient in areas of sparse control, and minimizing the areal effect of any wells deviating from the regional pattern. The apparent uniformity of the contours is thus somewhat misleading, but the contour values probably are more realistic; the addition of the 25 Asamera deep tests tends to confirm this, as only minor adjustments were required in Figures 5, 8 and 9.

The coincidence of both gravity and magnetic geophysical anomalies with the Birdtail-Waskada Axis has been noted. Figures 10 and 11 show composite gravity and magnetic maps for southwestern Manitoba. The trends of the principal anomalies have been noted, and the postulated extension of the major anomalies associated with the Churchill-Superior boundary zone, the Moose Lake Syncline, and the Birdtail-Waskada Axis are delineated on the Precambrian structure map (Fig. 9). Although no local structural features are known to be associated with any of the small-scale geophysical anomalies, the coincidence of the Moose Lake Syncline with the major gravity high suggests that geophysical anomalies, particularly gravity highs, may reflect structural anomalies and hence probably are the most likely targets in any exploration programme designed to test for structural/stratigraphic traps in the Winnipeg Formation. Of particular interest are those geophysical anomalies that occur within a

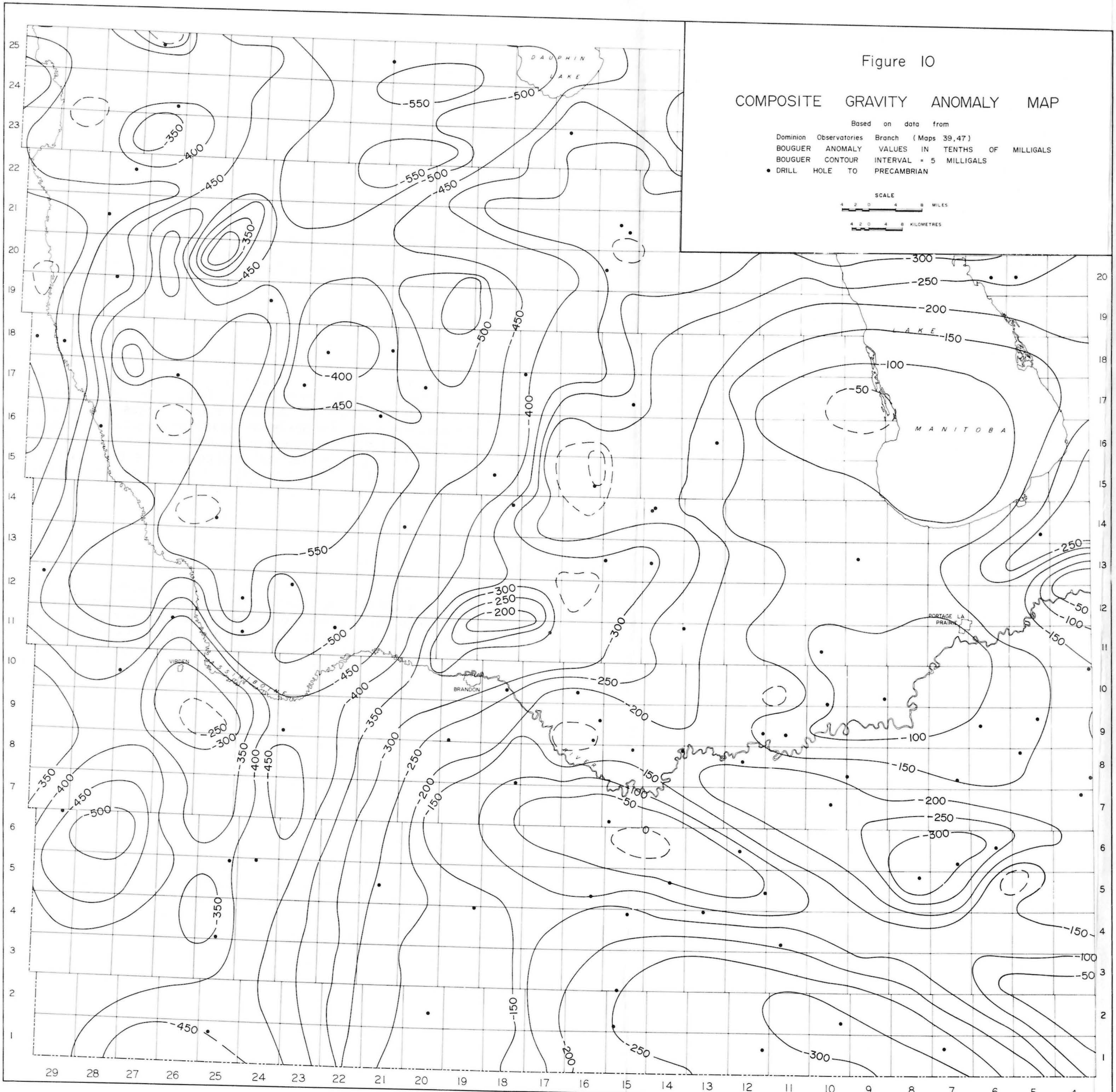

Figure 10

COMPOSITE GRAVITY ANOMALY MAP

favourable facies area (i.e. transition facies as described later). Possible specific target areas will be noted later.

Lithofacies

LOWER WINNIPEG

Sand distribution in the Lower Winnipeg unit (i.e. the lower 50% slice of the Winnipeg Formation) is outlined in Figure 12. At least one sand bed is shown to be present throughout the entire map-area. This is, in fact, a single blanket-type sand at the base of the formation, correlative with the basal part of the Black Island Member. Almost all wells drilled to basement encountered this sand, although considerable variation in thickness is evident as shown by the stratigraphic cross-sections (Figs. 1, 2, 3) and by the lithologic map (Fig. 13). The basal sand is thinnest in the southeastern part of the map area, in the vicinity of the "Carman Sand", where thicknesses range from less than 5 feet (1.5 m) to 15 feet (4.6 m). It thickens to the north, partly because of coalescing with stratigraphically higher sands that appear in the section towards the north. It also thickens to the southwest, as shown by the 16-16-1-27 well (Figs. 1, 12). The overall pattern of distribution of sand, other than for the basal sand, is somewhat irregular. In general, a thick basinal shaly facies is evident to the south, passing northward to a "transitional facies" of two or more sands (i.e. one or more sands above the basal sand); as many as six discrete sands have been noted. This, in turn, passes northward to a thinner, shelf facies where the entire Lower Winnipeg unit has graded laterally to sand (i.e. one sand bed).

This pattern is by no means regular. The principal anomalous area is the north-south trending belt of relatively thick transition facies in ranges 17 to 25 west. This belt is seen to be roughly coincident with the Birdtail-Waskada structural axis noted previously.

Although accurate correlation of individual sand beds is not possible because of the sparse well control, a close examination of all available logs (e.g. cross-sections, Figs. 1, 2, 3) suggests that the individual sand beds in the transition facies appear to be correlative and continuous over considerable areas, and appear to represent sand tongues extending basinward from the main sand (shelf) facies to the north. If these sands are laterally continuous the possibility of oil entrapment in these sands will be severely limited since any oil would have tended to migrate northward, up the dip component in this direction, towards the shelf area, which is open to outcrop along Lake Winnipeg. Possible exceptions to this generalization can be noted, however, since the facies trends are in large part discordant to the regional structural dip (Figs. 5, 12 and 14). Local entrapment appears to be possible along the northeast edge of the belt of transition facies extending northward between ranges 17 and 25, provided that the detailed configuration of the northeastward limit of the sand is such as to provide a closed up-dip sand pinchout. The areas northeast and southeast of Brandon appear to offer the best possibilities for trapping conditions. These potential traps are also shown by the lithologic map (Fig. 13) and by stratigraphic cross-sections A-A' and B-B' (Figs. 1 and 2), which approximate dip sections. No definite closure can be outlined, however, because of insufficient well control, and the traps may be open to the northwest. A more detailed evaluation of these potential traps is presented in a later section.

The possibility also exists that the above-noted transition sands do not represent continuous sand tongues, but rather are a series of discontinuous (bar-type?) sands, occurring at approximately correlative stratigraphic positions. In this case, the possibility of oil entrapment is greatly enhanced. In either case, the area of the transition facies, which shows the maximum interbedding of sand and shale beds, represents the optimum stratigraphic environment for oil entrapment, and hence the favoured exploration area.

UPPER WINNIPEG

In detail, the sand distribution in the Upper Winnipeg unit (i.e. the upper 50% slice of the Winnipeg Formation) differs considerably from that of the Lower Winnipeg. The regional pattern, however, is generally similar, although considerably more irregular, with a basinal shale facies to the south, passing northward to a transitional facies of interbedded sand and shale, and finally to a shelf sand facies north of approximately latitude 52° N (Fig. 14). No blanket sand is present in the Upper Winnipeg, and extensive areas to the south consist entirely of shale. An irregular southward extending lobe of transition facies is evident west of Brandon in roughly the same area as for the Lower Winnipeg, and roughly coincident with the Birdtail-Waskada Axis.

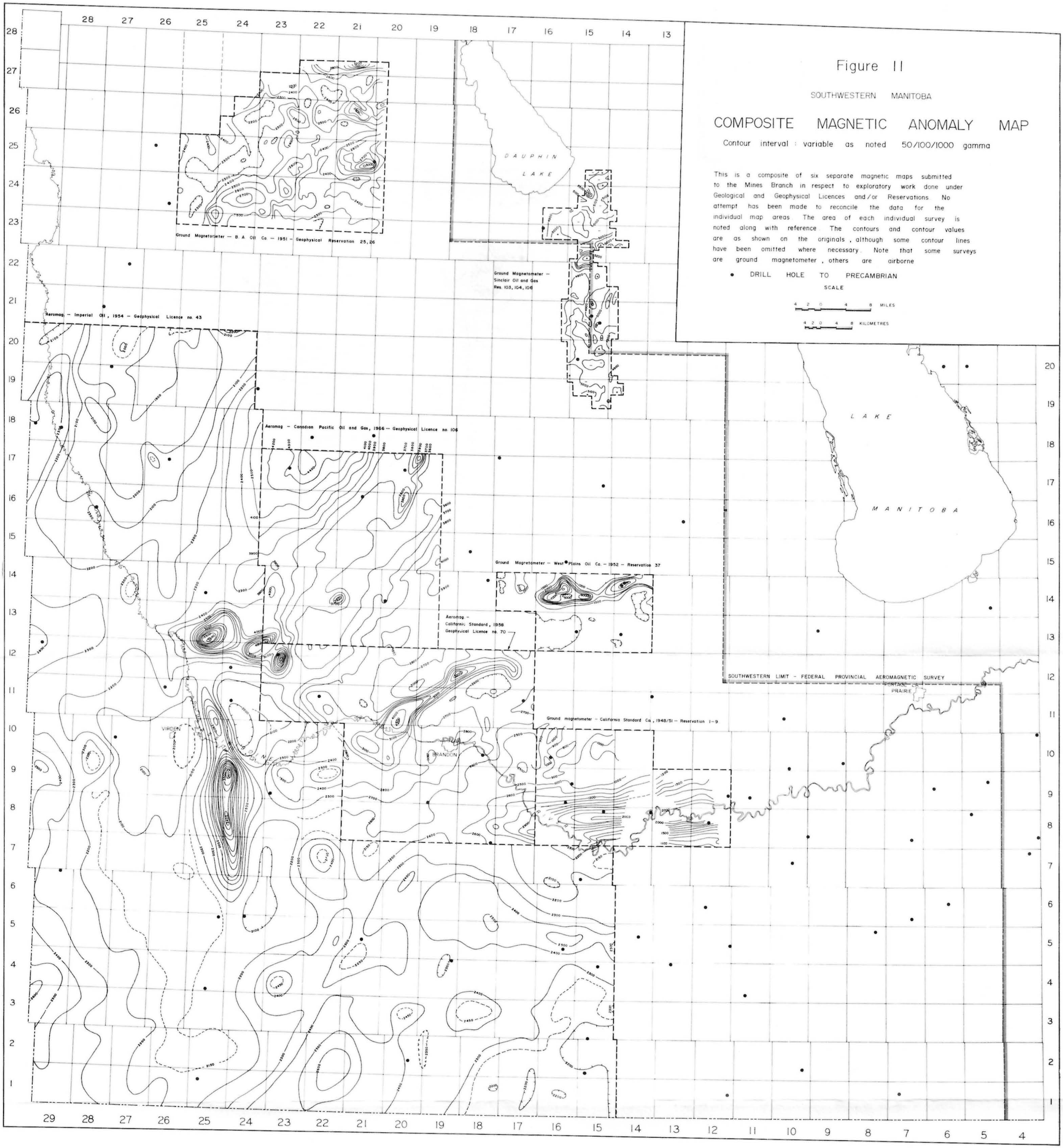

Figure 11

SOUTHWESTERN MANITOBA

COMPOSITE MAGNETIC ANOMALY MAP

Contour interval : variable as noted 50/100/1000 gamma

This is a composite of six separate magnetic maps submitted to the Mines Branch in respect to exploratory work done under Geological and Geophysical Licences and/or Reservations. No attempt has been made to reconcile the data for the individual map areas. The area of each individual survey is noted along with reference. The contours and contour values are as shown on the originals, although some contour lines have been omitted where necessary. Note that some surveys are ground magnetometer, others are airborne

• DRILL HOLE TO PRECAMBRIAN

SCALE

4 2 0 4 8 MILES

4 2 0 4 8 KILOMETRES

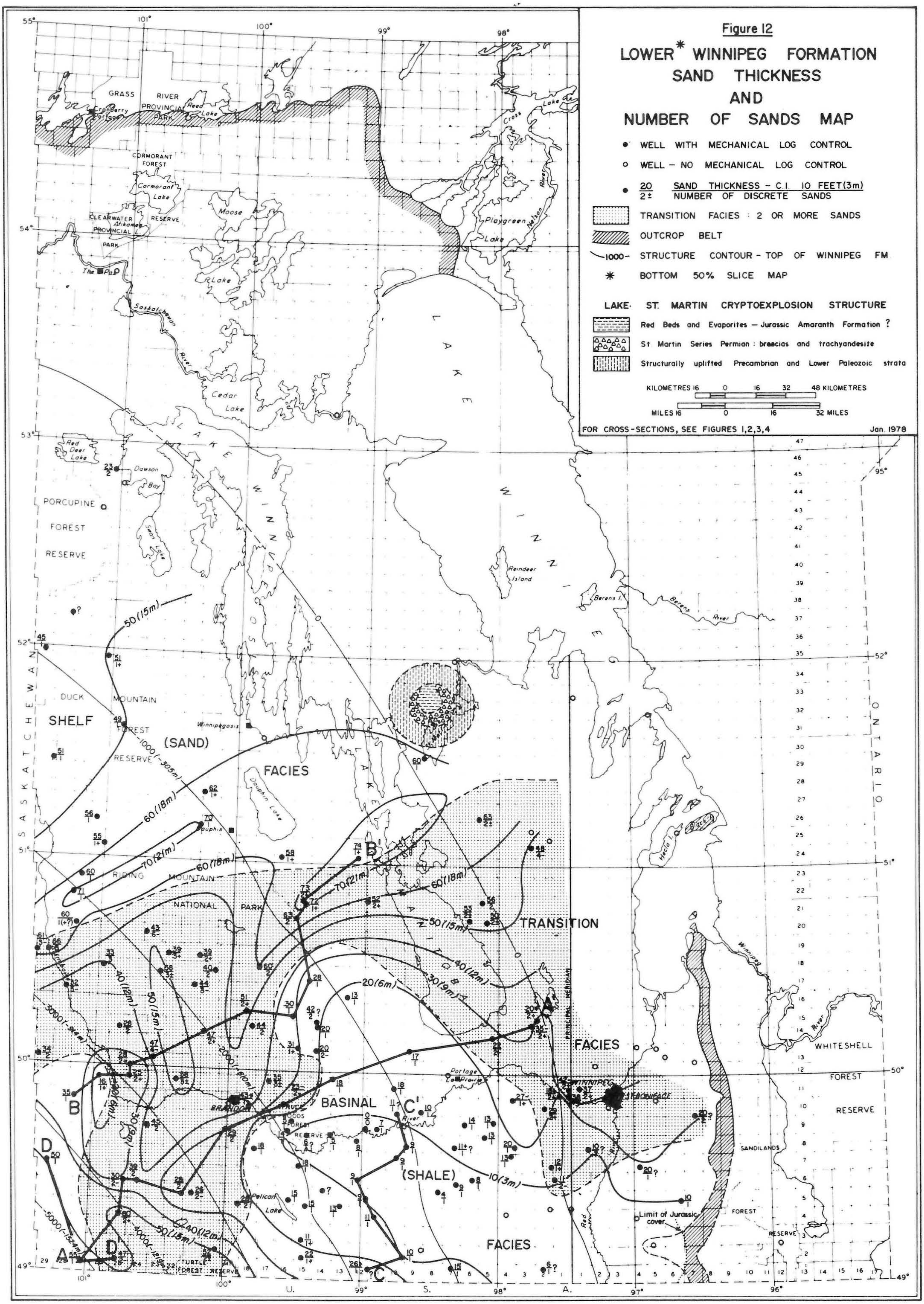

Figure 12

LOWER* WINNIPEG FORMATION SAND THICKNESS AND NUMBER OF SANDS MAP

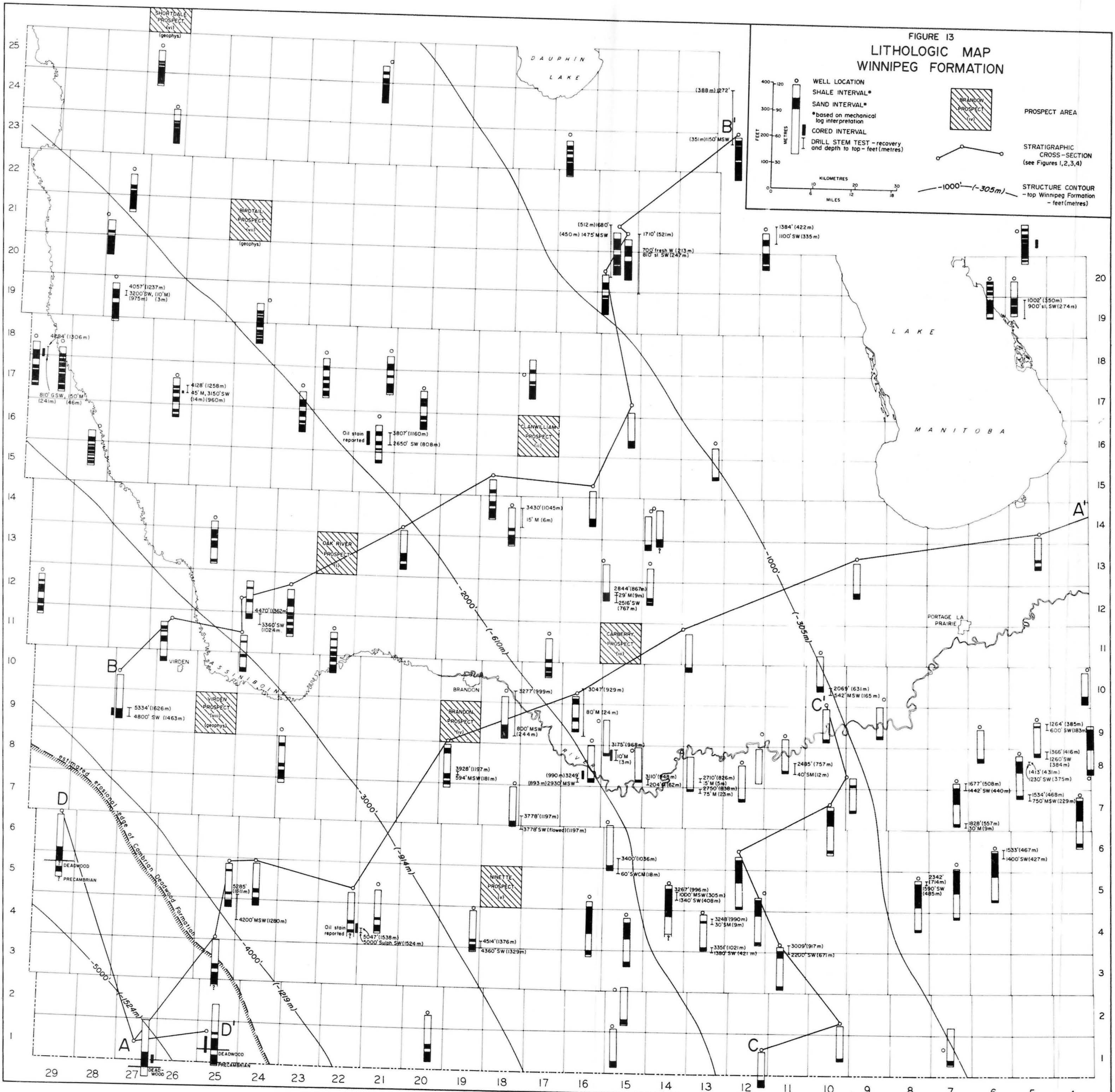
FIGURE 13
LITHOLOGIC MAP
WINNIPEG FORMATION
WELL LOCATION
SHALE INTERVAL*
SAND INTERVAL*
*based on mechanical log interpretation
CORED INTERVAL
DRILL STEM TEST - recovery and depth to top - feet (metres)
FEET
METRES
KILOMETRES
MILES
PROSPECT AREA
STRATIGRAPHIC CROSS-SECTION (see Figures 1,2,3,4)
STRUCTURE CONTOUR - top Winnipeg Formation - feet (metres)
DAUPHIN LAKE
LAKE MANITOBA
PORTAGE LA PRAIRIE
VIRDEN
BRANDON
ASSINIBOINE RIVER
SHORTDALE PROSPECT (vi) (geophys)
BIRDTAIL PROSPECT (vii) (geophys)
CLANWILLIAM PROSPECT (ii)
OAK RIVER PROSPECT (i)
CARBERRY PROSPECT (iii)
VIRDEN PROSPECT (viii) (geophys)
BRANDON PROSPECT (iv)
NINETTE PROSPECT (v)
estimated erosional edge of Cambrian Deadwood Formation
-1000' (-305m)
-2000' (-610m)
-3000' (-914m)
-4000' (-1219m)
-5000' (-1524m)
A A' B B' C C' D D'
DEADWOOD
PRECAMBRIAN
Oil stain reported

The principal anomalous feature is the "Carman Sand", the thick east-west trending bar-like sand that extends from the outcrop belt just west of the Sandilands Forest Reserve (Range 8 East) to Pelican Lake (Range 16 West) — a distance of about 150 miles (241 km). Width of the sand body ranges from less than 15 miles (24 km) to more than 60 miles (97 km). This sand body apparently occurs entirely within the basinal shale facies, although the eastward extent, and the possible relation to an eastern source area, are not known because of erosional truncation of the unit. The trend of the "Carman Sand" is seen to parallel closely the regional Ordovician isopach trends shown in Figures 5, 6, 7.

Lithologically, the "Carman Sand" (in the relatively few samples examined) is a fine- to medium-grained well sorted uniform and virtually unconsolidated sand. Mechanical logs show that it is an extremely clean sand with no appreciable shale interbeds. Because of its excellent reservoir characteristics (see mechanical logs, Fig. 3, and Table III of D.S.T. data), this sand has been the target for considerable exploration drilling in the hopes of finding irregularities or discontinuities in the distribution of the sand, which could give rise to trapping conditions. For instance, in the Pelican Lake area, the 1-27-5-14 well was drilled because the 16-33-4-13 test hole intersected only a thin section of sand, suggesting a possible pinchout up-dip from the thick sand in the 7-34-4-15 well (Andrichuk, 1959). However, the 1-27-5-14 well drilled to test this potential trap, intersected an exceptionally thick interval of "Carman Sand" (Fig. 14). The presently available data strongly suggest that the "Carman Sand" is a single, continuous, relatively uniform sand body throughout its indicated extent. The only area where stratigraphic pinchout seems possible is near the western limit of the sand, in the Pelican Lake area, where the sand body is narrow and shows very rapid thickness changes.

Since the trend of the "Carman Sand" body is almost exactly at right angles to the structure contours, the sand is open up-dip to the outcrop belt. The configuration of the sand body, at least along its northern edge appears to be relatively uniform, so the possibility of oil entrapment on the flanks of the sand body is limited. Hydrodynamic entrapment has been mentioned as a possibility, but if the down-dip extent of the sand is limited, as shown in Figure 14, this would virtually rule out any possibility of hydrodynamic trapping.

By contrast, the configuration of the southeastward extending lobe of transition facies west of Brandon is seen to be much more favourable for providing trapping conditions. For example, sand in the 10-28-12-23 well passes up-dip to shale in the 2-7-14-20 well (Figs. 2, 14). Entrapment, however, would depend on the exact configuration of the sand pinchout, and this potential trap could be open to the northwest, towards the main area of transition facies.

Entrapment in the sands shown south and east of Brandon is also a possibility. The mechanical log response of these sands, however, is relatively poor (Fig. 1).

The foregoing has presented the regional facies patterns and discussed some of the general areas of possible oil entrapment. A more detailed discussion of some of these prospective areas, including sample studies, is presented in a subsequent section.

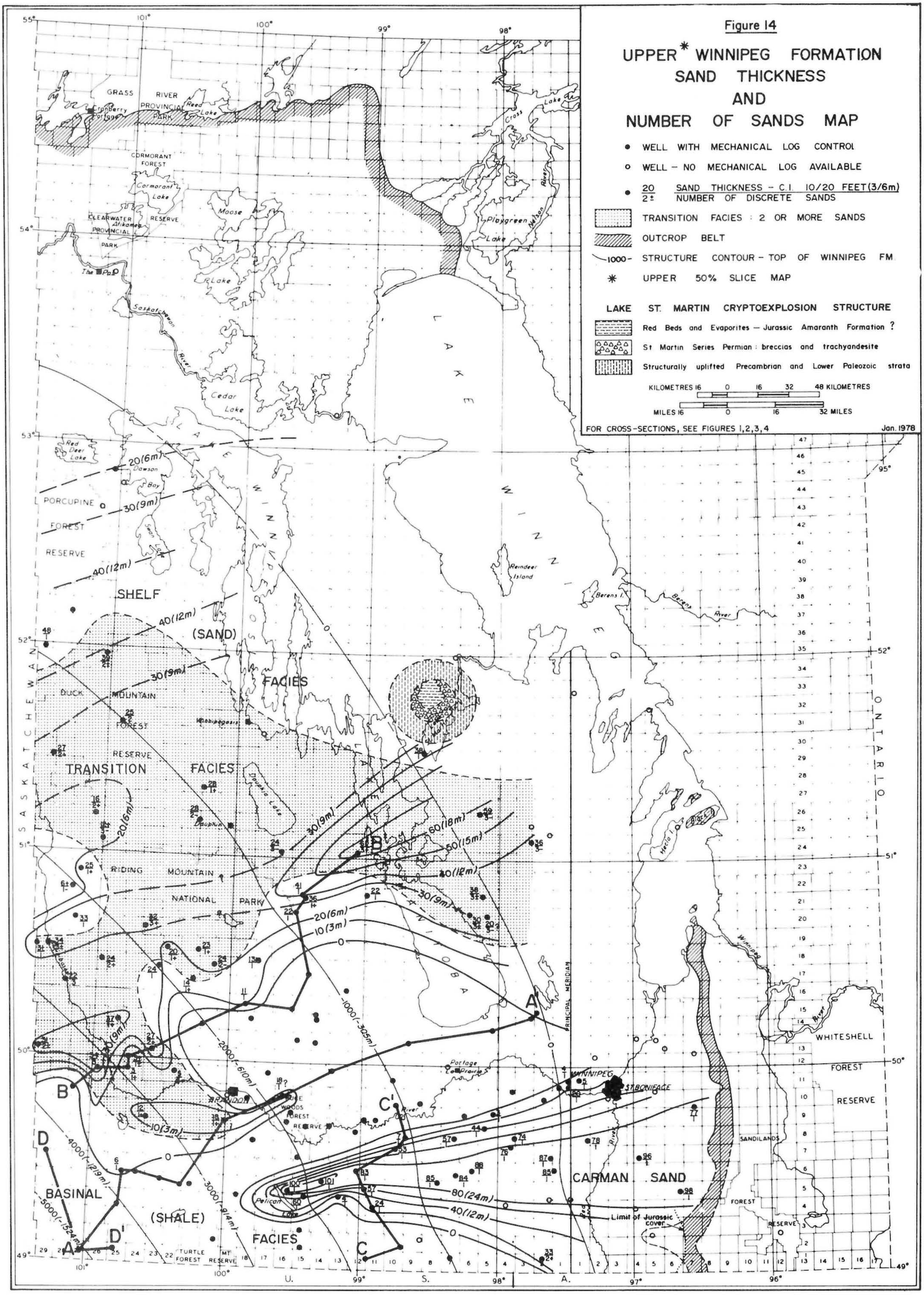

Figure 14
UPPER* WINNIPEG FORMATION SAND THICKNESS AND NUMBER OF SANDS MAP
WELL WITH MECHANICAL LOG CONTROL
WELL - NO MECHANICAL LOG AVAILABLE
20 SAND THICKNESS - C.I. 10/20 FEET (3/6m)
2± NUMBER OF DISCRETE SANDS
TRANSITION FACIES : 2 OR MORE SANDS
OUTCROP BELT
1000 STRUCTURE CONTOUR - TOP OF WINNIPEG FM.
* UPPER 50% SLICE MAP
LAKE ST. MARTIN CRYPTOEXPLOSION STRUCTURE
Red Beds and Evaporites — Jurassic Amaranth Formation ?
St. Martin Series Permian : breccias and trachyandesite
Structurally uplifted Precambrian and Lower Paleozoic strata
KILOMETRES 16 0 16 32 48 KILOMETRES
MILES 16 0 16 32 MILES
FOR CROSS-SECTIONS, SEE FIGURES 1,2,3,4
Jan. 1978
SHELF (SAND) FACIES
TRANSITION FACIES
BASINAL (SHALE) FACIES
CARMAN SAND
LAKE WINNIPEG
LAKE WINNIPEGOSIS
LAKE MANITOBA
SASKATCHEWAN
ONTARIO
WINNIPEG
ST. BONIFACE
BRANDON
DUCK MOUNTAIN FOREST RESERVE
RIDING MOUNTAIN NATIONAL PARK
PORCUPINE FOREST RESERVE
GRASS RIVER PROVINCIAL PARK
CLEARWATER PROVINCIAL PARK
WHITESHELL FOREST RESERVE
TURTLE MT. FOREST RESERVE
PRINCIPAL MERIDIAN
U. S. A.
Limit of Jurassic cover

PALEOGEOGRAPHY

This study deals primarily with the distribution of sand beds in the Winnipeg Formation, as related to possible oil accumulation, but a brief discussion of some of the possible causes for this sand distribution is in order since it can aid materially in evaluation of the lithofacies data. As noted previously, the regional isopach trends (both actual and restored) are east-west with a gradual and relatively uniform thickening to the south, accompanied by a general change from a sand facies in the north to a shale facies in the south. This is indicative of a regional transgression of Winnipeg seas from the south, and progressive tectonic subsidence along an east-west axis, which, as noted previously, is anomalous relative to the overall Williston Basin tectonic framework.

Although Winnipeg strata in Manitoba overlap unconformably the eroded Precambrian surface, the period of erosion can be dated as primarily Cambro-Ordovician. The thick sequence of sands and shales comprising the Cambrian Deadwood Formation, as discussed previously, was deposited throughout much of Saskatchewan and North Dakota. These beds must once have covered much of southwestern Manitoba, but extensive pre-Middle Ordovician erosion has truncated these strata so that only a thin wedge of Cambrian strata remains in the extreme southwestern corner of the Province.

Vigrass (1971) and others report some moderate relief on the pre-Winnipeg erosion surface in Saskatchewan and North Dakota, but the writer sees no evidence of any relief in excess of a few feet or tens of feet (a few metres), at least in the southern part of the Province. The several pronounced anomalies on the Precambrian surface (Fig. 9) can be attributed to true post-Winnipeg structural deformation, possibly resulting from meteorite impact. In addition to the extreme flatness of the pre-Winnipeg surface, there is a pronounced lack of residual basal clastic material. No appreciable thicknesses of granite wash types of deposits have been noted, but a highly weathered zone up to several tens of feet thick (e.g. 10 feet (3 m) in Grand Rapids core hole 818, tp. 48, rge. 13) commonly is present. This "shale" zone has been included in the Winnipeg Formation on the basis of mechanical log response. By contrast, in the extreme northern part of the map area, local variations in thickness of the Winnipeg Formation become evident (Fig. 5), and moderate relief probably existed on the Precambrian paleo-surface. The rolling Precambrian terrain exposed immediately north of the erosional edge of the Winnipeg strata possibly reflects relief inherited from the pre-Winnipeg unconformity.

Although the Upper and Lower Winnipeg lithofacies maps are slice maps of the formation rather than marker-defined time-stratigraphic units, the general uniformity in relative stratigraphic position of the medial marker bed (Figs. 1, 2, 3), where it is definable, indicates that, at least for the southern part of the map-area, the "slice unit" does not depart greatly from a marker defined unit. A reasonable estimate of the paleogeography can thus be made from these maps. Farther north, in the shelf or high sand facies, interpretation becomes highly questionable as evidenced by the previously noted divergent conclusions reached by Vigrass (1971) and Paterson (1971).

The basal sandstone of the Winnipeg Formation is present throughout the map-area and probably represents a basal, transgressive shoreline sand. Although there is little evidence of diachroneity in the southern part of the map-area, as evidenced by the persistence of the medial marker bed, this basal sand is undoubtedly transgressive or diachronous in a regional sense, rising stratigraphically to the north. Near the northern limit of occurrence the overlying Red River strata are in direct contact with a thin basal sand, and in places the basal Red River beds are themselves sandy.

Near-shore, high-energy, shallow-marine to shoreline conditions, possibly at times terrestrial, prevailed in the northern area of the high sand facies. The northern edge of the transition facies, as shown in the Lower Winnipeg facies map (Fig. 12) possibly approximates the average shoreline position during early Winnipeg time. Southward, in the area of the transition facies, the sands interfinger with normal marine pale green to brown waxy kaolinitic shales. Some mixing of lithofacies is evident, but in general there is a fairly sharp separation into clean sand, with relatively "clean" shale interbeds. The sand beds in this transition facies may represent continuous sand tongues extending southward (basinward) from the near-shore facies, or may possibly represent a series of discrete offshore bar-type deposits. The normal expected facies pattern should be one of uniform decreasing sand content to the south. Variations from this pattern may result from variation in bottom topography, variation in type and amount of sediment supply, variation in offshore or longshore currents, and/or tectonic effects in areas of both provenance and deposition. The indicated interbedding of sands and shales probably reflects repeated minor marine transgressions and regressions controlled by these same factors. It is difficult or impossible to differentiate between the effects of the above-noted factors with the limited data available.

The general configuration of the transition facies (Figs. 12, 14) is believed to reflect the pattern of sand transport, which is a complex function of all of the above factors. Vigrass (1971) has shown directions of transport for both of his Lower and Upper Winnipeg units, and the results of the present study largely agree with Vigrass' interpretations. The southward extending lobe of the transition facies (vicinity ranges 18-25W) in the Lower Winnipeg, coincides approximately with the Birdtail-Waskada Axis, and it is suggested that minor tectonic movement along this axis may have affected the depositional pattern of Winnipeg strata in this area.

The Upper Winnipeg facies map (Fig. 14) shows a considerable northward shift in position of the transition facies, suggesting a continued northward transgression and continuing subsidence and deepening of the Williston Basin during later Winnipeg time. The rather irregular southward extending lobe of transition facies is once again seen to coincide approximately with the position of the Birdtail-Waskada axis.

The "Carman Sand" of the Upper Winnipeg comprises the single largest and most uniformly extensive sand body in the Winnipeg Formation, except for the basal sand. The origin of this feature is uncertain, but as suggested previously, it probably represents an offshore bar type of deposit which showed considerable depositional relief above the adjacent areas. Marine conditions shoreward of the bar apparently were sufficiently restricted in some areas (e.g. the 7-35-7-4 well), so that dark brown to black shales were deposited rather than the typical clean pale green kaolinitic shales. The bar narrows towards the west and terminates in the vicinity of Pelican Lake, indicating a probable westward direction of longshore sand transport from a source area east of the present erosional edge of the unit.

One other factor that is not readily apparent on any of the maps, but which may have had a pronounced effect on Winnipeg sand distribution, is the Precambrian paleotopography immediately east of the present erosional edge of the Winnipeg Formation. An examination of the sparse data along this edge shows several apparently anomalous areas where the Precambrian surface appears to be structurally high relative to the regional basement trend (Fig. 9). Northeast of Winnipeg, for instance, and close to the projected northern edge of the "Carman Sand", the Precambrian outcrops immediately east of the Winnipeg outcrop belt are 100 feet (30 m) to 300 feet (91 m) higher than expected. Inasmuch as these are fresh unweathered Precambrian outcrops, and consequently must have been subjected to late (Pleistocene ?) erosion, the original relief on the Precambrian surface, in Winnipeg time, must have been considerably greater. Similarly, at The Narrows of Lake Winnipeg (tp. 32), the Precambrian surface is seen to rise at least 80 feet (24 m) over a distance of only 3 miles (5 km), in an area where the regional dip is only 10 to 12 feet per mile (1.9 to 2.3 m per km). The present position of the erosional edge of the Paleozoic strata may thus represent, at places, a structural and/or paleotopographic break, rather than being an entirely "accidental" erosional feature. It is not presently possible, however, to ascertain: (a) if the Precambrian highs existed as paleotopographic features during Winnipeg time; (b) if the highs are the result of structural activity (folding or faulting) during Winnipeg time, or; (c) if they are the result of later post-Winnipeg structural adjustment. If a Precambrian paleotopographic high did exist during Winnipeg time northeast of Winnipeg, and east of the present limit of Winnipeg strata, this feature could have formed a barrier to the longshore transport of sand so that sand undergoing westward transport by longshore currents would have been diverted south of the high and deposited as the "Carman Sand". The shale facies north of the "Carman Sand" would have been deposited in the lee of this high, and the anomalously thin section of shaly Winnipeg strata in the vicinity of tp. 13, rge. 5E could possibly reflect "starved" conditions immediately west of the high.

The close of Winnipeg sedimentation was marked by a transitional change from deposition of terrigenous clastics to deposition of relatively clean carbonates (biomicrites). Little core is available for this interval (Appendix I), but outcrop sections, well samples and mechanical logs indicate an interbedding of argillaceous beds with limestones and dolomitic limestones. This transitional change from clastic deposition to carbonate deposition reflects a pronounced marine transgression at the end of Winnipeg time, with a drowning of the northern and eastern source areas that supplied the terrigenous Winnipeg clastics. However, no change in tectonic pattern is evident, inasmuch as the trends of the Red River isopachs coincide with those of the Winnipeg Formation. Virtually no further clastic detritus was supplied to the sedimentary basin in southwestern Manitoba (Williston Basin) during Red River time, and clean biogenic carbonate deposition, probably in a moderately deep infratidal environment prevailed throughout southwestern Manitoba. In all likelihood these extremely stable conditions extended through to the Hudson Bay Basin, across what is presently the Precambrian Shield area, and also extended far north of the present erosional edge of the unit. The lithology and fauna of the Red River Formation are essentially the same in southwestern Manitoba as in the Hudson Bay area (Cumming, 1971).

Post-Winnipeg Paleogeography

The present limits of the Winnipeg Formation are controlled by later erosion, although the northern edge probably corresponds fairly closely with the depositional edge of the unit. The present configuration of the outcrop belt is the result of Pleistocene erosion, but the regional pattern probably was established much earlier, although direct evidence of this is limited.

A period of late Paleozoic - early Mesozoic tectonic uplift probably was largely responsible for most of the erosion and truncation along the eastern limits of the Winnipeg outcrop belt. This period of uplift also gave rise to emergence of the Precambrian Shield as a major paleogeographic feature. Uplift is indicated primarily by the existence of several deep pre-Mesozoic channels, especially the channel south of Winnipeg (Fig. 5), in the vicinity of Dominion City (tp. 2, rge. 3E), where Red Beds and Evaporites of the Jura-Triassic Amaranth (Watrous) Formation rest directly on shales of the Winnipeg Formation. Extrapolation of this channel to the east indicates that, in this area at least, Winnipeg strata must have been completely truncated, and the Precambrian Shield exposed by Jura-Triassic time. This pattern of late Paleozoic or early Mesozoic uplift and erosion probably can be applied generally to the entire eastern edge of the Winnipeg outcrop belt, since a second outlier of Amaranth strata occurs to the north, in the Lake St. Martin area. In addition, the presence of a deeply incised Cretaceous channel in the Arborg area, with Cretaceous sands and clays resting directly on lower Red River strata (Fig. 8, tp. 24, rge. 1E) indicates that post-Jurassic — pre-Cretaceous uplift also may have been an important factor. Other periods of uplift and erosion may have affected the Winnipeg outcrop belt, but further direct evidence is lacking.

The tectonic framework implied by this uplift, or several periods of uplift, represents a marked change from the tectonic framework that existed not only during Ordovician time, but throughout most of Paleozoic time. The uplift appears to have occurred along a north-south trending, or slightly northwest trending belt paralleling the present outcrop edge.

One factor suggesting the existence of a possible further period of post-Jurassic or post-Cretaceous tectonism is the apparent break in slope of the Jurassic and Cretaceous strata. If southwest/northeast cross-sections are drawn through the Jurassic and Cretaceous outliers in the Dominion City, Arborg, and Lake St. Martin areas, it will be seen that the elevations of these outliers are structurally low as compared to the regional trends established in the main area of occurrence to the west. This apparent break in slope suggests a possible structural downwarping along the same north-south axis that was the site of earlier differential uplift and erosion.

In summary, an extremely complex sequence of multiple episodes of uplift, erosion and subsidence, with differing tectonic frameworks, have affected the configuration and structure of the outcrop belt of the Winnipeg Formation. The net effect, however, has been to expose along the eastern portion of the outcrop belt what is essentially a dip section of the Winnipeg Formation, with the thin shelf facies exposed in the north, passing to the relatively thick basinal facies to the south. This changing pattern of tectonism has had a profound effect on deposition of the Winnipeg strata, on the present relation of the Winnipeg facies to the regional structural pattern, and consequently on the potential for oil and gas entrapment.

REPORTED OIL SHOWS AND OIL POTENTIAL

Oil or gas shows in the Winnipeg Formation have been reported for only two test holes in Manitoba — S.V. Warnez 5-13-5-22 and Dome Strathclair 8-34-16-21 (Andrichuk, 1959). Descriptions for both cores are included in Appendix I. Complete lists of all drill stem tests and formation water analyses for the Winnipeg Formation are included in Appendices III and IV, along with a formation water salinity map (Fig. 15). In general, salinities are seen to decrease towards the outcrop belt, reflecting the down-dip incursion of meteoric water into the sand reservoirs.

No oil shows are known for Saskatchewan (Paterson, 1971). No oil production is obtained from either the North Dakota or Montana portions of the Williston Basin, although some shows have been reported from these areas, and condensate gas has been produced from the Nesson Anticline area in North Dakota.

A detailed evaluation of the overall potential for oil generation and accumulation in the Winnipeg Formation is beyond the scope of this report. However, the potential of the Winnipeg Formation for oil accumulation can be related not only to the level of oil and gas shows or production, as noted above, but also to some extent to the potential of the shales of the Winnipeg Formation as possible source beds for petroleum. Few data are available for source bed evaluation. Shale samples for the 2-20-11-24, 5-13-5-22 and 16-33-4-13 wells, from the Mines Branch core and sample library, were analyzed by an exploration company using the solvent extraction method (Philippi, 1965). The results, referred to Philippi's reference scale, ranged from poor to very poor (30-100 ppm) for the 5-13-5-22 and 16-33-4-13 wells to fair (150-350 ppm) for the 2-20-11-24 well. For the analyzed samples it appears, as might be expected, that the darker coloured olive to grey shales are better source rocks than the pale greenish and grey shales, which are the more common rock type.

Recent studies by Williams (1974) and Dow (1974) have been able to determine source bed units for the various oil accumulations in the Williston Basin area. Williams (op. cit.) indicates that the shales of the Winnipeg Formation meet the minimum requirements for petroleum source beds of 0.4% organic carbon, but only in certain limited areas of the basin. The Winnipeg shales appear to be the source rocks for what Williams refers to as Type I oils, the only type found in Ordovician or Silurian strata. Dow (op. cit.) suggests that emplacement of Type I oils in Ordovician and Silurian strata has been primarily by vertical migration along fractures, and that the several thin but persistent anhydrite layers in the upper Red River (i.e. Fort Garry Member of Manitoba) probably acted as barriers to such vertical migration. The limited occurrence of Type I oils in Devonian and Mississippian strata is accounted for by migration along minor faults with sufficient displacement to bypass the impermeable anhydrite beds. The much thicker salt and anhydrite beds of the Devonian Prairie Evaporite Formation apparently provide the ultimate barrier to vertical migration of Type I oils, as Dow (op. cit.) indicates that no Type I oils are known to occur above the Prairie Evaporite.

Dow (op. cit.) indicates that oil generation in the Winnipeg shales probably occurred only in the deeper parts of the basin, below approximately the -5 000 foot (-1 500 m) depth contour, which passes through the extreme southwest corner of the province (Fig. 5). Furthermore, within this area, only some of the Winnipeg shale beds have a sufficiently high organic content to have been effective as source rocks. This favourable area is in eastern Montana and adjacent parts of North Dakota, the area of Ordovician oil production.

The implications of the studies of Dow and Williams relative to the potential for oil accumulation in the Winnipeg and/or Red River Formations in Manitoba are not particularly favourable, especially if vertical migration is the primary mode of petroleum emplacement as suggested. However, neither Dow nor Williams discusses the possibility of lateral migration in the porous sands of the Winnipeg Formation; this would seem to be a valid possibility, and would have much more favourable implications for the prospects of oil accumulation in Manitoba.

Another factor to be considered, in the light of the recent Cambrian oil discovery in North Dakota, is the possibility of migration of oil from Cambrian strata into the overlying Winnipeg Formation. Geochemical studies of the Cambrian oil would be valuable in determining the possible contribution of Cambrian source rocks to Lower Paleozoic oil accumulations in the Williston Basin.

The foregoing discussions have presented a regional review of the structure and facies patterns of the Winnipeg Formation and a brief review of oil shows. Several general areas showing potential for oil entrapment have been noted. The following section will present a more detailed evaluation of several specific target areas, including lithologic data and correlation with available geophysical data.

Potential stratigraphic traps

i) OAK RIVER PROSPECT (tp. 13, rge. 22W)

From the lithologic map (Fig. 13), cross-section B-B' (Fig. 2), and facies map (Fig. 14), it is evident that the upper Winnipeg sands, which are fairly well developed in the 4-27-11-22, 10-28-12-23 and 3-17-12-24 wells, pinch out up dip. No equivalent Upper Winnipeg sands are present in the 2-7-14-20 well, which is directly up dip from 10-28-12-23. However, as noted previously, the possibility exists that the pinchout edge of the Upper Winnipeg sands, as shown by the northeastward edge of the transition facies or sand isopach, and which has been contoured so as to parallel the structure contours, may in fact cut obliquely across the structure so that the potential trap could be open to the northwest.

Examination of cuttings for the 10-28-12-23 well (very poor samples) indicates a fine- to medium-grained, well rounded, well sorted sand. Samples consist of loose sand suggesting a porous, friable, poorly consolidated sandstone such as is typical of the formation in outcrop. This is supported by the nature of the E-log response which shows uniform low resistivity and high negative S.P., indicative of a clean porous sand with high salt-water saturation. Grain size increases somewhat toward the base of the sand, where medium sand grains are common. The samples show no evidence of visible oil stain, but the interval was not drill stem tested. In summary, the Upper Winnipeg sand in the 10-28-12-23 well appears to comprise an excellent reservoir sand.

Samples for the 3-17-12-24 well (fair) show a mixture of very fine to fine loose sand, fairly well consolidated fine sandstone with silty matrix, and soft, very sandy and silty shale. The mechanical log response indicates that these lithologies probably occur as interbeds two to five feet thick. The relatively tight, consolidated nature of at least some of the sand is reflected in a higher resistivity response over the sand intervals (oil saturation can also give rise to higher resistivity response, but no oil stain was observed). The upper sand interval in the 3-17-12-24 well apparently represents a facies intermediate between the pure sand facies of the 10-28-12-23 well and the pure shale facies of the 2-7-14-20 well; the 12-24 well is not situated between these two wells, but it does point out the type of facies change that can be expected to occur in this area.

An examination of the geophysical maps (Figs. 10, 11) shows that the area of well developed sand in the 10-28-12-23 well is roughly coincident with a small but prominent magnetic high and a small but well defined gravity high. These geophysical anomalies appear to lie just east of the Birdtail-Waskada Axis, or Churchill-Superior boundary zone, although admittedly the geophysical definition of this feature is by no means clear in this area. If the coincidence of geophysical anomalies with the Winnipeg lithofacies anomaly is the result of a genetic or cause and effect relation, the sand body may be localized in the area of the geophysical anomalies, and an exploratory hole up dip from the 10-28-12-23 well would seem to be a valid prospect.

For any exploratory test hole, all possible targets or reservoir horizons must be identified and evaluated. Only a brief comment on targets other than the Winnipeg Formation is possible in this report. For the Oak River prospect, the location falls within the subcrop belt of the Devonian Duperow Formation. Paleotopographic entrapment in the Duperow beds is a possibility, but available data for this area give no evidence of appreciable paleotopographic relief. Although other porous reservoir strata are present in the section (e.g. Dawson Bay and Winnipegosis Formations), there is no evidence for any structural or stratigraphic anomalies, such as reefs, that might give rise to entrapment. The Winnipeg strata appear to offer the only potential target horizon in this area.

ii) CLANWILLIAM PROSPECT (tp. 16, rge. 17W)

A well developed sand approximately 11 feet (3.4 m) thick is present in the Upper Winnipeg in the 2-21-15-18 well. This sand appears to pinch out to the northeast, in the 16-11-17-15 well, but here again the configuration of the pinchout edge is critical and the potential trap may be open to the north, towards the main area of Upper Winnipeg sand development.

Samples are available only to a depth of 3 560 feet (1 085 m) in the 2-21-15-18 well, about 7 feet (2.1 m) into the sand bed. Cuttings are poor and show only a few pieces of fine-grained well rounded but poorly sorted sand with a silty and slightly calcareous matrix. Some of this calcareous sand may possibly be cave from the transition zone at the base of the Red River Formation. The relatively high resistivity response over the sand interval (Fig. 2) suggests that the sand probably is tight and may not be a good reservoir bed. Here again it must be noted that oil saturation can cause high resistivity, but no evidence of oil stain was seen.

A second sand, approximately 13 feet (4 m) thick, is present at the top of the Lower Winnipeg, and this sand also appears to pinch out to the northeast, although this trap also may be open to the north. A relatively high resistivity response is evident for this sand, suggesting that it also may be relatively tight and silty or calcareous. A similar resistive sand occurs at the top of the Lower Winnipeg in the 16-26-14-18 well; samples for this interval show only loose fine to coarse rounded to subangular sand with a trace of calcareous matrix. No drill stem tests were taken for either the 2-21-15-18 or 16-26-14-18 well.

No magnetic data are available for the prospect area, but the location is on the northwestern edge of a fairly prominent gravity high (Fig. 10).

The Clanwilliam prospect is located within the subcrop belt of the Devonian Duperow Formation. There is no evidence of any paleotopographic relief on the erosion surface in this area, but a prominent erosional high is present immediately to the northwest, in tp. 18, rge. 18W, so the possibility of oil accumulation in an unconformity trap cannot be ruled out. Other porous reservoir beds are present in the area, but there is no evidence of any Winnipegosis reef buildup or any reef-associated structures. No specific targets, other than the Winnipeg Formation, can be identified at this location.

iii) CARBERRY PROSPECT (tp. 11, rge. 15W)

Sands present in both the Lower and Upper Winnipeg in the 11-9-10-16 and 7-26-11-17 wells are seen to pinch out to the northeast (Figs. 1, 12, 13, 14). As for the other prospects, the exact configuration of the sand pinchout relative to the structure contours will determine whether or not a closed trap exists. The electric log responses over the sand intervals in the 11-9-10-16 well (Fig. 1) are not strong, and the quality of the sands as potential reservoirs is uncertain. In particular, the neutron log shows no appreciable response across the sandy intervals, whereas a strong neutron response occurs over well developed sands in other holes. Well samples for 11-9-10-16 were of no use in estimating reservoir quality because of extensive cave, including much sand and shale from the Mesozoic section. The quality of the potential reservoir sands in the 10-16 well is thus uncertain.

Cuttings for the 7-26-11-17 well recovered fairly good samples of fine- to medium-grained well rounded and sorted loose sand along with a few pieces of moderately well sorted sandstone with fine silty matrix. This sand, at the top of the Lower Winnipeg, appears to comprise a favourable reservoir bed; a strong neutron response is indicated. Also of interest is the basal sand, or sands, in the 11-17 well. The lithologic map (Fig. 13) shows two separate sand beds at the base of the Winnipeg, separated by a 4-foot (1.2 m) shale break. Although there is no evidence of up-dip pinchout or porosity decrease for these basal sands, well cuttings from this interval gave good recovery of fine to very fine grained moderately well consolidated sandstone with fine silty matrix which shows a distinct spotty yellowish brown discoloration strongly suggestive of oil staining. The presence of oil staining could not be positively confirmed, however, as no fluorescence could be obtained from the samples.

Available data do not indicate any expected sand pinchout or any structure that could give rise to trapping conditions in the basal sand in this area, but minor local topographic relief on the Precambrian surface could easily provide a local sand pinchout or porosity decrease. As noted previously, the basal Winnipeg sand is a blanket type sand which is apparently continuous throughout the map-area, but the sparsity of control leaves ample room for local sand pinchouts. Such features, however, would be entirely unpredictable unless associated with a geophysical anomaly reflecting either local basement relief or the presence of an erosion-resistant basement lithology.

The prospect area is located on the eastern flank of a poorly defined gravity high (Fig. 10). No magnetic data are available. The Paleozoic subcrop unit in the area comprises the lower part of the Devonian Duperow Formation. No paleotopography or structure is evident in the area and, as for the previous prospects, no other specific target horizons can be defined, although porous reservoir beds are present.

iv) BRANDON PROSPECT (tp. 9, rge. 19W)

The lithologic map (Fig. 13) and stratigraphic cross-section A-A' (Fig. 1) indicate the presence of a 15 to 20-foot (4.6 to 6.1 m) sandy zone in the upper Winnipeg in the 3-5-9-19 well. This zone shows only a moderate response on mechanical logs, including a small resistivity peak over part of the zone. Well cuttings recovered only shale and silty shale with a small amount of loose, fine to medium well rounded sand grains. Quality of the potential reservoir is thus uncertain.

This sand appears to pinch out up-dip to the northeast, in the 16-10-10-18 well, where the mechanical logs show only a slight suggestion of sandy development. However, this upper sand may be correlative with, and possibly continuous with, the Upper Winnipeg sand in the 11-9-10-16 well (see Carberry Prospect). Configuration of the potential trap is thus highly uncertain.

No gravity or magnetic anomalies are evident in the area of the Brandon prospect.

The prospect area is located on a major topographic scarp on the Paleozoic erosion surface. This scarp is formed at the erosional edge of the Mississippian Lodgepole Formation, as a result of differential erosion of the soft shales of the upper Devonian Lyleton Formation and the basal Mississippian Bakken Formation. Relief of 250 to 300 feet (76 to 91 m) is indicated across this scarp (Stratigraphic Map Series M-2), and this portion of the escarpment is seen to form a closed topographic high on the erosion surface. Although potential for entrapment exists in the Lodgepole and Bakken strata, the 7 exploratory wells drilled to date along this scarp have not provided any oil or gas shows. No evidence of structural deformation or reef development is known in this area, so no other target horizons can be defined.

v) NINETTE PROSPECT (tp. 5, rge. 18W)

The Ninette prospect is located on the northeastern edge of the Lower Winnipeg transition facies (Fig. 12). A thin, 10-foot (3 m) sand occurs 10 feet (3 m) above the basal sandstone in the 13-36-4-19 well; this sand also is present in wells to the southwest of the 4-19 well, except possibly 16-16-1-27 (Fig. 13). In up-dip wells (3-1-8-18, 13-5-7-15), this sand has pinched out, so the possibility of entrapment exists, although configuration of the sand pinchout is uncertain.

A drill stem test of the Lower Winnipeg in the 13-36-4-19 well, including portions of both basal sands, recovered 4 360 feet (1 329 m) of salt water at a depth of 4 500 feet (1 372 m), indicating excellent reservoir characteristics.

One interesting feature of this prospect is the reported occurrence of oil staining in the Warnez 5-13-5-22 well, 18 miles (29 km) to the west. On re-examination of this core (see Appendix I) only a trace of questionable relict staining was evident in the basal sand; no fluorescence was observed but the medium- to coarse-grained basal sandstone was seen to comprise an excellent, highly porous reservoir bed. (The sand overlying the basal sand was not cored in the Warnez well.) Local entrapment in the basal sand may thus be a possibility in this area, although no specific targets can be suggested.

Figures 10 and 11 show little evidence of any geophysical anomalies in the area, although a small easterly trending magnetic high occurs just north of the prospect.

The Ninette Prospect falls within the subcrop belt of the Mississippian Lodgepole Formation (Scallion Member), but below the position of the known reservoir beds, which subcrop approximately 15 miles (24 km) to the southwest. No structural deformation or reef development is known to occur in the area, so no other specific target horizons can be indicated.

Potential structural traps

A number of local structural anomalies have been noted and evaluated in a previous section (Hartney, Lake St. Martin and Highrock Lake). Although there is no direct evidence of any other local structural anomalies, it has been pointed out that some post-Winnipeg structural deformation has occurred along the postulated southern extension of the Churchill-Superior Boundary Zone (i.e. the Moose Lake Syncline and the Birdtail-Waskada Axis), as defined by the major geophysical anomaly patterns. It has also been noted that lithofacies anomalies show some correspondence with this trend, and that a favourable facies with a maximum interbedding of sand and shale occurs along much of this trend. If undiscovered structures are to be found, the best prospects would appear to be in the vicinity of localized geophysical anomalies, especially gravity highs, that occur along the Birdtail-Waskada Axis/Churchill-Superior Boundary Zone and that are coincident with a favourable, transition facies. On this basis the following possible target areas can be noted (ref. Figs. 10, 11, 12, 13, 14):

vi) Shortdale Prospect - tp. 26, rge. 26
vii) Birdtail Prospect - tp. 21, rge. 24
viii) Virden Prospect - tp. 9, rge. 25

The only documented example of exploratory drilling based on detailed gravity and magnetic surveys was carried out in the McCreary area (vicinity tp. 21, rge. 15). This area falls within the favourable facies area of both the Lower and Upper Winnipeg units (Figs. 12, 14), and the apparent objective of the programme was to locate a structural trap or basement high by means of detailed ground gravity and magnetic surveys. A number of fairly prominent anomalies were defined, several of which were assessed as possible basement highs. The 15-14-21-15 well was subsequently drilled to test the principal anomaly; results showed slightly anomalous values with respect to basement elevation (Fig. 9), but Winnipeg thickness, and lithology (Fig 5) appear normal. At least in this particular case, there is at best limited correlation between geophysical anomalies and basement structure or topography. Despite this lack of correlation in the McCreary area, the writer believes that the proposed geophysical targets noted along the Birdtail-Waskada Axis offer better prospects because of the structural activity known to have occurred at places along this trend. Detailed ground geophysical surveys and depth interpretations, etc. would be required to define these targets more clearly.

The above-proposed structural (i.e. gravity) targets differ from the previously defined stratigraphic targets in that a number of target horizons other than the Winnipeg Formation can be suggested for most areas. For most targets there is a possibility of Winnipegosis reef development as well as development of domal structures associated with early multiple-sequence salt collapse and/or draping over buried reefs. The Birdtail-Waskada Axis coincides with the Winnipegosis reef trends, so it would seem possible that local reef development could have been controlled by minor tectonic movements in the vicinity of local geophysical anomalies occurring along this trend. Also, considerable paleotopographic relief occurs on the Paleozoic erosion surface in this area, so the possibility of entrapment on paleotopographic highs must also be considered.

CONCLUSIONS

Available data indicate a relatively low value for source rock potential in Winnipeg strata in the Manitoba portion of the Williston Basin, but data from deeper areas of the basin indicate that the shales of the Winnipeg Formation are source rocks, in some areas, and, in fact, are the source of all known Lower Paleozoic (Ordovician and Silurian) accumulations in the Williston Basin. The sparsity of oil shows and lack of production from the Winnipeg Formation, on both a local and regional basis also is a negative factor. On the positive side, excellent reservoir beds are present along with complex facies changes, and several areas of possible stratigraphic entrapment can be delineated, although data are not sufficient to determine if full stratigraphic closure does occur. No structural traps are known, but geophysical (gravity) anomalies along the Birdtail-Waskada axis offer potential structural/stratigraphic targets. All the "prospects" outlined in this report are admittedly "long shot" wildcats, but are believed to be the best prospects definable on the basis of presently available data. It should be pointed out that most of the deep test holes in Manitoba have been drilled to test suspected anomalies in shallower horizons, and only a few holes have been drilled specifically to test the Winnipeg Formation. The lack of oil shows to date, in the Winnipeg Formation, almost certainly reflects, in part, this lack of selectivity in drilling targets.

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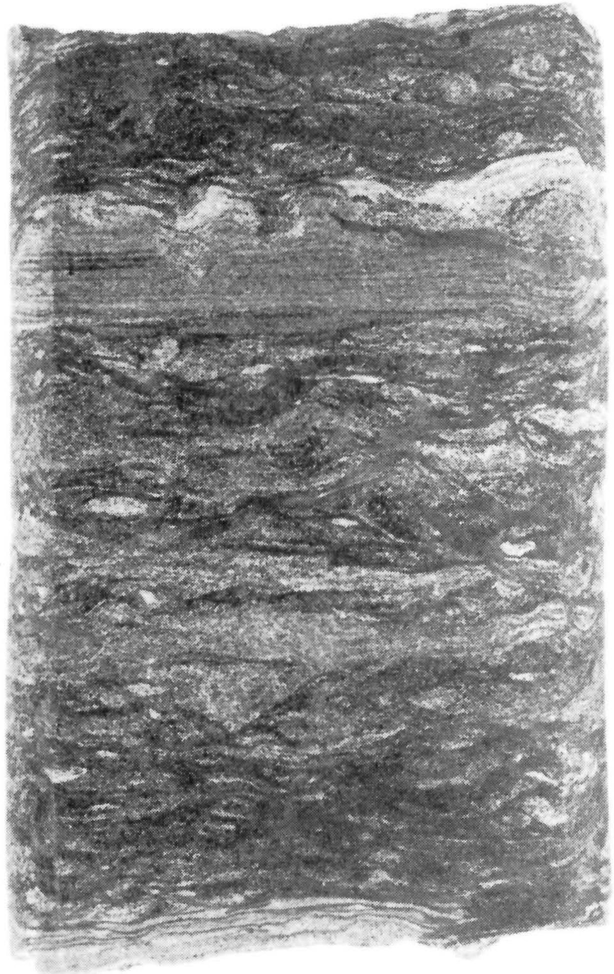
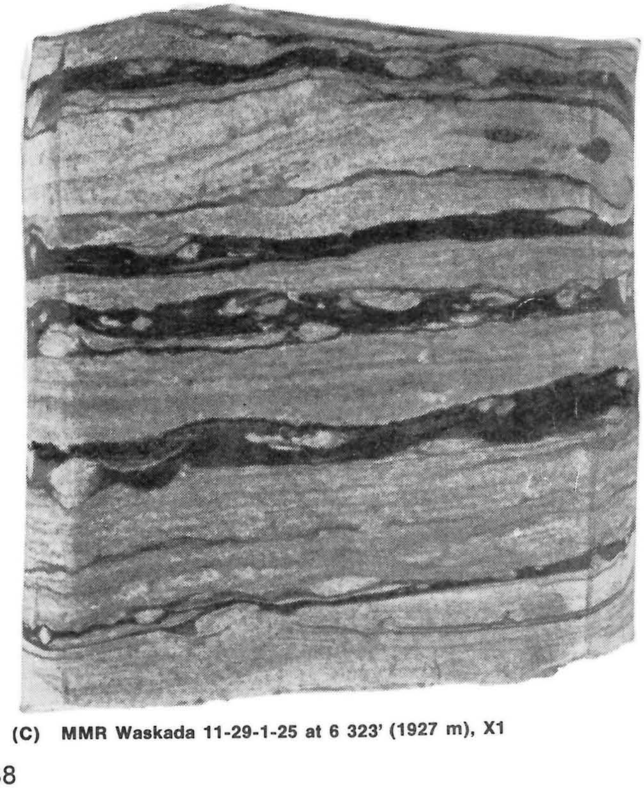
Appendix I

Core descriptions and core sample photographs

(A) MMR Waskada 11-29-1-25 at 6 322' (1927 m), X1

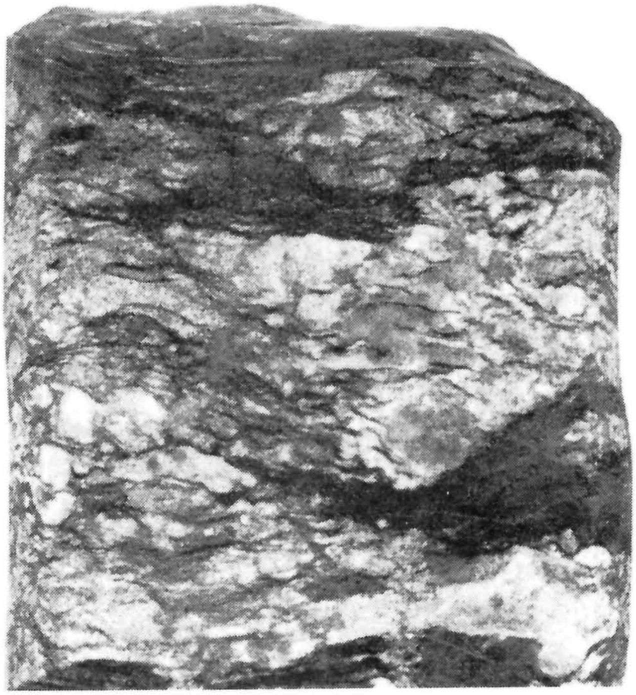


(B) MMR Waskada 11-29-1-25 at 6 321' (1926 m), X1



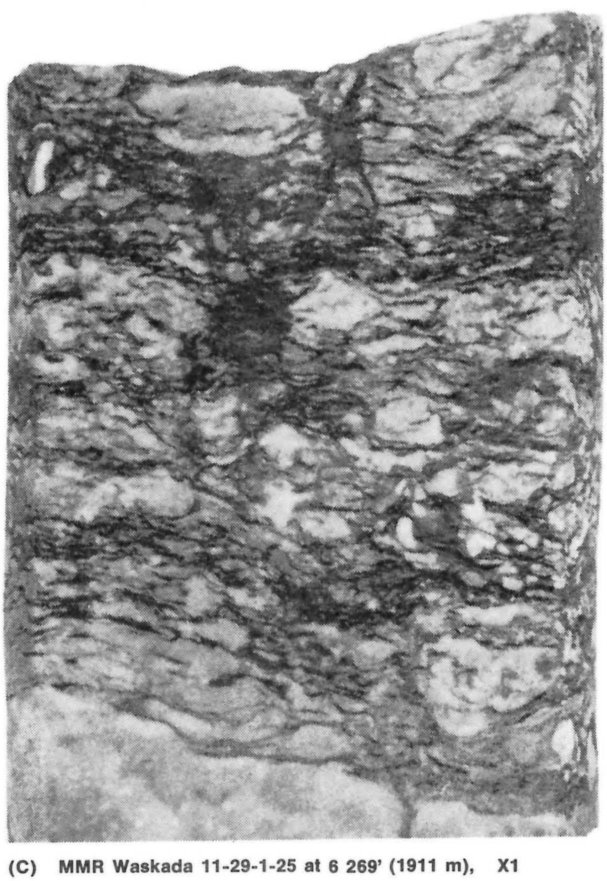
(C) MMR Waskada 11-29-1-25 at 6 323' (1927 m), X1

PLATE I. DEADWOOD FORMATION



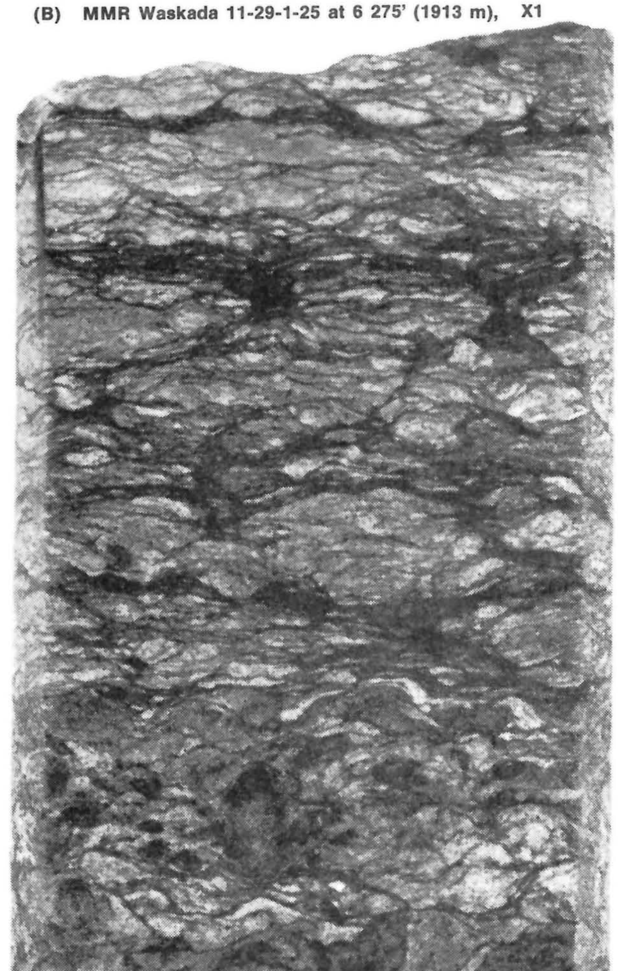
(A) MMR Waskada 11-29-1-25 at 6 268' (1910 m), X1

(B) MMR Waskada 11-29-1-25 at 6 275' (1913 m), X1

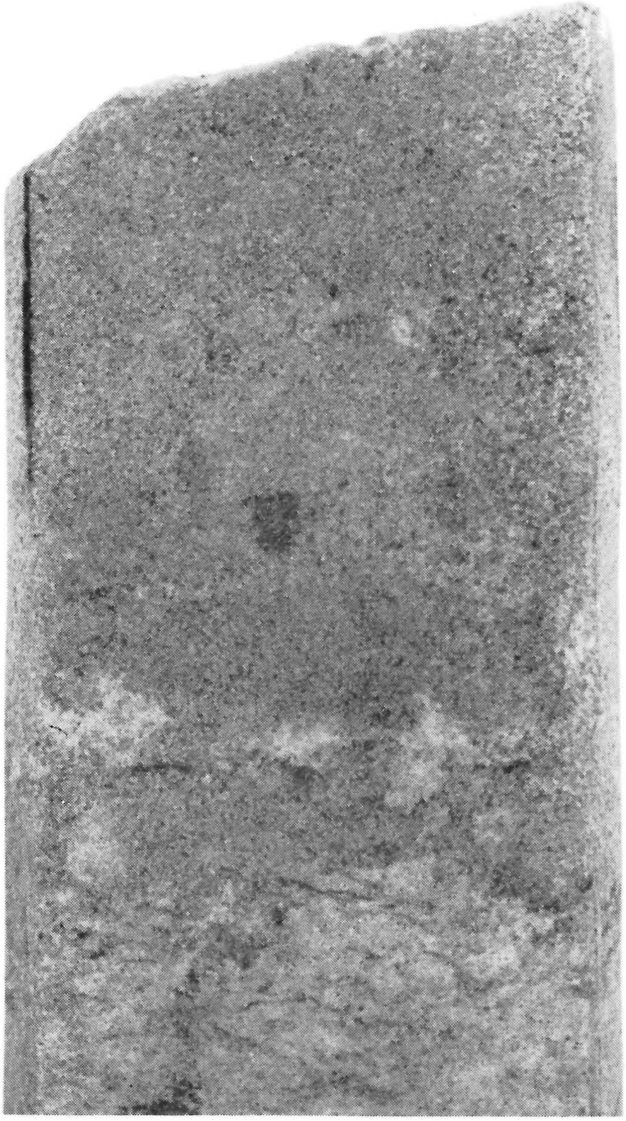


(C) MMR Waskada 11-29-1-25 at 6 269' (1911 m), X1

PLATE II. WINNIPEG FORMATION

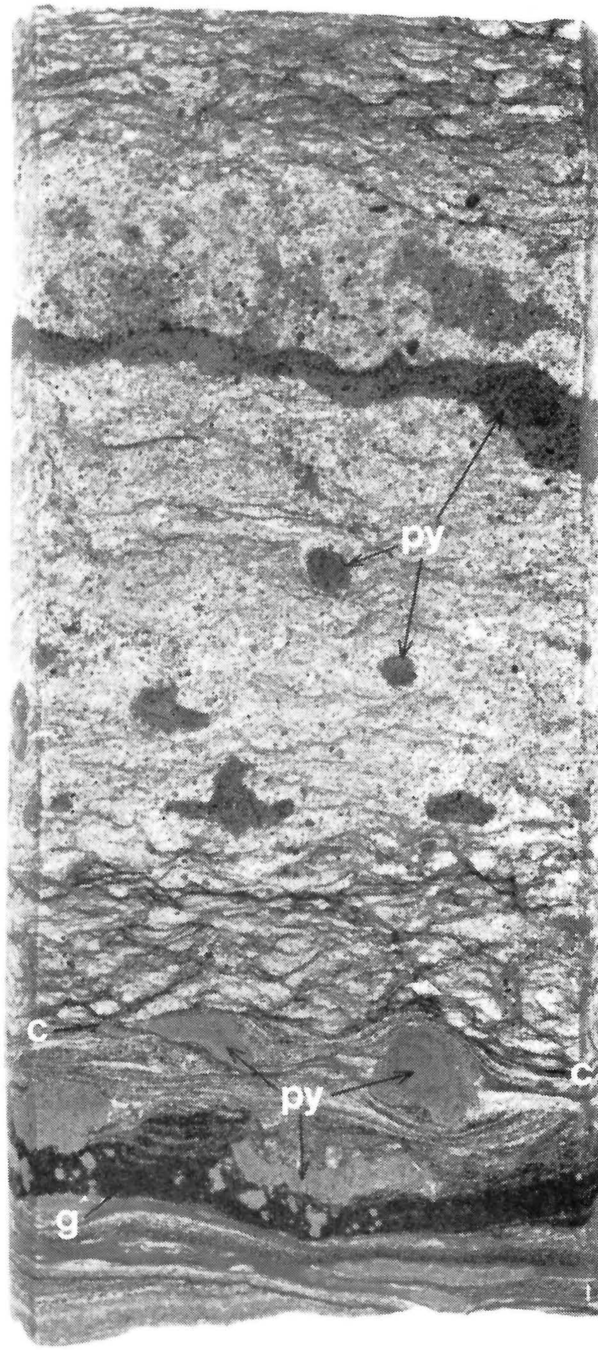


(D) MMR Waskada 11-29-1-25 at 6 296' (1919 m), X1



(A) MMR Waskada 11-29-1-25 at 6 315' (1924 m), X1

(B) MMR Waskada 11-29-1-25 at 6 316' (1925 m), X1



(C) MMR Waskada 11-29-1-25 at 6 318' (1926 m), X1

py pyrite
q quartzite fragment
g glauconite - rich band.
c contact, Winnipeg / Deadwood

PLATE III. WINNIPEG FORMATION

M.M.R. WASKADA 11-29-1-25

K.B. Elev. 1 555 feet (474 m)

Ordovician - Winnipeg Formation E-log top at 6 144 feet (1 873 m)

Core #6	6 264' - 6 324' (1 909 m to 1 928 m) Recovered 60 feet (18.3 m)
3'8" (1.12 m)	Shale, medium dark grey to olive grey, moderately fissile or platy, irregular to subconchoidal fracture, clean (almost white streak) with no appreciable sand or silt (kaolinitic ?). Grades sharply to:
3'9" (1.14 m)	Argillaceous sandstone or sandy shale, highly mottled appearance with irregular to rounded patches and stringers of white fine-grained sandstone in matrix of medium dark grey sandy silty shale. Possibly burrowed in part, but sandstone patches are so irregular as to appear largely fragmented. Clean sandstone bands up to 1 inch (3 cm). Sand in part appears to have porphyroblastic cement (anhydrite?). Grades over 1 foot (.3 m) zone to: (See Plate II,a,b)
3'4" (0.99 m)	Shale, dark olive grey, slightly silty to very fine sandy and pyritic, slightly fissile. (See Plate II,c)
2'0" (0.61 m)	Sandy shale to shaly sandstone, mottled as above, fragmental, possibly in part burrowed. Sharp irregular contact with:
39'10" (12.14 m)	Sandstone, massive, fine to medium grained at top grading to coarse at base, subrounded to rounded, polished (some faceted overgrowths?), well sorted, no matrix hence excellent porosity. Except for the several slightly argillaceous zones noted below, this section constitutes a single sand, the "basal sandstone" unit of the Winnipeg Formation. Several irregular concretionary patches of pyrite up to 3 inches (7 cm) in diameter in both clean and argillaceous sections. (See Plate II,e) From 11' to 19'8" (3.35 m to 5.99 m). Slightly to moderately argillaceous especially at top and bottom with numerous irregular argillaceous partings. Mottled nodular appearance. (See Plate II,d) From 26'4" to 26'10" (8.03 m to 8.12 m). Minor argillaceous partings. From 30' to 34'10" (9.14 m to 10.62 m). Minor argillaceous partings and stringers imparting nodular appearance; some yellowish alteration.
1'6" (0.46 m)	Basal zone. Sandstone, coarse grained, slightly argillaceous; highly pyritic with abundant irregular sandy pyrite concretions ½" to 2" (1 to 5 cm), some showing concentric banding. Some concretions may be reworked fragmental material since pyrite is abundant in upper part of underlying Deadwood. One irregular bed of pyrite ¼ inch (6 mm) thick. Irregular quartzite fragments to ½ inch (13 mm) at top of zone. Contact with underlying Deadwood is sharp, gently irregular or undulating, and essentially conformable to bedding with almost no evidence of inclusion of fragments of the underlying beds. (See Plate IIIb,c)
	Cambrian - Deadwood Formation E-log top 6 314 feet (1 925 m).
4'9" (1.45 m)	Siltstone to fine sandstone, medium dark greenish grey, streaked and banded, tight, highly glauconitic, argillaceous. In part shows fine uniform to slightly irregular lamination with minor faint cross-bedding; in part irregular nodular fragmental appearing with nodular inclusions of siltstone in argillaceous matrix, possibly in part burrowed. Glauconite occurs as dark greenish-black rounded grains, fine sand-size, in places comprising more than 50% of the

rock. Upper 18 inches (46 cm) contains abundant pyrite as disseminated grains, small patches and irregular nodules to 2 inches (7 cm) in diameter. Grades to: (See Plate Ia,b)

1'10" (0.3 m) — Thin, irregularly interbedded light buff, finely laminated to slightly cross-bedded siltstone, slightly glauconitic, and medium greenish-grey shale. Interbedding highly irregular and lensy, from 1/16 inch to 1 inch (2 mm to 25 mm). (See Plate Ic)

Well cuttings indicate that the balance of the Deadwood section, from 6 324' to 6 372' (1 926 m to 1 942 m) consists of siltstone grading downward to fine sandstone, in part glauconitic. Relatively compact and tight towards the top but showing excellent intergranular porosity towards the base. Minor fine shaly partings or interbeds. Precambrian weathered zone must be very thin, as the first sample to show Precambrian material contains relatively fresh looking pink to grey biotite granite.

LANDA WARNEZ 5-13-5-22

K.B. Elev. 1 635 feet (498 m)

Ordovician - Winnipeg Formation E-log top at 4 912 feet (1 497 m)

Core #15 — 5 030' - 5 038' (1 533 m to 1 536 m). Recovered 8 feet (2.4 m).

8' (2.44 m) — Shale, silty, medium grey to olive brown, moderately fissile, rather dull luster, irregular to subconchoidal fracture, faint brecciated texture in part with fine flat fragments of brownish shale in matrix of more greenish silty shale. Scattered reddish silty patches, probably limonitic with trace of relict sulphide. Becomes more brownish towards base. At 5 feet (1.5 m), one 8-inch (20 cm) band of sandy shale with medium rounded frosted sand grains and some sand-size limonite oolites.

Core #16 — 5 038' - 5 061' (1 536 m to 1 543 m). Recovered 22 feet (6.7 m).

3' (0.91 m) — Shale, medium dark grey, massive, silty to fine sandy. Sand shows patchy to lensy distribution, possibly burrowed but burrows poorly defined.

5' (1.52 m) — Shale, medium greenish grey, massive to moderately fissile, smooth, relative pure with only slight silt content.

1'6" (0.45 m) — Transition zone. Medium grey fine sandy silty shale showing patchy sand distribution, possibly burrowed. Grades to:

2' (0.61 m) — Sandstone, hard, partly cemented (anhydrite ?), fine to very fine grained, highly disrupted texture at least in part bioturbated with several vertical burrows to 8 inches (20 cm), but mostly shows lenticular, pseudo-breccia texture. Dark brownish streaks possibly bituminous or oil stained but no fluorescence obtainable. Base of unit fairly sharp but irregular with shale rip-up fragments in sand. Vertical sand-filled burrows extend into underlying shale.

1'8" (0.51 m) — Shale, medium grey, massive to slightly fissile, smooth, waxy, clean white streak. Considerable fine disseminated reddish specks, probably hematite after pyrite.

0'6" (0.15 m) — Transition zone. Medium dark brownish to greenish grey shale with lenses (burrows) of relatively clean sand.

8'10" (2.69 m)	Sandstone, massive, medium to coarse grained, well sorted, rounded and frosted, very soft and friable with no appreciable matrix or cement. Excellent porosity. Some brownish streaks, possibly oil stained but no fluorescence obtainable.

CHEVRON HARTNEY 16-33-5-24

K.B. Elev. 1 420 feet (433 m)

Ordovician - Winnipeg Formation E-log top at 4 954 feet (1 510 m)

Core #60	4 979' - 4 992' (1 516 m to 1 522 m). Recovered 12 feet (3.7 m).
1' (0.30 m)	Shale, massive, medium grey to brownish-grey, smooth, clean (white streak); abundant coarse brown limonite oolites showing patchy dissemination and commonly associated with floating fine to medium rounded frosted sand grains.
2' (0.61 m)	Shale, medium greyish green, abundant patchy limonitic oolites but little or no associated sand. Core badly disaggregated into platy fragments.
2' (0.61 m)	Shale, as Unit 1, more massive, oolitic. Oolites concentrated in tubular burrows.
7' (2.13 m)	Shale, medium greenish grey, clean (white streak), only trace sand, no oolites; scattered dark grey to black irregular rounded phosphatic ? fragments, and trace thin-shelled brachiopod fragments. Core badly broken.

ARCO SHILO 10-2-9-16

K.B. Elev. 1 239 feet (378 m)

Ordovician - Winnipeg Formation E-log top at 3 124 feet (952 m)

Core #1	3 220' - 3 250' (981 m to 991 m). Recovered 30 feet (9.1 m).
27' (8.2 m)	Shale, medium grey to greenish grey, massive, slightly fissile, blocky fracture, becomes slightly silty to very fine sandy in lower part. Grades to:
	Basal Sandstone Unit
3' (0.9 m)	Sandstone, massive, medium grained; upper 1.5 feet (0.46 m) impure argillaceous; irregular mottled (burrowed ?) appearance. Grades to clean tight sandstone with coarse porphyroblastic anhydrite cement. (Hole bottoms approximately 14 feet above basement, at top of basal sandstone. The small resistivity peak at the top of the basal sand reflects the tight, cemented nature of the sand. Log response indicates that the lower part of the sand is porous and uncemented).
	Base Winnipeg Formation, E-log 3 264 feet (995 m).

ARCO SHILO 10-24-9-16

K.B. Elev. 1 223 feet (373 m)

Ordovician - Winnipeg Formation E-log top at 3 065 feet (934 m)

Core #1	3 175' - 3 215' (968 m to 980 m). Recovered 40 feet (12.2 m).
7'6" (2.29 m)	Shale, medium grey to greenish grey, faint fine banding, moderately fissile, some slickensides.
7' (2.13 m)	Shale as above with patchy inclusions of fine sandstone becoming abundant in bottom 2 feet (0.61 m), and grading to argillaceous sandstone.
	Basal Sandstone Unit
4'6" (1.37 m)	Sandstone, light grey, fine to medium grained, well cemented with calcite and pyrite; pyrite cement abundant near base. Very sharp undulatory, uncomformable contact with underlying Precambrian. No evidence of basement fragments in sandstone.
	Precambrian E-log top at 3 914 feet (974 m)
21' (6.4 m)	"Greenstone". Soft, green, fine-grained, well banded (dips 50^{o} - 60^{o}), highly fractured and slickensided. Stockworks appearance with fractures fillings of quartz and calcite.

CHEVRON DALY 15-18-10-27

K.B. Elev. 1 614 feet (492 m)

Ordovician - Winnipeg Formation E-log top at 5 210 feet (1 588 m)

Core #23	5 353' - 5 363' (1 632 m to 1 635 m). Recovered 8'2" (2.49 m).
4' (1.22 m)	Sand, coarse grained, highly friable to unconsolidated. Pale yellow brown color, possibly oil stained? Grades to:
3' (0.91 m)	Sandstone, more consolidated but still moderately friable, some fine silty matrix and trace clear crystalline cement (anhydrite?). Considerable soft yellowish patchy material at top (not identified). Becomes increasingly more consolidated towards base, and mottled due to presence of pyritic patches. Sharp, irregular, highly pyritic contact with:
1'2" (0.36 m)	Shale, light grey with medium yellowish mottling (oil stain ??), considerable fine patchy pyrite. Common fine black flakes, probably biotite.
	Base Winnipeg Formation, E-log 5 368 feet (1 636 m)

DOME STRATHCLAIR 8-34-16-21

K.B. Elev. 1 991 feet (607 m)

Ordovician Winnipeg Formation E-log top at 3 780 feet (1 152 m)

Core #5	3 802' - 3 852' (1 159 m to 1 174 m). Recovered 50 feet (15.2 m).
6' (1.8 m)	Shale, medium light greenish grey, faintly banded, silty, clean (white streak) (kaolinitic ?). Trace pyrite, in part oxidized to hematite, and medium floating sand grains. Sand abundant in 4-inch (10 cm) bed at 1 foot (30 cm); possibly burrowed texture.
0'4" (0.1 m)	Silty shale, medium greenish grey with abundant tubular burrows consisting primarily of siltstone. In cross-section, burrows range from slightly flattened ovoids to lenses.
2'6" (0.76 m)	Shale, medium light greenish grey, only slightly silty. Trace very fine sand-filled burrows, becoming more common towards base.
1' (0.3 m)	Sandy shale to argillaceous sandstone. Transition zone. Sandstone fine to very fine grained, well rounded and sorted, appears highly burrowed. Patchy brownish staining, possibly oil stain but no fluorescence obtained.
13'6" (4.1 m)	Sandstone, soft and friable, very poorly consolidated, almost no visible matrix or cement, excellent porosity, medium to coarse grained, well rounded and sorted, frosted and pitted. Patchy argillaceous stringers in upper 5 feet (1.5 m) and lower 3 feet (0.9 m). Trace fine pyritic stringers and yellow limonitic staining. Some brown patchy stain, possibly oil, but no fluorescence. Pronounced tubular burrowed structures towards base.
7' (2.1 m)	Shale, very silty to partly very fine sandy, medium light greenish grey with abundant lenticular and tubular silt filled burrows. Trace thin-walled chitinous fossil fragments.
17'6" (5.3 m)	Shale, massive, medium grey streak (not as "clean" as above), hackly fracture. After 3 feet (1 m) grades to medium olive brown. Lower half of core almost completely disaggregated into ½ to 1 inch (1 to 3 cm) chips. At 12 feet (3.7 m) grades to medium olive green with abundant scattered brown medium sand size limonitic oolites, in places concentrated along bedding planes and in places as filling of ¼" to ½" (8 to 12 mm) burrows. Trace silt to fine sand towards base.
2'6" (0.7 m)	Sandstone, partly calcareous, hard, well cemented, fine to very fine grained, 8-inch (20 cm) argillaceous transition zone to top and scattered argillaceous partings throughout. Well developed cross-cutting horizontal burrows (¼ inch, 6 mm) at base. One inch (2.5 cm) round carbonate inclusion or concretion 6 inches (15 cm) above base.

PASCAR #2 CORE HOLE (NE 11-25-3W)

K.B. Elev. approx. 840 feet (256 m)

Ordovician - Red River Formation

Core #24	575' - 600' (175 m to 183 m). Recovered 13 feet (4.0 m).
5' (1.52 m)	Calcareous dolomite or dolomitic limestone, mottled medium yellowish brown to light greyish brown, very finely crystalline, tight to slight intergranular porosity; patchy and disseminated pyrite common.
1' (0.30 m)	Interbedded calcareous dolomite and medium dark grey slightly calcareous shale; very silty and pyritic, with a few scattered floating fine to medium sand grains. Some fine black organic partings.
	Ordovician - Winnipeg Formation Top 581 feet (177 m)
4" (0.10 m)	Shale, calcareous, medium grey, massive, dull, slightly silty, disaggregates in water.
5' (1.52 m)	Shale non-calcareous, light to medium grey, slightly greenish to brownish, massive to slightly fissile, dull to waxy luster, minor disseminated pyrite; a few scattered brown medium to coarse grained limonite oolites and floating sand grains towards base. Grades sharply to:
1'6" (0.46 m)	Sandstone, medium light grey, tight, massive, moderately friable, fine to medium grained, well rounded and frosted, argillaceous matrix; patches of light buff dolomitic cement give mottled appearance. (Most of 12 feet (3.66 m) of missing core probably from this interval.)
Cores #25, 26, 27	600' - 675' (183 m to 206 m) No recovery. Probably all friable sand.
Core #28	675' - 700' (206 m to 213 m). Recovered 13 feet (4.0 m).
13' (4.0 m)	Sandstone, light grey, very friable and poorly consolidated, fine to medium grained, well sorted, slightly coarser grained towards base, excellent porosity; massive with no shaly beds or impurities other than trace pyrite.
	Precambrian basement reported at 713 feet (213 m), total depth of hole.

GRAND RAPIDS CORE HOLE NO. 818 (13-22-48-13 WPM)

K.B. Elev. 765.6 feet (233.3 m)

Ordovician - Red River Formation

Core #29	426.5' - 474' (130 m to 144 m). Recovered 14 feet (4.3 m).
8' (2.43 m)	Dolomite, faintly mottled light grey to yellowish brown, very finely crystalline to microcrystalline, slight intergranular to pin-point and fine vuggy porosity, slightly darker towards base with disseminated and patchy pyrite. Bottom 6 inches (15 cm) shows medium to fine rounded and frosted floating sand grains.

Ordovician - Winnipeg Formation Top at 434.5 feet (132.4 m)

1'6" (0.46 m)	Sandstone, dolomitic irregularly mottled light buff to dark grey, medium to coarse grained, moderately well sorted, tight, scattered pyrite. In part has burrowed appearance.
2'6" (0.76 m)	Variable. Silty shale to medium grained sandstone, medium light grey and greenish grey, well rounded and frosted; sorting ranges from fairly good to poor. Fair to good banding and fine shale lamination. Pyrite common to abundant in finer grained samples. (Most of the 33.5 feet (10.2 m) of missing core is probably unconsolidated sandstone from this interval.)

Precambrian Top at approx. 400 feet (143 m)

2' (0.61 m)	Highly weathered granite or granodiorite. Weathered in situ, not reworked. Consists of irregular quartz grains and biotite flakes in white kaolinitic matrix. Grades downward to fresh granodiorite at about 480 feet (146 m).

WINNIPEG CENTRAL GAS CORE HOLE NO. 4 (approx. 13-10-2 EPM, Winnipeg)

K.B. Elev. approx. 766 feet (233 m)

Ordovician - Red River Formation

491' - 518' (149.7 m - 157.9 m)	Limestone, argillaceous, dolomitic, mottled and streaked shades of medium dark to light reddish and brownish grey, very finely crystalline granular with scattered fossil fragments (biomicrite). Shale content increases erratically towards base with several non-calcareous shale beds to 1 inch (2.5 cm) in thickness. Passes sharply to:

Ordovician - Winnipeg Formation

518' - 527' (157.9 m - 160.6 m)	Shale, non-calcareous except for a few inches near top; dark dusky reddish brown at top, grading to brownish grey; massive to poorly fissile, disaggregates in water; medium to coarse rounded and frosted sand grains and brown limonitic oolites become prominent towards base, and unit grades in part to very argillaceous sandstone. Oolites are not present in more sandy intervals.
527' - 531' (160.6 m to 161.8 m)	Shale, medium grey to greenish grey, reddish stain in upper 1 foot (0.3 m), massive, flat subconchoidal fracture, some patchy disseminated pyrite, trace conodonts; a few scattered rounded frosted sand grains. Becomes increasingly sandy towards base.
5315 - 578.5' (161.8 m to 176.3 m)	No core recovery. Probably unconsolidated sand. Sand reported in sludge returns.
578.5' - 590' (176.3 m - 179.8 m)	Shale as above, grading to olive green in bottom one foot (0.3 m), with fine silty patches.
590' - 600' (179.8 m - 182.9 m)	Shale, medium to light grey and greenish grey, massive to moderately fissile, silty, slightly pyritic and micaceous.
600' - 630' (182.9 m - 192 m)	Recovered 8'6" (2.6 m). 2' (0.61 m): Interbedded medium light grey shale and sandy shale to argillaceous sandstone, medium to coarse grained, rounded and frosted; disseminated pyrite and some patches pyrite cement.

	2'6" (0.76 m): Argillaceous sandstone as above, moderately well consolidated: patchy crystalline (anhydrite ?) cement and minor patchy pyrite cement; irregular, nodular, possibly burrowed appearance. More argillaceous towards base. 3'0" (0.91 m): Shale, silty and sandy, medium light brownish to greenish grey; abundant coarse brown limonitic oolites occur in patches, with some associated medium to coarse sand grains. 1'0" (0.30 m): Shale, medium grey; some lighter colored shale fragments. Scattered sand grains towards base and some small black phosphatic nodules.
630' - 640' (192 m - 195 m)	Shale, medium light grey to greenish-grey, waxy, clean (white streak); silty with scattered sand grains in upper 4 feet (1.22 m), grading to sandstone in part. Bottom 6 feet (1.83 m) only slightly silty and sandy.
640' - 650' (195 m - 198 m)	Recovered 6 feet (1.83 m). Shale as above with sand patches in bottom 1.5 feet (0.46 m).
650' - 660' (198 m - 210 m)	Core missing. Includes contact with underlying Precambrian.
	Precambrian
663' - 673' (202 m - 205 m)	Gneissic granite, faintly banded to massive; appears almost fresh, unweathered.

Appendix II
Well data tables

TABLE II: WELL DATA — WINNIPEG AND DEADWOOD FORMATIONS

Well location	K.B. Elev. feet/(metres)	Depth to Winnipeg	Depth to Precambrian	Total thickness	Sand thickness	Number of Sands. Upper	Number of Sands. Lower
13-5-6E	967 (295)	312 (95)	488 (149)	176 (54)	98 (30)	1	0
10-7-4E	800 (244)	356 (109)	536 (163)	180 (55)	96 (29)	1	0
12-8-1E	784 (239)	624 (190)	795 (242)	171 (52)	81 (25)	1	2
3-10-7E	884 (269)	194 (59)	355 (108)	161 (49)	97 (30)	1	2
15-11-1E	795 (242)	672 (205)	799 (244)	127 (39)	42 (13)	1+	2
1-28-1-2W	830 (253)	1044 (318)	1180 (360)	136 (41)	39 (12)	2-	1
13-24-1-12	1536 (468)	3320 (1012)	3452 (1052)	132 (40)	26 (8)	0	1
16-16-1-27	1497 (456)	6625 (2019)	-	175 (53)	55 (17)	0	1
Deadwood 6800 (2073 m). Total depth 6838 (2084 m) in Deadwood							
16-11-2-10	1578 (481)	2983 (909)	3115 (949)	132 (40)	10 (3)	0	1
13-5-2-15	1561 (476)	4002 (1220)	4147 (1264)	143 (43)	22 (7)	0	1
8-15-2-20	1914 (583)	5187 (1581)	5360 (1634)	173 (53)	52 (16)	0	2
3-9-4-11	1546 (471)	3014 (919)	3173 (967)	159 (48)	35 (11)	1	1
16-33-4-13	1427 (435)	3230 (985)	3365 (1026)	135 (41)	17 (5)	1	1
7-34-4-15	1498 (457)	3551 (1082)	3733 (1138)	182 (55)	75 (23)	1	1
13-36-4-19	1628 (496)	4400 (1341)	4555 (1388)	155 (47)	28 (9)	0	2
5-3-4-25	1518 (463)	5688 (1734)	5854(?) (1784)	166 (51)	60 (18)	0	2+
2-35-5-8	1449 (442)	2342 (714)	2532 (772)	190 (58)	89 (27)	1	1
1-27-5-14	1408 (429)	3242 (988)	3426+(1044+)	184+(56+)	101+(31+)	1	?
5-13-5-22	1635 (498)	4912 (1497)	5072+(1546+)	149+(45+)	18+(5+)	0	2+
16-33-5-24	1420 (433)	4954 (1510)	5110 (1558)	156 (48)	39 (12)	0	2
9-35-5-25	1425 (434)	5170 (1576)	5332 (1625)	162 (49)	68 (21)	1	2-
20-6-1	787 (240)	826 (252)	1007 (307)	181 (55)	95 (29)	1	2-
9-22-6-6	951 (290)	1538 (469)	1727 (526)	189 (58)	96 (29)	1	1
13-16-6-12	1331 (406)	2832 (863)	3028 (923)	196 (60)	92 (28)	1	1
7-35-7-4	826 (252)	1143 (348)	1332 (406)	189 (58)	89 (27)	1	1+
16-22-7-10	1415 (431)	2530 (771)	2710 (826)	180 (55)	62 (19)	1	1
13-5-7-15	1258 (383)	3277 (999)	3424 (1043)	147 (45)	18 (5)	0	1
4-6-8-3	814 (248)	1102 (339)	-	-	-	-	-
16-12-8-4	818 (249)	1070 (326)	1250 (381)	180 (55)	94 (28)	1	1
7-32-8-5	914 (279)	1397 (426)	1553 (473)	156 (48)	57 (17)	1	1
6-11-8-7	1006 (307)	1680 (512)	1840 (561)	160 (49)	68 (21)	1	1
13-7-8-9	1205 (367)	2263 (690)	2390 (728)	127 (39)	16 (5)	1	1
16-21-8-12	1145 (349)	2539 (774)	2674 (815)	135 (41)	8 (2)	0	1
8-36-8-14	1047 (319)	2630 (802)	2760 (841)	130 (40)	5 (2)	0	1
7-35-8-15	1220 (372)	2994 (913)	3124 (952)	130 (40)	6 (2)	0	1
3-1-8-18	1364 (416)	3668 (1118)	3814 (1162)	146 (45)	16 (5)	0	1
5-26-0-5	836 (255)	1264 (385)	1390 (424)	126 (38)	16 (5)	1	1
8-20-9-6	977 (298)	1571 (479)	1690 (515)	119 (36)	14 (4)	0	1
13-10-9-11	1187 (362)	2395 (730)	2522 (769)	127 (39)	7 (2)	0	1
3-5-9-19	1374 (419)	3822 (1165)	3983 (1214)	161 (49)	47 (14)	1-	2
10-36-10-4	803 (245)	1067 (325)	1185 (361)	118 (36)	27 (8)	0	1
5-3-10-10	1182 (360)	2210 (674)	2333 (711)	123 (37)	11 (3)	0	1
11-9-10-16	1238 (377)	3073 (937)	3208 (978)	135 (41)	41 (12)	1	2
16-10-10-18	1211 (369)	3296 (1005)	3445+(1050+)	149+(45+)	43+(13)	0	1
15-18-10-27	1614 (492)	5210 (1588)	5368 (1636)	158 (48)	35 (11)	0	1
NW1-11-1	791 (241)	732 (223)	866+(264+)	134+(41+)	58+(18+)	1	3
NE4-11-1	791 (241)	786 (240)	906 (276)	120 (37)	31 (9)	3	2
NE13-11-1	793 (242)	720 (219)	842 (257)	122 (37)	46 (14)	1	2
2-16-11-10	976 (297)	1952 (595)	2082 (636)	130 (40)	18 (5)	0	1
5-31-11-13	1303 (397)	2648 (807)	2790 (850)	142 (43)	36 (11)	0	2
7-26-11-17	1311 (400)	3100 (945)	3245 (989)	145 (44)	35 (11)	0	3
4-27-11-22	1381 (421)	3912 (1192)	4065 (1239)	153 (47)	63 (19)	2-	3
2-20-11-24	1503 (458)	4422 (1348)	4558 (1389)	136 (41)	28 (9)	1+	2
3-17-12-24	1550 (472)	4344 (1324)	4488 (1368)	144 (44)	31 (9)	1+	2+
16-20-13-9	853 (260)	1606 (490)	1735 (529)	129 (39)	17 (5)	0	1
3-19-13-15	1285 (392)	2738 (834)	2872 (875)	134 (41)	31 (9)	0	1
16-36-14-3	895 (273)	939 (286)	1058 (322)	119 (36)	35 (11)	0	2
7-11-14-5	830 (253)	1100 (335)	1218 (371)	118 (36)	22 (7)	0	2
5-29-14-14	1142 (348)	2377 (725)	2500 (762)	123 (37)	20 (6)	0	1
15-29-14-14	1162 (354)	2381 (726)	2550 (777)	169 (52)	42 (13)	0	2
16-26-14-18	1824 (556)	3430 (1045)	3570 (1088)	140 (43)	44 (13)	0	2
2-7-14-20	1824 (556)	3847 (1173)	3989 (1215)	141 (43)	47 (14)	0	2
12-10-14-25	1643 (501)	4260 (1298)	4414 (1345)	154 (47)	65 (20)	1	2
4-6-15-2	888 (271)	939 (286)	1045 (319)	106 (32)	28 (9)	1	2

Note: 5072 + (1310+) indicates minimum depth or thickness value; hole not drilled sufficiently deep to obtain complete data. 1± for number of sands indicates uncertainty as to whether or not sand sufficiently well defined to be "discrete". Metric values shown in parenthesis (metres) are converted only to nearest value.

TABLE II: WELL DATA — WINNIPEG AND DEADWOOD FORMATIONS (cont'd)

Well location	K.B. Elev. feet/(metres)	Depth to Winnipeg	Depth to Precambrian	Total thickness	Sand thickness	Number of Sands. Upper	Number of Sands. Lower
13-12-15-16	1371 (418)	2678 (816)	2810 (856)	132 (40)	30 (9)	0	1
2-21-15-18	1941 (592)	3516 (1072)	3665 (1117)	149 (45)	62 (19)	1	2
12-13-16-13	966 (294)	1917 (584)	2038 (621)	121 (37)	13 (4)	0	1
8-34-16-21	1991 (607)	3780 (1152)	3920 (1195)	140 (43)	58 (18)	1	3-
16-11-17-15	1218 (371)	2296 (700)	2428 (740)	132 (40)	28 (9)	0	1
12-23-17-20	2060 (628)	3638 (1109)	3780 (1152)	142 (43)	65 (20)	2	2
6-23-17-23	1862 (568)	3788 (1155)	3938 (1200)	150 (46)	82 (25)	1	3-
1-27-17-26	1971 (546)	4100 (1250)	4244 (1294)	144 (44)	57 (17)	2+	3+
16-18-18-29	1597 (487)	4268 (1301)	4428 (1350)	160 (49)	92 (28)	1	3
16-32-19-27	1821 (555)	4025 (1227)	4168 (1270)	143 (44)	93 (28)	1	1
14-17-20-5	840 (256)	937 (286)	1069 (326)	132 (40)	50 (15)	0	2-
16-15-20-6	833 (254)	974 (297)	1116 (340)	142 (43)	83 (25)	3	2
4-20-20-15	1093 (333)	1950 (594)	2098 (639)	148 (45)	85 (26)	1	2
16-20-21-5	863 (263)	896 (273)	1046 (319)	150 (46)	94 (29)	3	2
16-19-21-11	904 (276)	1410 (430)	1549 (472)	139 (42)	74 (23)	1+	2+
15-14-21-15	985 (300)	1730 (527)	1884 (574)	154 (47)	108 (33)	1+	1+
14-22-21-15	961 (293)	1708 (521)	1868 (569)	160 (49)	114 (35)	1	2+
4-19-21-27	1613 (492)	3926 (1197)	4057 (1237)	131 (40)	77 (23)	1	1
13-34-23-12	865 (264)	1291 (393)	1450 (442)	159 (48)	135 (41)	3+	1+
6-33-23-16	943 (287)	1688 (515)	1820 (555)	132 (40)	82 (25)	3	1+
1-24-24-3	855 (261)	620 (189)	765 (233)	145 (44)	84 (26)	3-	4-
1-11-24-26	1823 (556)	3395 (1035)	3522 (1074)	127 (39)	67 (20)	3-	1+
5-6-26-5	930 (283)	824 (251)	972 (296)	148 (45)	122 (37)	3-	2-
8-30-29-8	805 (245)	765 (233)	896 (273)	131 (40)	98 (30)	1	1
2-2-31-25	2305 (703)	3254 (992)	3370 (1027)	115 (35)	74 (23)	2	1
16-35-34-26	1834 (559)	2590 (789)	2698 (822)	108 (33)	90 (27)	2	1+
13-3-35-29	1369 (417)	2356 (718)	2470 (752)	114 (35)	93 (28)	1	1
9-1-37-28	1186 (361)	1932 (589)	2035 (620)	103 (31)	?	?	?
11-8-45-25	875 (267)	1042 (318)	1108 (338)	66 (20)	43 (13)	1	2
14A-27-11-26	1514 (461)	4644 (1415)	4794 (1461)	150 (46)	50 (15)	3-	1
10-28-12-23	1621 (494)	4150 (1265)	4328 (1319)	178 (54)	74 (23)	1+	4-
10-2-9-16	1239 (378)	3124 (952)	3264 (995)	140 (43)	14 (4)	0	1
10-24-9-16	1223 (373)	3065 (934)	3194 (974)	129 (39)	5 (2)	0+	1
15-10-2W	786 (240)	860 (262)	1011 (308)	151 (46)	58 (18)	1	2
			SUPPLEMENT				
1-29-1-7W	1553 (473)	2564 (782)	2704 (824)	140 (43)	15 (5)	0	1
11-29-1-25	1555 (474)	6144 (1873)	6372 (1942)	170 (52)	47 (14)	0	2-
	Deadwood 6314 (1925 m) - Deadwood thickness 58 (18 m)						
4-4-3-15	1542 (470)	3875 (1181)	4017 (1224)	142 (43)	11 (3)	0	1+
16-13-5-12	1502 (458)	2987 (910)	3165 (965)	178 (54)	66 (20)	1	1
13-11-5-16	1572 (479)	3764 (1147)	3972 (1213)	208 (63)	115 (35)	1	1
16-16-5-21	1590 (485)	4742 (1445)	4907 (1496)	165 (50)	26 (8)	0	2-
4-11-6-7	1010 (308)	1751 (534)	1940 (591)	189 (58)	93 (28)	1	1
16-34-6-29	1677 (511)	6173 (1881)	6402 (1951)	172 (52)	50 (15)	0	1
	Deadwood 6345 (1934 m) - Deadwood thickness 57 (17 m)						
1-12-7-2	793 (242)	863 (263)	1047 (319)	184 (56)	99 (30)	1	1+
15-12-9-12	1200 (366)	2496 (761)	2622 (799)	126 (38)	0+	0	0+
15-6-9-23	1429 (436)	4490 (1369)	4664 (1422)	174 (53)	57 (17)	1+	2
2-12-10-9	1006 (307)	1858 (383)	1977 (603)	119 (36)	10 (3)	0	1
16-29-12-29	1721 (525)	5271 (1607)	5420 (1652)	149 (45)	65 (20)	2	2
13-17-13-14	1300 (396)	2600 (792)	2735 (834)	135 (41)	20 (6)	0	2-
2-14-16-28	1279 (390)	4050 (1234)	4192 (1278)	142 (43)	54 (16)	3	5
15-31-17-17	2078 (633)	3362 (1025)	3508 (1069)	146 (45)	73 (22)	1	2
13-13-18-21	1988 (606)	3578 (1091)	3718 (1133)	140 (43)	62 (19)	1	2+
2-17-18-22	1898 (579)	3683 (1123)	3830 (1167)	144 (44)	59 (18)	1+	3+
2-14-18-29	1589 (484)	4190 (1277)	4354 (1327)	164 (50)	100 (30)	3	3
5-19-19-23	2049 (625)	3847 (1173)	3995 (1218)	148 (45)	75 (23)	3+	6-
15-22-22-27	2069 (631)	3922 (1195)	4065 (1239)	143 (44)	85 (26)	1+	1
1-24-25-21	1106 (337)	2061 (628)	2200 (671)	139 (42)	98 (30)	1+	1
4-28-25-26	1864 (568)	3330 (1015)	3461 (1055)	131 (40)	72 (22)	2	1
4-30-27-20	1050 (320)	1850 (564)	1995 (608)	145 (44)	90 (27)	1+	1+
2-12-29-29A	2028 (618)	3438 (1048)	3570 (1088)	132 (40)	78 (24)	2+	1

TABLE III — TABLE OF DRILL STEM TEST RESULTS — WINNIPEG FORMATION

Well location	Formations tested	DST. Interval feet/(metres)	Recovery	VO	FP	SI	SIP
12-8-1E	Winnipeg	622-712 (190-217)	Rec. 322' (98m) WM, 300' (91m) MW	60	317-343	30	355
1-28-1-2W	Winnipeg	1050-1075 (320-328)	Rec. 1030' (314m) SW	30	300-410	10	425
		1170-1206 (357-368)	SW to surface in 21 min.	25	215-510	10	540
3-9-4-11	Winnipeg	3009-3040 (917-927)	Rec. 2200' (671m) SW	40		15	
16-33-4-13	Winnipeg	3248-3263 (990-995)	Rec. 30' (9m) SM	60		30	
		3351-3370 (1021-1027)	Rec. 1380' (421m) SW	40	757	15	1820
13-36-4-19	Winnipeg	4514-4540 (1376-1384)	Rec. 4360' (1329m) SW	30	2050	15	2090
2-35-5-8	Winnipeg	2342-2365 (714-721)	Rec. 1590' (485m) SW	60		15	
1-27-5-14	Winnipeg	3267-3292 (996-1003)	Rec. 1000' (305m) MSW, 1340' (408m) SW	16	1130	30	1250
5-13-5-22	Winnipeg	5047-5061 (1538-1543)	Rec. 5000' (1524m) sulphurous SW	60			
9-35-5-25	Winnipeg	5285-5380 (1611-1640)	Rec. 4200' (1280m) SW	30	1740-2200	30	2520
9-22-6-6	Winnipeg	1533-1563 (467-476)	Rec. 1400' (427m) SW	60	590	15	610
13-5-7-15	Winnipeg	3400-3456 (1036-1053)	Rec. 60' (18m) SWCM	60	75	30	495
7-32-8-5	Winnipeg	1413-1423 (431-434)	Rec. 1230' (375m) SW	30	425	30	425
		1534-1560 (468-475)	Rec. 750' (229m) MSW	30	235	30	540
6-11-8-7	Red River-Winnipeg	1677-1702 (511-519)	Rec. 1442' (440m) SW	60	580	30	660
	Winnipeg	1828-1843 (557-561)	Rec. 30' (9m) M	60	0	30	615
8-36-8-14	Winnipeg	2710-2722 (826-830)	Rec. 15' (5m) M	40	0	20	0
		2750-2765 (838-843)	Rec. 75' (23m) M	40	0	15	0
7-35-8-15	Winnipeg	3110-3132 (948-955)	Rec. 204' (62m) M	60	225	60	1275
3-1-8-18	Winnipeg	3778-3826 (1152-1166)	Rec. 3778' (1152m) SW (flowed)	45	1600-1900		
5-26-9-5	Winnipeg	1264-1288 (385-393)	Rec. 600' (183m) SW	60	40-272	15	505
		1366-1396 (416-426)	Rec. 1260' (384m) SW	60	75-595	15	605
13-10-9-11	Winnipeg	2485-2525 (757-770)	Rec. 40' (12m) sl. SM	30	0		
10-2-9-16	Winnipeg	3249-3264 (990-995)	Rec. 2930' (893m) MSW & SW	30	732-1397	45	1624
10-24-9-16	Winnipeg	3175-3215 (968-980)	Rec. 10' (3m) M	30	22-29	45	260
3-5-9-19	Winnipeg	3928-3937 (1197-1200)	Rec. 594' (181m) MSW	60	300		
NE-15-10-2	Red River-Winnipeg	828-907 (252-276)	Rec. 328' (100m) sl. MSW	60	385-400	30	410
11-9-10-16	Red River-Winnipeg	3047-3222 (929-982)	Rec. 80' (24m) M	75	0	30	0
15-18-10-27	Winnipeg	5334-5368 (1626-1636)	Rec. 4800' (1463m) sl. GSW, skunky odor	60	2100(?)	15	2400(?)
2-16-11-10	Winnipeg-Precambrian	2069-2094 (631-638)	Rec. 542' (165m) SW	40	85-255	30	931
3-17-12-24	Winnipeg	4470-4511 (1362-1375)	Rec. 3360' (1024m) SW	20	1280-1780	15	1900
3-19-13-15	Winnipeg	2844-2854 (867-870)	Rec. 20' (6m) M	30	0	30	0
16-26-14-18	Winnipeg	3430-3500 (1045-1067)	Rec. 15' (5m) M	60	190	20	200
8-34-16-21	Winnipeg	3807-3852 (1160-1174)	Rec. 2650' (808m) SW	62	550-1275	15	1280
1-27-17-26W	Winnipeg	4128-4154 (1258-1266)	Rec. 45' (14m), 3150' (960m) SW	50	875-1625	0	
16-18-18-28	Winnipeg	4284-4310 (1306-1314)	Rec. 810' (247m) GSW, 150' (46m) M	50	0-500		
16-32-19-27	Winnipeg	4057-4073 (1237-1241)	Rec. 3200' (975m) SW, 10' (3m) M	45	1200-1650		
14-17-20-5	Winnipeg-Precambrian	1003-1072 (306-327)	Rec. 900' (274m) M, sl. SW	75	375-400	30	400
16-15-20-6	Winnipeg-Precambrian	1101-1123 (336-342)	Rec. 20' (6m) M	60	30	30	310
16-19-21-11	Red River-Winnipeg	1384-1450 (422-442)	Rec. 1100' (335m) SW	30	340-596	30	630
15-14-21-15	Red River-Winnipeg-Precambrian	1710-1935 (521-590)	Rec. 700' (213m) W, 810' (247m) sl. SW	30	732-762	45	763
14-22-21-15	Red River-Winnipeg-Precambrian	1680-1880 (512-573)	Rec. 1475' (450m) SW	30	704-743	30	760
13-34-23-12	Red River-Winnipeg-Precambrian	1272-1478 (388-450)	Rec. 1150' (351m) MSW	90	538-552	60	552
1-24-24-3	Red River-Winnipeg	614-639 (187-195)	Rec. 515' (157m) fresh W	15	208-237	15	239
5-6-26-5	Red River-Winnipeg	820-840 (250-256)	Rec. 720' (219m) fresh W	15	285-306	15	305
8-30-29-8	Red River-Winnipeg	760-827 (232-252)	Rec. 735' (224m) fresh W	15	343-350	15	350
11-8-45-25	Red River-Winnipeg-Precambrian	1025-1138 (312-347)	Rec. 995' (303m) W	5/30	464-491	60/30	491

TABLE IV — FORMATION WATER ANALYSES — WINNIPEG FORMATION

Well location	Depth feet/(metres)	Specific Gravity at 16°C	Resistivity at 20°C	ph at 22°C	Na+K	Ca	Mg	SO_4	Cl	HCO_3	Total Solids
12-8-1E	622-712 M (190-217)	1.003	3.15	7.9	694	34	8	316	800	210	2,062
1-28-1-2W	1050-1075 B (320-328)				17,176	1,782	581	3,543	28,662	85	51,829
	1170-1206 (357-368)				17,158	1,650	457	4,552	27,297	104	51,218
13-36-4-19	4515-4540 M (1376-1384)				38,718	3,171	499	4,113	63,693	98	110,292
	4514-4540 B				38,099	3,183	496	4,148	62,662	207	108,795
1-27-5-14	3267-3292 (996-1003)	1.089	0.076	6.8	43,425	3,712	1,188	3,954	74,000	175	126,365
5-13-5-22	5047-5061 T (1538-1543)				49,328	4,849	1,121	2,878	85,530	488	144,194
	5047-5061 M				51,814	6,370	883	2,915	91,597	159	153,738
	5047-5061 B				53,759	4,315	1,323	2,472	92,506	146	154,521
9-35-5-25	5285-5380 (1611-1640)	1.146	0.057	6.6	76,405	5,656	1,065	1,608	129,750	60	214,514
9-22-6-6	1533-1563 T (467-476)		0.09 at 21.7°C		36,629	2,886	346	4,709	58,840	512	103,921
	1533-1563 M		0.07 at 21.7°C		41,198	3,619	494	4,471	67,757	593	118,112
	1533-1563 B		0.06 at 21.7°C		47,905	3,218	497	4,065	77,948	146	133,779
13-5-7-15	3400-3456 T (1036-1053)				22,415	4,454	512	4,289	40,642	244	72,556
	3400-3456 B				20,678	4,587	482	4,251	37,913	634	68,545
7-32-8-5	1534-1560 (468-475)	1.089	0.09	5.5	42,213	4,386	969	2,216	74,000	115	123,841
6-11-8-7*	1677-1702 (511-519)	1.084	0.09	6.0	41,587	2,706	819	4,742	67,750	135	117,670
8-36-8-14	2710-2722 (826-830)				7,062	1,380	625	3,585	12,313	342	25,307
	2750-2765 (838-843)				7,857	1,422	707	3,650	13,733	464	27,833
5-26-9-5	1264-1288 B (385-393)				44,965	4,763	1,004	2,294	78,858	232	132,116
	1366-1396 M (416-426)				48,852	5,802	1,068	2,085	87,168	49	145,024
	1366-1396 B				49,177	5,793	1,068	2,075	87,654	61	145,768
10-2-9-16	3249-3264 M (990-995)	1.075	0.07 at 24°C	7.5	39,149	4,152	509	4,078	66,119	110	114,117
3-5-9-19	3928-3937 (1197-1200)	1.086	0.08	5.0	47,231	2,898	665	4,215	76,750	110	131,813
NE-15-10-2*	828-907 (252-276)	1.043	0.144	7.5	19,711	2,147	308	3,370	32,500	200	58,134
15-18-10-27	5334-5368 (1626-1636)				94,600	6,098	718	10,050	162,600	10	274,076
2-16-11-10	2069-2094 (631-638)	1.0598	0.093 at 25.4°C	7.5	25,845	3,433	716	3,308	45,500	122	78,924
3-17-12-24	4470-4511 (1362-1375)				80,435	5,708	738	2,212	134,652	61	223,806
3-9-13-15	2852-2879 (869-878)	1.099	0.07	5.5	49,700	3,395	602	3,881	81,500	110	139,132
8-34-16-21	3807-3852 (1160-1174)	1.157	0.052	6.0	87,326	4,344	946	2,847	143,000	85	238,505
1-27-17-26	4128-4154 (1258-1266)				110,458	2,873	845	2,806	175,307	104	292,393
16-18-18-29	4284-4310 (1306-1314)				94,355	4,282	817	2,657	153,470	110	255,691
16-32-19-27	4057-4073 (1237-1241)				99,321	3,777	866	2,669	160,385	85	267,103
14-17-20-5	1003-1072 (306-327)	1.022	0.62 at 23.9°C	7.5	9,107	942	185	3,484	13,527	256	27,501
13-3-35-29*	2355-2373 (718-723)	1.126	0.055	6.0	72,203	2,444	900	4,729	114,724	100	195,049

* Indicates that D.S.T. interval includes a portion of the overlying Red River Formation B, M, T: Sample taken from bottom, middle or top of fluid column.

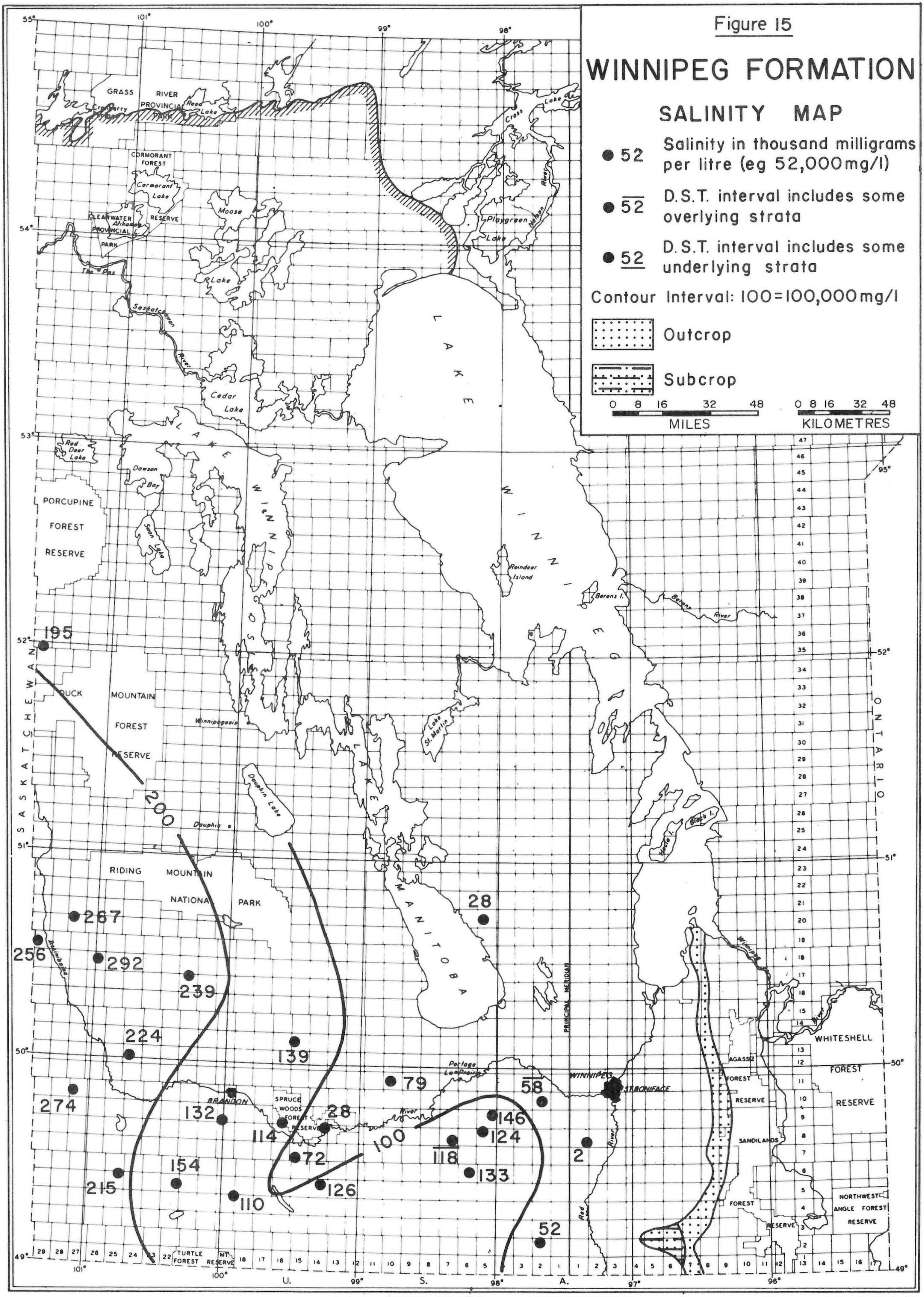


Figure 15
WINNIPEG FORMATION
SALINITY MAP
52 Salinity in thousand milligrams per litre (eg 52,000mg/l)
52 D.S.T. interval includes some overlying strata
52 D.S.T. interval includes some underlying strata
Contour Interval: 100=100,000mg/l
Outcrop
Subcrop
0 8 16 32 48 MILES
0 8 16 32 48 KILOMETRES
LAKE WINNIPEG
LAKE WINNIPEGOSIS
LAKE MANITOBA
SASKATCHEWAN
ONTARIO
U. S. A.
200
100
195
267
256
292
239
224
274
139
132
114
28
72
154
215
110
126
79
58
146
124
118
133
2
52
28
WINNIPEG
ST. BONIFACE
BRANDON
DUCK MOUNTAIN FOREST RESERVE
PORCUPINE FOREST RESERVE
RIDING MOUNTAIN NATIONAL PARK
SPRUCE WOODS FOREST RESERVE
TURTLE MT. FOREST RESERVE
WHITESHELL FOREST RESERVE
AGASSIZ FOREST RESERVE
SANDILANDS FOREST RESERVE
NORTHWEST ANGLE FOREST RESERVE
CORMORANT FOREST RESERVE
CLEARWATER PROVINCIAL PARK
GRASS RIVER PROVINCIAL PARK
PRINCIPAL MERIDIAN