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STRATIGRAPHY OF MANITOBA, AN INTRODUCTION AND REVIEW

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INTRODUCTION

The following section of the Symposium deals with post-Precambrian sedimentary rocks of southwestern Manitoba and the Hudson Bay area. The seven papers presented include most of the known recent stratigraphic research projects.

In recent years, stratigraphic studies in Manitoba have focussed primarily on the Hudson Bay area. Up to 1960, the Paleozoic sediments around the bay were believed to represent merely a thin layer of shelf-type carbonates—an outlier of the main sedimentary basins to the south and southwest. In the early 1960's, however, aeromagnetic and seismic studies by the Geological Survey of Canada (Bower, 1960; Hood, 1964; Hobson, 1964, 1968) indicated that the sedimentary section in the Hudson Bay area was much thicker than previously believed and probably comprised a major new Paleozoic sedimentary basin. Since 1962, exploration by oil companies, notably Sogepet and Aquitaine, and by the Geological Survey of Canada (Operation Winisk) was extremely fast and complete, and by 1967 essentially all of the available outcrops had been examined in considerable detail. In addition, three onshore stratigraphic test holes had been completed to Precambrian basement, and a maximum onshore thickness of 2,913 feet of Ordovician, Silurian and Devonian strata had been intersected. Seismic studies of the Kaskattama test hole (Lat. 57°3'N, Long. 90°04'W) provided new velocity data indicating that previous determinations of basement depth by seismic means probably were in error becauseof a high velocity refractor in the Ordovician section. Revised estimates gave a sedimentary thickness in excess of 8,000 feet in the central offshore portion of the basin (Hodgkinson, 1969). No data have yet been released on the partially completed offshore test by Aquitaine.

Three papers dealing with the Hudson Bay Basin are presented in this Symposium and represent the most recent results of Geological Survey of Canada studies carried out under Operation Winisk. These studies, in conjunction with the Winisk report (Geol. Surv., Canada, Paper 67-60) and the Earth Science Symposium on Hudson Bay (Hood, 1969), provide a completely up-to-date résumé of the geology of the Hudson Bay Basin. An excellent earlier review is that by Nelson and Johnson (1966).

By contrast, exploration of the sedimentary strata of southwestern Manitoba has been extremely slow, and in some respects, less complete. The large scale, multi-discipline, helicopter-supported operation, typified by Operation Winisk, provided in less than five years, more complete outcrop coverage for the Hudson Bay area than has been accumulated during the last one hundred years in southwestern Manitoba. In southwestern Manitoba, however, a vastly greater amount of subsurface control is available from the more than 2,460 wells.

The Paleozoic and Mesozoic strata of southwestern Manitoba form a wedge-like segment on the northeastern flank of the Williston and Elk Point sedimentary basins. The Williston Basin, centred in northwestern North Dakota, has been tectonically active from Ordovician through Cretaceous time, and during most of this interval was the principal feature controlling the pattern of sedimentation in southwestern Manitoba. During Devonian time, however, subsidence was related to the Elk Point Basin, centred in south-central Saskatchewan. The maximum thickness of sedimentary strata is found in the extreme southwestern corner of the Province, where Paleozoic strata are up to 4,000 feet thick, and Mesozoic strata up to 3,500 feet thick.

The outcrop belt of Paleozoic sediments in southwestern Manitoba provides virtually the only exposures of these strata for the entire Canadian portion of the Williston-Elk Point Basin area. Consequently, exploration of these outcrops started very early (circa 1859), with notable contributions by Dowling (1900), Okulitch (1943), Baillie (1950, 1951, 1952), Stearn (1956) and McCammon (1960). Exploration interest increased greatly in the late 1940's and early 1950's when deep oil well test holes began to provide subsurface data to tie in with the outcrop studies. In January, 1951, the first oil discovery in the Williston Basin area, Calstan Daly 15-18-10-27, obtained limited production from the Mississippian Lodgepole limestone, and during the next twenty years sixteen oil fields were discovered, all in stratigraphic traps in Mississippian strata. However, of the 2,464 holes drilled up to 1970, only one hundred and twelve penetrated the complete stratigraphic section, so subsurface data are not as complete as one might expect. For instance, of the approximately 1,100 wells in the Virden producing area, it was not until 1970 that a well penetrated as deep as the base of the Devonian Prairie Evaporite—and this in an area where salt collapse structures are believed to be highly important in localizing oil accumulation.

Subsurface reports include those by Baillie (1953), Andrichuk (1959), Porter and Fuller (1959), King (1964) and McCabe (1967).

Despite extensive subsurface exploration, studies of the outcrop belt have been few since the above-noted Paleozoic studies by Baillie. Stearn and McCammon, and the Mesozoic studies by Wickenden(1945); one exception is the study of the economic potential of the clays and shales of Manitoba (Bannatyne, 1970). The three stratigraphic papers presented in this symposium are thus a welcome addition. The study by Cowan of the Ordovician and Silurian of the south Interlake area includes much recent core hole data, which has provided the first complete lithologic section for the outcrop belt. The paper by Norris and Uyeno on Devonian stratigraphy includes faunal and lithologic data for many large new quarry exposures not previously reported in detail in the literature. The paper by Vigrass on the Ordovician Winnipeg Formation in western Canada provides a regional interpretation of the origin of the complex sand bodies occurring in the Winnipeg Formation.

One important new source of data is the Manitoba Mines Branch stratigraphic core hole programme. This involves a series of shallow core holes to a depth of up to 200 feet. During 1969 and 1970, a total of 2,500 feet of core was obtained from twenty-four holes in Ordovician, Silurian, Devonian, Jurassic and Tertiary outcrop belts. These holes are located so as to help define type sections, and determine the stratigraphic positions of principal outcrops; this is important because less than one-half of the total stratigraphic section is exposed in outcrop, and the relative stratigraphic position of many outcrops is uncertain. Core holes are especially important for Devonian strata in view of the complex structural relief now known to exist throughout the outcrop belt. The core holes also provide data essential to an inventory of the industrial mineral potential of southwestern Manitoba, and much of these new data are included in the paper on industrial minerals presented by Bannatyne in this symposium.

Because of the incomplete stratigraphic coverage of the papers presented in this symposium, and because of their limitation, in most cases, to outcrop or near outcrop areas, it was decided that a general review of the entire stratigraphic succession of southwestern Manitoba would be desirable in order to give more comprehensive coverage and also to place the subsequent papers in a regional setting. The following is a review of the sedimentary and tectonic framework of southwestern Manitoba, based primarily on a revised series of isopach-structure contour maps. The treatment is of necessity brief, and the emphasis is on new information and interpretations. Certain formations, such as the Cretaceous shales, are omitted because little new information is available, and no further comment is necessary on the up-to-date coverage of the Hudson Bay Basin.

PRECAMBRIAN EROSION SURFACE

The present configuration of the Precambrian erosion surface is shown in Figure 1. This surface reflects original topographic relief on the unconformity, as well as the sum total of all subsequent tectonic activity. The surface is generally very uniform; only five anomalous features have been noted.

The most prominent feature is the recently recognized Lake St. Martin crypto-explosion crater (LSM, Figures 1 to 6, 16; vic. tp. 32, rge. 8WPM) (McCabe and Bannatyne, 1970a), where structural relief in excess of 1,000 feet is evident on the Precambrian surface. The structure is of approximate Permian age and is discussed in more detail in a later section on the pre-Mesozoic erosion surface.

The second feature is the Precambrian inlier near Hodgson (vic. tp. 29, rge. 2WPM); the origin of this feature is not known. It may be a paleotopographic elevation on the Precambrian surface with a local relief of approximately 500 feet, in which case it is the only significant paleotopographic high known to occur in Manitoba; alternatively, it may reflect later structural uplift or may be a second crypto-explosion crater.

The third feature has been designated as the Moose Lake Syncline (McCabe, 1967). It is shown by the northeast trending flexure of the structure contours in the area northwest of Lake Winnipeg, and is roughly coincident with the two main gravity anomalies. The synclinal structure is also shown by the configuration of the Ordovician and Silurian outcrop belts (Figures 2 to 6), indicating a post-Silurian age. Other structural and stratigraphic anomalies occur along the southern extension of the geophysical anomaly trend, although these are not evident on the Precambrian structure map. This suggests that minor tectonic movements have occurred along this axis since Precambrian time. The southern portion of this anomaly trend, from approximately Riding Mountain south to the United States border, has been designated the Birdtail-Waskada axis (Figure 7), and is the site of numerous sharply defined structure and isopach anomalies, mostly related to post-Middle Devonian salt collapse.

The major gravity trends and associated magnetic anomalies (Figure 1) occur on the southwestern extension of the Thompson Nickel Belt, presumably the boundary zone between the Churchill and Superior Precambrian crustal blocks, although there is now considerable debate as to the exact location of this "boundary zone". Nevertheless, a zone of geophysical anomalies is present, and the area east of this zone is generally older and shows a different tectonic grain, dominated by east-west trending greenstone belts (or their magnetic expression). It will be shown later that the Manitoba portion of the sedimentary basin has shown an anomalous tectonic behaviour throughout much of Paleozoic time, and it seems probable that the Superior crustal block, which underlies most of the Manitoba portion of the basin, has shown a somewhat different response to the regional tectonic forces causing both basin subsidence and basin uplift; the Manitoba portion of the basin appears to have undergone slightly greater subsidence during periods of deposition, and slightly greater uplift during periods of erosion.

The fourth basement anomaly is located on the northwestern flank of the "Hartney Structure" (vic. tp. 5, rge. 24WPM). In one well (L-M Imp. Hartney 1-29-5-24) the Ordovician Red River Formation was intersected at a normal depth, but the hole continued through an "extra" 300 feet of Red River type lithology and bottomed in Red River beds at a depth approximately 100 feet below the expected regional Precambrian surface. The structural low apparently is the result of deep, reverse-type faulting causing repetition of the Red River section.

The fifth feature shown by the Precambrian structure map is the gentle east-west trending anticlinal flexure south of Winnipeg; it is roughly coincident with the southern edge of the Carman Sand of the Winnipeg Formation (see next section).

ORDOVICIAN

Winnipeg Formation

The structure contour-isopach map of the Winnipeg Formation is shown in Figure 2. Vigrass (this volume) also shows regional isopach and structure maps for the entire Canadian portion of the Winnipeg sedimentary basin, as well as cross-sections and a detailed discussion of stratigraphy and lithology. The following will offer only a few supplementary comments.

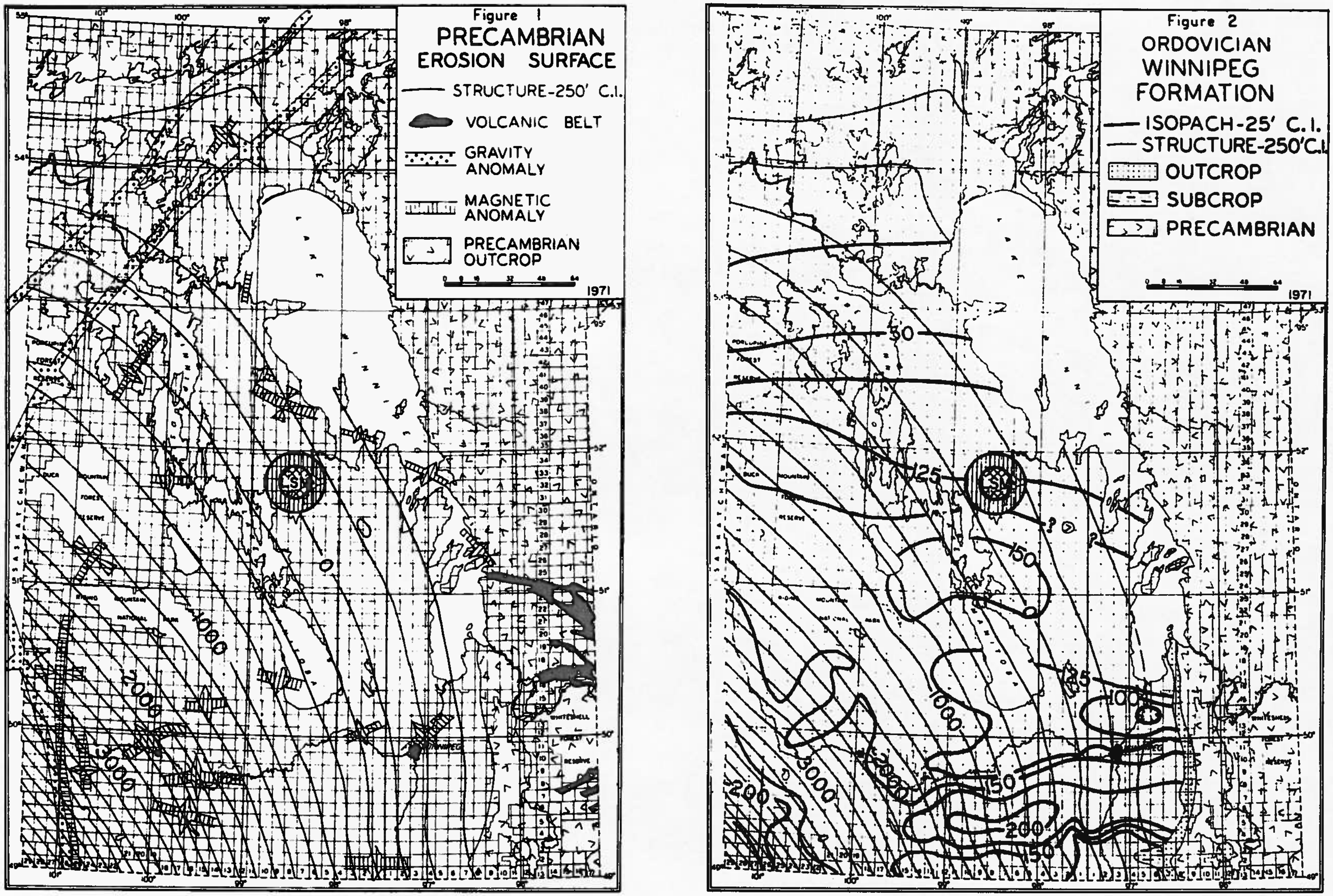
Differential compaction of the shales flanking the Carman sand body (shown by the pronounced isopach thick south of Winnipeg) occurred largely during later Ordovician time, as evidenced by the thickening of the Red River strata on the flanks of the Carman Sand. An isopach of the total Ordovician section shows little evidence of any anomaly in the area of the Carman sand body, indicating that most differential compaction had occurred before the end of Ordovician time. Furthermore, this indicates that there was little tectonic sudsidence associated with formation of the Carman sand body. However, the slight flexure of the structure contours on the Precambrian basement (Figure 1) indicates that formation of the sand body may have been related to a minor tectonic flexure.

If the previously noted Precambrian inlier near Hodgson (vic. tp. 29, rge. 2WPM) represents a paleotopographic high or hill, the Winnipeg strata will thin and pinch out on the flanks of the high; if the inlier represents a later structural uplift, no thinning will occur, and Winnipeg strata will outcrop on the flanks of the structure—as they do on the flank of the Lake St. Martin structure.

The east-west trend of the isopachs in Manitoba is somewhat anomalous. Deposition of the Winnipeg strata is related to subsidence of the Williston Basin, which, during Winnipeg time, was centred in northwestern North Dakota. In a regional context, the Winnipeg isopach trends should be more or less concentric to the basin. The roughly east-west trend in Manitoba appears to reflect a relatively greater amount of subsidence and deposition in the Manitoba portion of the basin.

Red River Formation

The most prominent feature of the Red River isopach map



Figures 1,2: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.

(Figure 3) is the relatively rapid and uniform northward thinning of the unit, and, as in the case of the Winnipeg Formation, the rather unexpected east-west to northeast isopach trend. The only anomalous features are: the east-west trending thin south of Winnipeg, which is coincident with the area of the underlying Carman sand body and is due to differential compaction of the Winnipeg shale on the flanks of the Carman Sand during Red. River time; and the local thickening (>300 feet) in the Hartney area (tp. 5, rge. 24WPM), associated with the "Hartney Structure" (described later).

Regionally, Red River deposition is related to subsidence of the Williston Basin, so it appears that the indicated isopach pattern is the result of greater differential subsidence of the Manitoba portion of the basin, the portion underlain by the Superior crustal block (*see*, Porter and Fuller, 1959, Fig. 11). This supports the writer's previous suggestion, that basement tectonic features, notably the Churchill and Superior crustal blocks and the associated boundary zone, have exerted broad regional tectonic control, or have modified regional tectonic patterns at various times during deposition of Paleozoic and Mesozoic sediments. The northeast trend of the isopachs, towards the Hudson Bay Basin, suggests that the two basins were connected in Ordovician time; the lithologic and faunal similarities between the two basins support this suggestion. Uplift of the Precambrian shield and erosion of Red River strata probably did not occur until late Paleozoic time.

The northward thinning is reflected in the lithofacies of the Dog Head, Cat Head and Selkirk Members of the Red River Formation, which change from dolomitic limestone in the south to non-calcareous dolomite in the north. The change in the Dog Head and Selkirk Members apparently occurs fairly abruptly in the vicinity of township 40 (approximately at the 250-foot isopach). The occurrence in the Lake St. Martin area, of an interbedded limestone and dolomite sequence in the Selkirk Member, as noted by Cowan (this volume), is abnormal and does not fit the regional pattern. It is interesting, however, in that it may possibly reflect the original nature of the Selkirk Member prior to organic (?) reworking and dolomitization.

The northward change to dolomite occurs more rapidly and more erratically in the Cat Head Member, which appears to be essentially a more highly dolomitized phase of the mottled dolomitic limestone characteristic of the Dog Head and Selkirk Members. The occurrence of chert in the Cat Head suggests a slightly different environment of deposition, possibly resulting from a decreased rate of subsidence. A quarry opened in 1970 near Riverton has exposed dolomite beds believed to be correlative with the Cat Head; a core hole is planned to ascertain the exact stratigraphic position and thickness of these dolomite beds.

The addition of the Fort Garry Member at the top of the Red River outcrop section (McCabe and Bannatyne, 1970a) (Table I) represents a significant change in terminology and correlation. This unit was first noted in the subsurface of Saskatchewan and western Manitoba, where a marker-defined, predominantly dolomite unit was designated as the Herald Beds (Saskatchewan Geological Society, 1958; Brindle, 1960) or the Upper Red River (Porter and Fuller, 1959). Andrichuk (1959, p. 2360) noted the presence of this dolomite unit a short distance west of the outcrop belt in Manitoba but suggested that it changed facies to the east and was correlative with the Selkirk Member of the outcrop belt.

Sinclair (1959) suggested that the Cat Head Member, as exposed at the type section at The Narrows of Lake Winnipeg, was correlative with the upper dolomite unit of the Red River as described in the subsurface. He indicated that the Dog Head and Selkirk were the same, faunally, and discarded the term Selkirk. The subdivision of the Red River was thus simplified to two members, the lower Dog Head and the upper Cat Head (Table II). Sinclair's correlations were accepted by Porter and Fuller (1964), and Brindle (1960).

Recent core hole data (Cowan, this volume), water well data and quarry excavations offer almost positive proof that the original subdivision of the Red River into Dog Head, Cat Head and Selkirk is basically correct, but must be expanded to include an uppermost unit, the Fort Garry Member. The subsurface terminology was not applied because the marker defined beds do not correspond to the lithologic change from mottled dolomitic limestone to dolomite.

It should be noted that the above four-fold subdivision of the Red River is not applicable in all areas; to the north the entire Red River sequence changes to dolomite and subdivision is difficult or impossible.

It is not possible, in this brief review, to outline all supporting data for the suggested four-fold subdivision, other than to note that Sinclair's correlations are in error because he mistakenly accepted an earlier erroneous correlation. He determined that the so-called Upper Mottled at the north end of Lake Winnipeg was in fact Stony Mountain. Regional lithologic studies support Sinclair's faunal correlations. However, Sinclair accepted correlation of the dolomite underlying the Upper Mottled with the Cat Head; this placed the Cat Head as the uppermost unit of the Red River and equivalent to the subsurface dolomite unit. In fact, the "Cat Head" in this area probably is "Fort Garry" and not correlative with the type section of Cat Head as Sinclair indicated. It is hoped that detailed faunal (conodont) studies of the Cat Head and Fort Garry Members may help clarify this problem. Additional core holes are also planned.

Stony Mountain Formation

The isopach of the Stony Mountain Formation (Figure 4) shows a decrease in the rate of differential subsidence (i.e. thickness change), and also the first evidence of a change in the tectonic framework. Thickening to the south or southeast is still dominant, but a minor thickening to the west is also indicated. The change in tectonic framework is reflected in the lithology. The lower Stony Mountain shaly beds (Gunn and Penitentiary Members) probably represent relatively deep water low-energy deposits and possibly mark the maximum extent of Ordovician transgression. In contrast, the upper Stony Mountain (Gunton) dolomite was deposited under very shallow marine (intertidal) conditions (Roehl, 1967; Cowan, this volume). These shallow marine to supratidal conditions continued throughout all of Stonewall and Interlake time and probably represent the regressive or offlap stage of the major Ordovician-Silurian depositional cycle (Tippecanoe Sequence of Sloss, 1963).

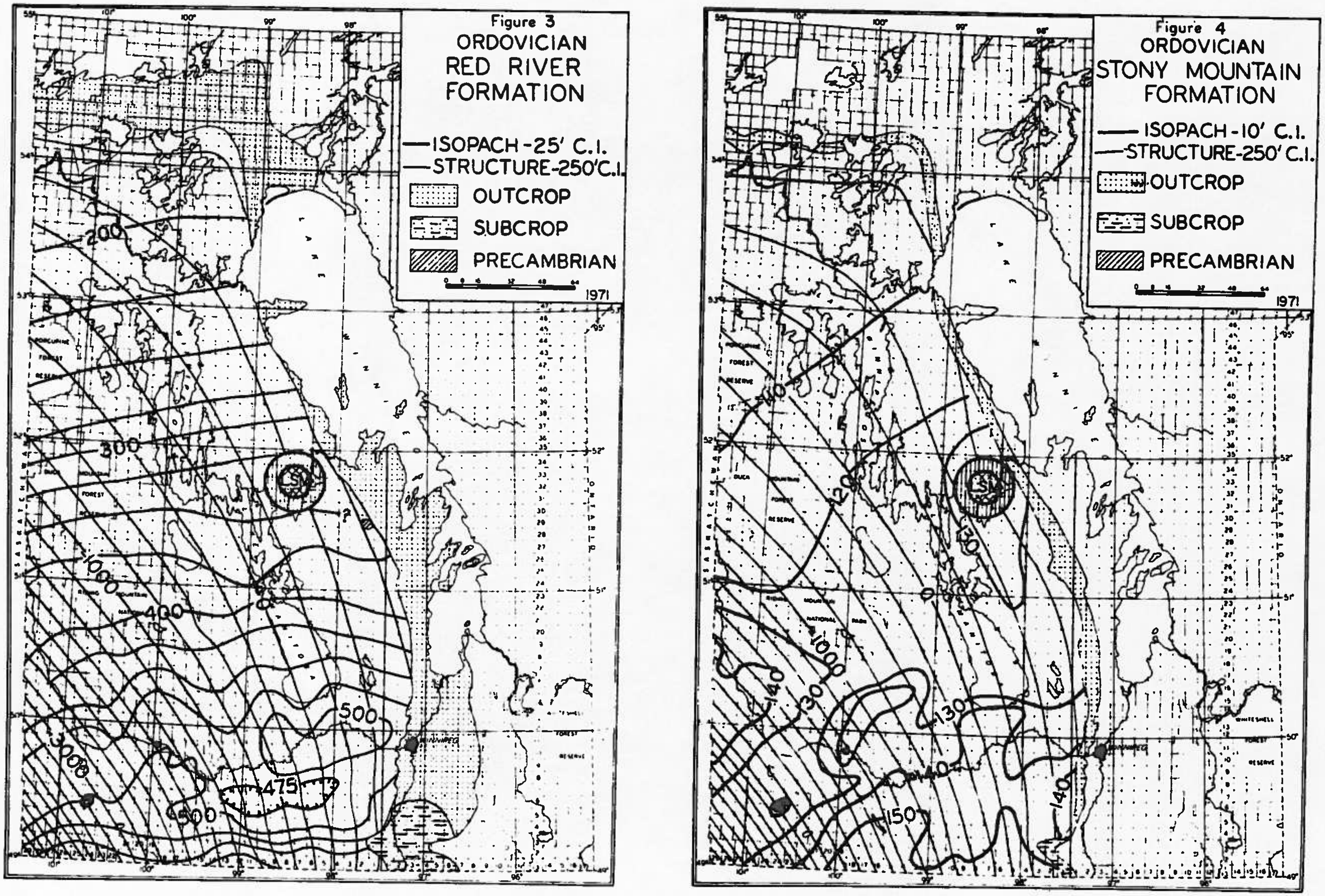
The lithofacies pattern indicated by Cowan (this volume) for the south Interlake area is representative of the regional pattern. In the area to the south, the lower Stony Mountain is thicker, dominantly argillaceous limestone and calcareous shale; to the north, the shale content decreases rather rapidly, accompanied by an increase in the degree of dolomitization. North of the Grand Rapids area, the lower Stony Mountain is difficult to distinguish as a separate stratigraphic unit, as the entire Ordovician sequence changes to a similar lithology—a mottled, in places argillaceous, dolomite.

Stonewall Formation

The Stonewall isopach (Figure 5) shows that the change in depositional framework initiated in Stony Mountain time was completed by Stonewall time. The Stonewall isopachs show a more "normal", relatively low rate of thickening to the west. The shallow marine to supratidal nature of the sediments (Roehl, 1967; Cowan, this volume) indicates slow deposition in a shallow, slowly subsiding basin in which sedimentation

TABLE I: Table of Geological Formations in Manitoba, showing basic lithology and the range of depositional thickness. Adapted from Davies *et al.*, 1962.

ERA	PERIOD		FORMATION (GROUP)	MEMBER	BASIC LITHOLOGY	THICKNESS FEET
CENOZOIC	Quat.	Recent			Soil, alluvial deposits, sand dunes, bogs.	
		Pleistocene			Glacial deposits	0 – 850
	Tertiary	Eocene to Pliocene	Not reported in Manitoba			
		Paleocene	Turtle Mountain ?		Shale, sandstone, lignite	– 480$^+$
MESOZOIC	Cretaceous		Boissevain		Sand and sandstone, greenish grey; kaolinitic shale	100 – 150
			Riding Mountain	Odanah	Hard grey siliceous shale	– 800$^+$
				Millwood	Greenish bentonitic shale	50 – 500
			Vermilion River	Pembina	Non-calc. shale, bentonite beds	100 – 400
				Boyne	Calcareous speckled shale	
				Morden	Carbonaceous shale; septarian concretions	50 – 200
			Favel		Calc. speckled shale, limestone bands	60 – 130
			Ashville	Ashville Sand	Non-cal. silty shale; 0-90' sand	120 – 370
			Swan River		Sand, sandstone, shale, clay, lignite	0 – 400
	Jurassic		Waskada		Varicoloured shale	0 – 160
			Melita		Varicoloured shale, calc. shale, limestone	340 – 480
			Reston		Argillaceous limestone and shale	0 – 170
			Amaranth	Upper: evaporite	Anhydrite, gypsum; shale, dolomite	0 – 170
				Lower: red beds	Dolomitic shale to siltstone, anhydritic	0 – 140
	Triassic		Not reported in Manitoba except Permian? Lake St. Martin cryptoexplosion structure			
PALEOZOIC	Permian					
	Pennsylvanian					
	Mississippian		Charles		Dolomite and anhydrite	– 120
			Mission Canyon		Limestone, dolomite, anhydrite; oil production	270 – 320
			Lodgepole	Whitewater Lake Virden Scallion Routledge	Limestone argillaceous and cherty; shale; oil production	480 – 580
			Bakken		Black shale and siltstone	10 – 50
	Devonian		Qu'Appelle Group	Lyleton	Red dolomitic shale	35 – 180
			Saskatchewan Group	Nisku	Fossiliferous limestone and dolomite	40 – 140
				Duperow	Shaly limestone, dolomite, anhydrite; cyclical	400 – 640
			Manitoba Group	Souris River First Red	Limestone, evaporite, shale; cyclical	210 – 310
				Dawson Bay Second Red	Limestone, anhydrite, basal red shale	140 – 220
			Elk Point Group	Prairie Evaporite	Halite, with potash, anhydrite, dolomite	0 – 425
				Winnipegosis	Dolomite, reef and inter-reef	30 – 350
				Elm Point	High-calcium limestone	0 – 45+
				Ashern	Dolomite and shale, brick red	5 – 60
	Silurian		Interlake Group		Dolomite	175 – 370
	Ordovician		Stonewall		Dolomite	30 – 70
			Stony Mountain	Gunton Penitentiary Gunn	Dolomite, upper part shaly Argillaceous dolomite Fossiliferous calc. shale; red, grey, green	100 – 160
			Red River	Fort Garry	Dolomite, minor limestone	175 – 500
				Selkirk	Dolomitic limestone, mottled.	
				Cat Head	Dolomite, cherty	
				Dog Head	Dolomitic limestone, mottled	
			Winnipeg		Quartzose sand, sandstone; shale	0 – 220
	Cambrian		Deadwood		Glauconitic sandstone	?
Precambrian						



Figures 3,4: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.

TABLE II: History of stratigraphic terminology, Red River Formation, Manitoba.

	Dowling (1900)	**Foerste (1929)**	**Porter & Fuller (1959)**	**Sinclair (1959)**	**McCabe & Bannatyne (1970)**
Red River Formation			**Upper Red River (Herald Beds)**	**Cat Head**	**Fort Garry**
	Upper Mottled	**Selkirk**	**Lower Red River** **(Yeoman Beds)**	**Dog Head**	**Selkirk**
	Cat Head	**Cat Head**			**Cat Head**
	Lower Mottled	**Dog Head**			**Dog Head**

was essentially keeping pace with subsidence.

SILURIAN

Interlake Group

The isopach of the total Interlake Group (Figure 6) shows a highly irregular pattern with little evidence of any regional variations in thickness. The top of the Interlake Group marks the top of the major pre-Middle Devonian unconformity surface; consequently the isopachs reflect, to a considerable extent, the effects of differential erosion and possibly incipient development of karst topography. Fracture fillings and irregular patches of red Ashern-type shale are common in the uppermost Interlake beds. Locally (vic. sec. 13, tp. 5, rge. 22WPM) red shale beds occur within the upper Interlake, but inasmuch as these can apparently be traced laterally, with a gradual decrease in argillaceous content, they are believed to represent Silurian beds rather than karst infill.

Detailed isopach maps for marker-defined units within the Interlake (Porter and Fuller, 1959; King, 1964) do not show any regional features, only an irregular pattern with no evidence of basin differentiation. The irregular pattern may reflect random development of biostromal or reefoid build-up in a relatively stable area undergoing slow uniform subsidence. The shallow marine to supratidal environment which prevailed throughout Interlake time shows that subsidence and deposition were in balance. Here again, the pattern of relative tectonic stability in the Manitoba portion of the sedimentary basin differs considerably from the more uniform subsidence in the remainder of the basin area (Porter and Fuller, 1959, Fig. 15).

The highest Silurian strata preserved in Manitoba represent only the upper part of the Middle Interlake (Porter and Fuller, 1959); the entire Upper Interlake, which attains a thickness in excess of 400 feet in the central part of the Williston Basin, has been eroded in Manitoba.

DEVONIAN

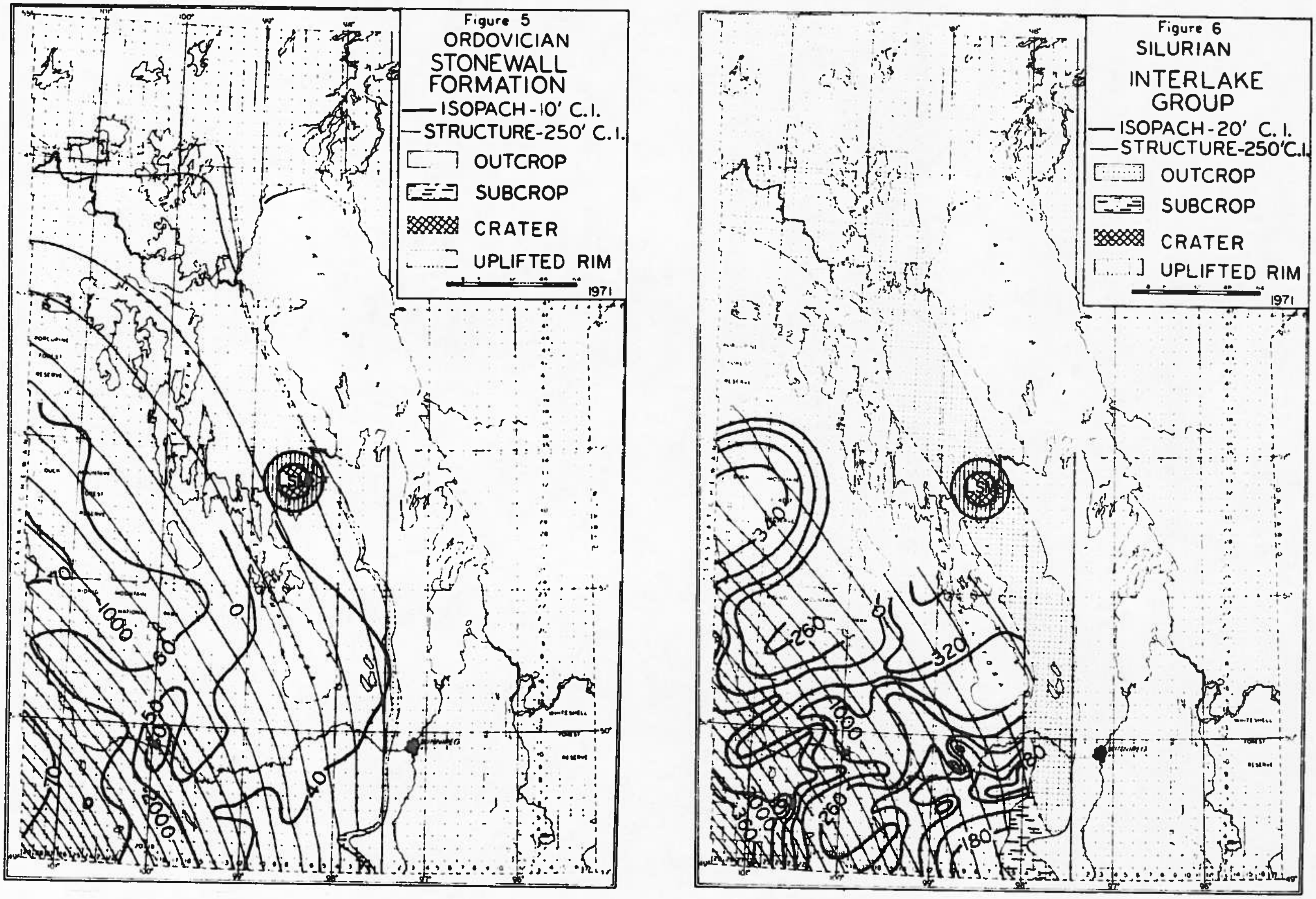
Following the period of uplift and erosion in late Silurian and/or early Devonian time, the next major depositional cycle (Kaskaskia Sequence of Sloss, 1963) was initiated in Early or Middle Devonian time with deposition of the Ashern Formation. An examination of the Devonian isopach maps (Figures 7 to 14) shows a major change in the tectonic framework. Throughout Devonian time the Elk Point Basin, rather than the Williston Basin, was the controlling tectonic element, although the degree of tectonic differentiation differed considerably for the various formations. The original extent of the basin to the northeast is uncertain but was undoubtedly great, as evidenced by the relatively thick basinal aspect of the strata exposed in the outcrop belt. As noted by Norris and Uyeno (this volume), the early Devonian megafaunas of southwestern Manitoba and Hudson Bay are different and belong to different faunal provinces, so it is doubtful if any direct connection between the Elk Point and Hudson Bay Basins existed during early Devonian time. However, by late Givetian time (Dawson Bay) faunal similarities are evident, and a sea connection may have existed.

One important effect of the change in tectonic framework is the change in relationship of the isopach and lithofacies trends to the trend of the outcrop belt. Because of the marked discordance between the isopach and outcrop trends the outcrop belt in effect exposes a dip section of the Devonian strata. In the case of the Winnipegosis in particular, this has resulted in exposure of a relatively thick, basinal facies to the northwest, and a thinner shelfward facies to the southeast. This pattern is exactly the opposite to that noted previously for the Ordovician strata.

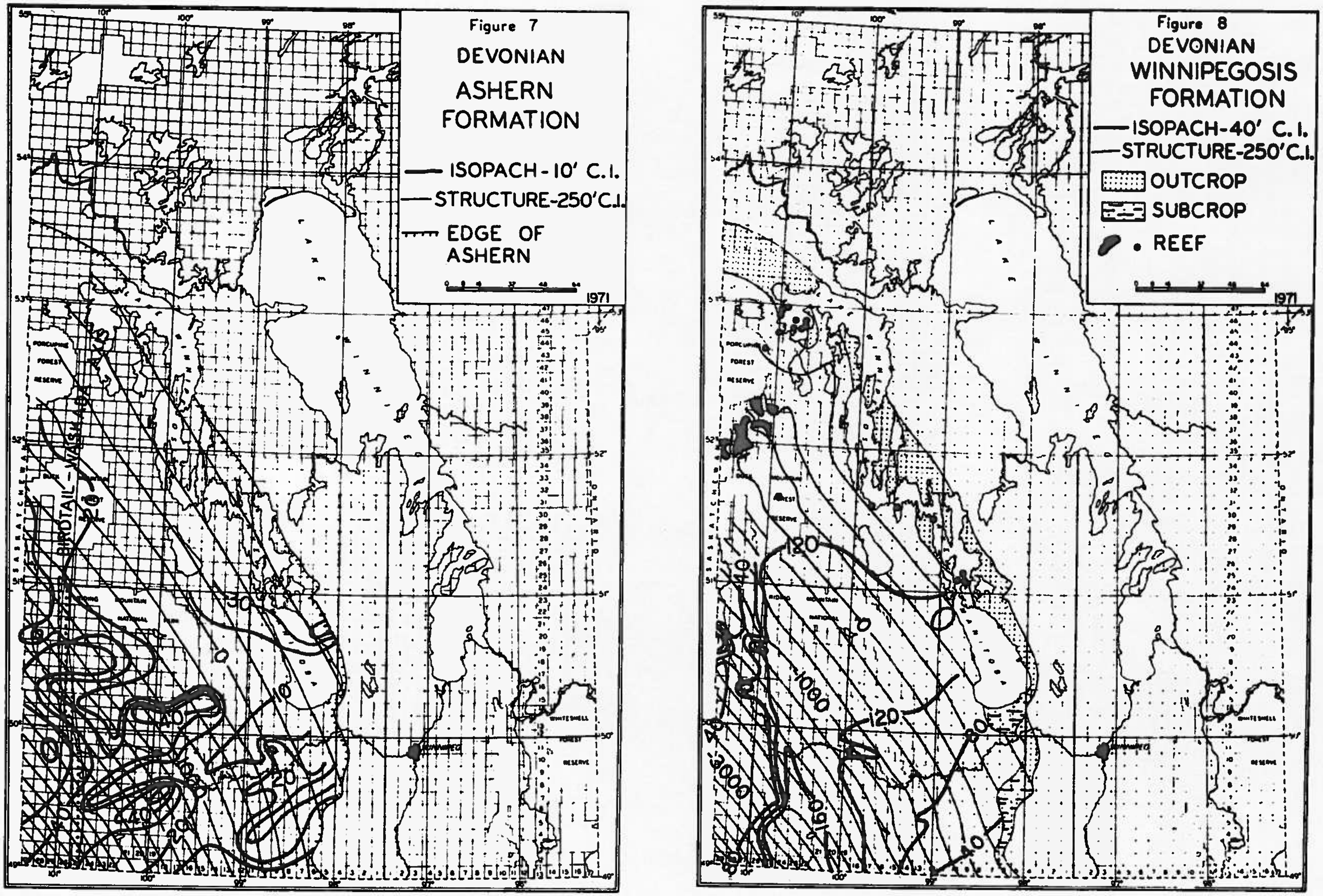
The lithology and correlations of the lower Devonian strata are well covered by Norris and Uyeno (this volume) and will not be discussed here.

Ashern Formation

The isopach of the Ashern Formation (Figure 7) shows a highly irregular, almost dendritic pattern which probably reflects deposition on an eroded Silurian surface of low to moderate relief, during the initial stages of the Devonian transgression. The reported occurrence of an unconformity at the top of the Ashern (Baillie, 1951; Norris and Uyeno, this



Figures 5.6: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.



Figures 7,8: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.

volume) indicates that post-Ashern erosion may have contributed to the irregularity of the isopach pattern. Examination of recent core holes shows evidence of thin intraformational breccia beds, but the magnitude of the erosional interval is uncertain.

Elm Point Formation

A separate map of the Elm Point Formation is not included as this unit is essentially lacking in the subsurface, where Ashern red beds are overlain directly by dolomite of the Winnipegosis Formation. Wells drilled as close as 15 miles southwest of the outcrop belt show no evidence of limestone development, although a few scattered subsurface occurrences of limestone in the Winnipegosis have been reported by McKennitt (1961). Recent core hole data indicate that the Elm Point probably is not a laterally continuous unit even in the outcrop belt. Mines Branch core hole M-4-70 (NE1/4 sec. 14, tp. 23, rge. 8WPM), located at the apparent contact between the Winnipegosis and Elm Point Formations, was expected to obtain a complete section of Elm Point limestone; instead, an intermediate type of lithology was intersected, consisting of interbedded limestone, dolomitic limestone and dolomite, approximately 50 feet thick. This suggests that the Elm Point represents an undolomitized inter-reef facies rather than a basal platform unit on which the Winnipegosis reefs were deposited. The reason for the localized occurrence of the limestone facies along the outcrop belt is not known.

Winnipegosis Formation

The Winnipegosis Formation comprises an almost completely dolomitized reef, inter-reef and fringing bank complex; the principal exception is the previously noted Elm Point "facies", which is included in the Winnipegosis in the isopach map (Figure 8). The unit shows a gradual, relatively uniform thickening to the northwest, from about 40 feet in the Manitou area to a maximum of 160 to 180 feet immediately east of the Birdtail-Waskada Axis. This is believed to represent a fringing bank type of deposit, laid down on the southeastern edge of the Elk Point Basin. West and north of the area of maximum bank build-up, the unit thins abruptly to about 40 feet in what is believed to be the basinal inter-reef area. This area is interrupted by local, sharply-defined areas where the Winnipegosis thickens abruptly to 200-350 feet in what are interpreted to be patch and pinnacle type reefs. Subsidence was apparently sufficiently rapid in the basinal areas so that only in local areas favourable for reef growth was deposition able to keep pace with subsidence. Elsewhere, the thin, fine-grained dolomites of the inter-reef facies suggest deposition in a starved basin. The reef configuration, as reflected by the structure contours on the overlying Souris River Formation, is well shown in the Swan River area (vic. tp. 36, rge. 28WPM; Stratigraphic Map Series DSR-2); reef shapes are irregular and apparently range from about 2 to 15 miles in diameter.

The Winnipegosis is overlain, in the southwestern part of the area by the evaporites of the Prairie Formation. To the north and east of the present area of Prairie evaporites the Winnipegosis is overlain by the basal "Second Red" of the Dawson Bay Formation. It is almost certain, however, that the Prairie evaporites originally extended much farther north and east. The entire outcrop belt of the Winnipegosis Formation, extending from The Narrows of Lake Manitoba to the Dawson Bay area, probably was overlain by salt which has subsequently been dissolved, resulting in collapse of the overlying Devonian and younger strata and draping over the underlying Winnipegosis reefs. This probably accounts for the pronounced structural irregularities evident in the Devonian outcrop belt; dips of 20 degrees or more are common on some of the small domes in the Dawson Bay area. The extensive development of brine springs along the outcrop belt suggests that salt solution is occurring at the present time.

The sharply-defined north-south trending edge of the fringing bank, in the southwestern part of the map-area, is somewhat abnormal relative to the general northeasterly trend of the isopachs in the shelf area. The location of the fringing bank coincides with the previously noted Birdtail-Waskada axis, indicating the possibility that the edge of the fringing bank, and also the edge of the Prairie salt beds, may have been structurally controlled by minor recurrent tectonism along this axis. North of approximately township 24, the fringing bank appears to revert to the northeast trend. However, a series of patch reefs are seen to occur along the northward continuation of the Birdtail-Waskada axis indicating that reef development may also, in part, have been localized along this axis.

Prairie Formation

The Prairie Formation, or Prairie Evaporite, is restricted to the subsurface (Figure 9), although, as noted previously, the evaporite beds at one time extended much farther north and east. The edge of the Prairie salt beds, throughout the map-area, is believed to represent a solution edge rather than a depositional edge; this is reflected by the gentle flexure of the structure contours along the salt edge.

The main body of evaporite is restricted primarily to the area west of the Winnipegosis fringing bank, where it comprises a thick, 425-foot, sequence of halite beds with minor anhydrite, and, near the top, a potash-rich interval of potential economic value (Bannatyne, this volume). A thin tongue of anhydrite beds extends eastward over part of the Winnipegosis fringing bank.

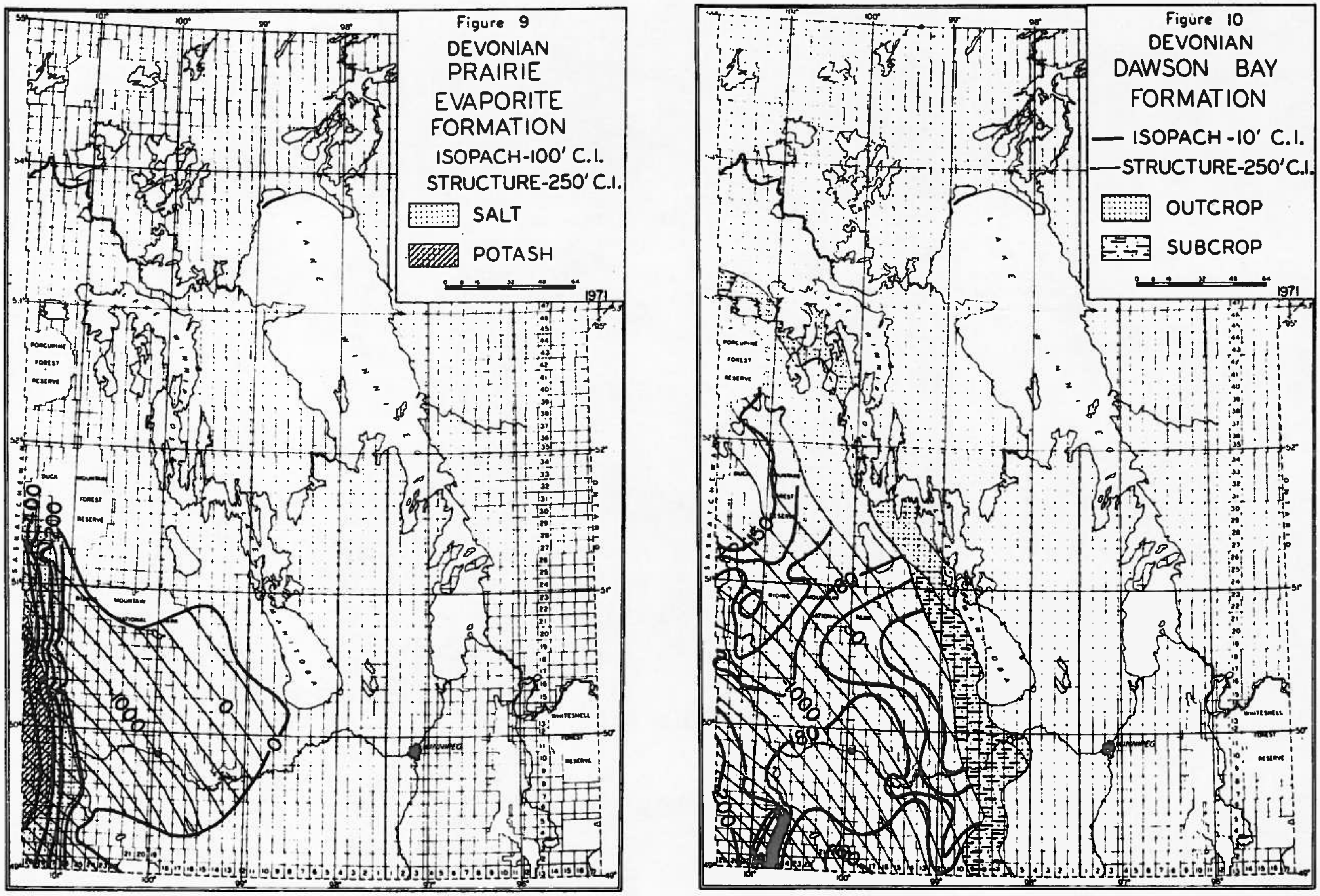
The contact between the Prairie Evaporite and the Winnipegosis appears conformable, although some workers have suggested a period of emergence and weathering prior to and during evaporite deposition. The contact with the overlying Dawson Bay Formation is unconformable. In Manitoba, evidence for this unconformity is the apparent truncation of the potash beds beneath the "Second Red" (Bannatyne, 1960). In some areas where salt solution is known to have occurred, the basal red beds of the Dawson Bay show a local increase in thickness, suggesting that the "Second Red" may, in part, represent the insoluble residue from this period of pre-Dawson Bay salt solution or erosion.

Dawson Bay Formation

The isopach pattern shown by the Dawson Bay Formation (Figure 10) is rather erratic. The sharply-defined thickening in the vicinity of townships 1-5, ranges 25-26 is due largely to a thickening of the basal red beds in an area of local salt solution along the edge of the Winnipegosis fringing bank. (As will be shown later, the time of salt solution was late Devonian to early Mississippian.). A general zone of thinning is evident in a north-south belt through the central part of the area, roughly coincident with the Birdtail-Waskada Axis. Somewhat surprisingly, the isopach shows a thickening to the east, towards the outcrop belt, where the thickest sections of Dawson Bay have been intersected. The irregularity in the Dawson Bay isopach, especially the apparent thickening east of the Birdtail-Waskada Axis, may possibly result from any or all of the following factors:

(i) pre-Dawson Bay solution of the underlying Prairie Evaporite,
(ii) solution of Dawson Bay evaporites from the present area of apparently thin Dawson Bay,
(iii) differential subsidence.

The lithology of the Dawson Bay is outlined by Norris and Uyeno (this volume). Although the outcrop and subsurface of



Figures 9,10: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.

Manitoba consist entirely of a shale-carbonate sequence, subsurface studies in Saskatchewan (Lane, 1959) indicate a thick sequence of evaporite beds, predominantly halite, at the top of the Dawson Bay sequence (Hubbard Evaporite).

These evaporite beds may have, at one time, extended into Manitoba; consequently, the apparent thickening of Dawson Bay to the east could possible reflect a combination of salt solution and facies change from evaporite to fringing carbonate bank. The changes in thickness along the outcrop belt indicate that lithofacies changes also can be expected; limited core hole data indicate that such lithofacies variations do occur.

Souris River Formation

Souris River strata show a gradual thickening towards an east-west trending axis of maximum subsidence in the central part of the map-area (Figure 11). [The marker used to define the top of the Souris River Formation in Manitoba occurs uniformly about 40 feet above the marker most commonly used to define this contact. The Manitoba marker corresponds to the top of the Manitoba Group as originally defined by Baillie (1953).] The isopach trends are markedly discordant to the outcrop belt so that considerable lithofacies variation can be expected along the outcrop belt. Only the lower one-half to two-thirds of the Souris River extends to outcrop; the upper part of the unit is buried beneath the onlapping Mesozoic strata.

As with the Dawson Bay, the configuration of the Souris River outcrop belt is irregular, probably because of the effect of salt collapse structures. Limited core hole drilling has confirmed the existence of considerable local structural relief, and it is highly probable that the previously mapped stratigraphic positions of many of the Souris River and Dawson Bay outcrops is in error. Further drilling is planned to clarify the structure and stratigraphy in the outcrop belt.

The lithology of the outcrop sequence has been described by Baillie (1950) and Norris and Uyeno (this volume). In the subsurface of Saskatchewan, four evaporite intervals (halite and anhydrite) are reported (Lane, 1964), with an aggregate thickness of up to 300 feet. Little evidence of these evaporite beds has been noted in Manitoba, however, the present distribution of evaporite beds in Saskatchewan is controlled, at least in part, by solution and it is thus possible that these evaporites at one time extended into Manitoba.

Shaly breccia beds in the Souris River Formation, near the town of Winnipegosis, may be solution breccias; if this is the case, the Souris River evaporites must have extended as far east as the outcrop belt.

A proposed revision of formation boundaries should be noted. Belyea (1970) has included the "First Red" as the uppermost unit of the Dawson Bay and indicated a probable Middle Devonian age. The older correlation which included the "First Red" as the basal unit of the Souris River, has been used in compilation of the isopach maps pending firm age determinations for these beds (*see*, Norris and Uyeno, this volume).

Duperow Formation

The Duperow Formation (Figure 12) and all younger Paleozoic formations, are completely overlapped by Jurassic and/or Cretaceous strata and are known only from subsurface well data. The limited extent of Duperow strata in Manitoba makes it difficult to determine the regional depositional pattern, but it seems similar to the Souris River, with thickening towards an east-west trending belt in the central part of the map-area. The most significant isopach feature is the local "thick" in the Napinka-Lauder area (tp. 3-6, rge. 27WPM). This feature is seen to coincide with a local structural high and ~~an~~ area ~~of~~ anomalously thin Prairie Evaporite; it apparently is the result of a period of early salt solution, during Duperow time, and is the earliest known major period of salt solution in Manitoba. Detailed maps in the potash exploration area also show a local area of incipient salt solution during Souris River and Duperow time; the St. Lazare 5-10-17-29 test hole shows a 30-foot thickening of the Duperow, as well as a 30-foot thickening of the Souris River; a structural low of 50 to 60 feet is evident on the top of the Prairie Evaporite. The top of the Duperow, however, shows a normal elevation, and the salt-potash sequence in the upper part of the Prairie Evaporite is also normal. This indicates limited or partial salt solution during Souris River-Duperow time, with solution occurring at the base of the evaporite sequence, presumably through the Winnipegosis aquifer.

Birdbear Formation (Nisku Formation)

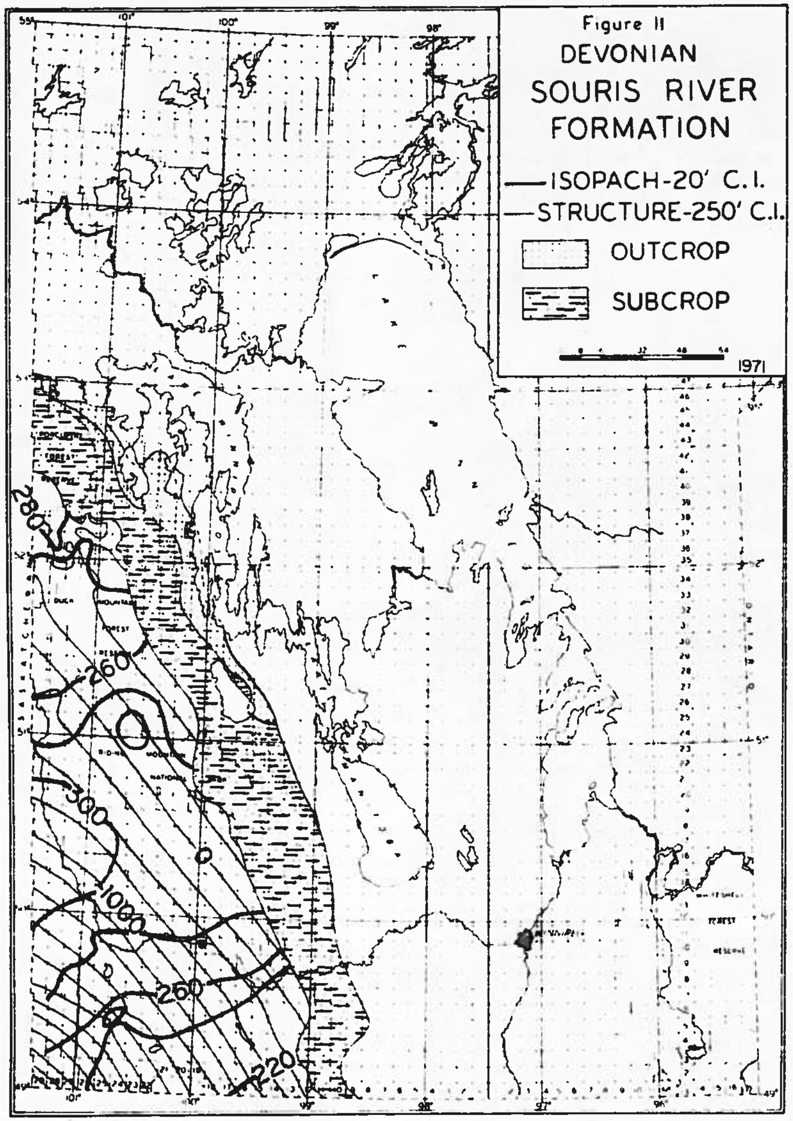
The Birdbear Formation comprises a relatively thin sequence of fossiliferous fragmental limestones and dolomites. The fossil content is sufficiently high that the unit has been considered to represent, in part, a biostromal deposit (Baillie, 1953). The Birdbear generally contains one or more zones of excellent porosity and permeability. Because the unit shows excellent reservoir characteristics and is unconformably overlain by the shales of the Lyleton Formation, which comprise an excellent cap rock for the stratigraphic trap, the Nisku has offered a prime target for oil exploration, and a large number of test holes have been drilled through the Mississippian to test the Nisku reservoir; results to date, however, have been negative.

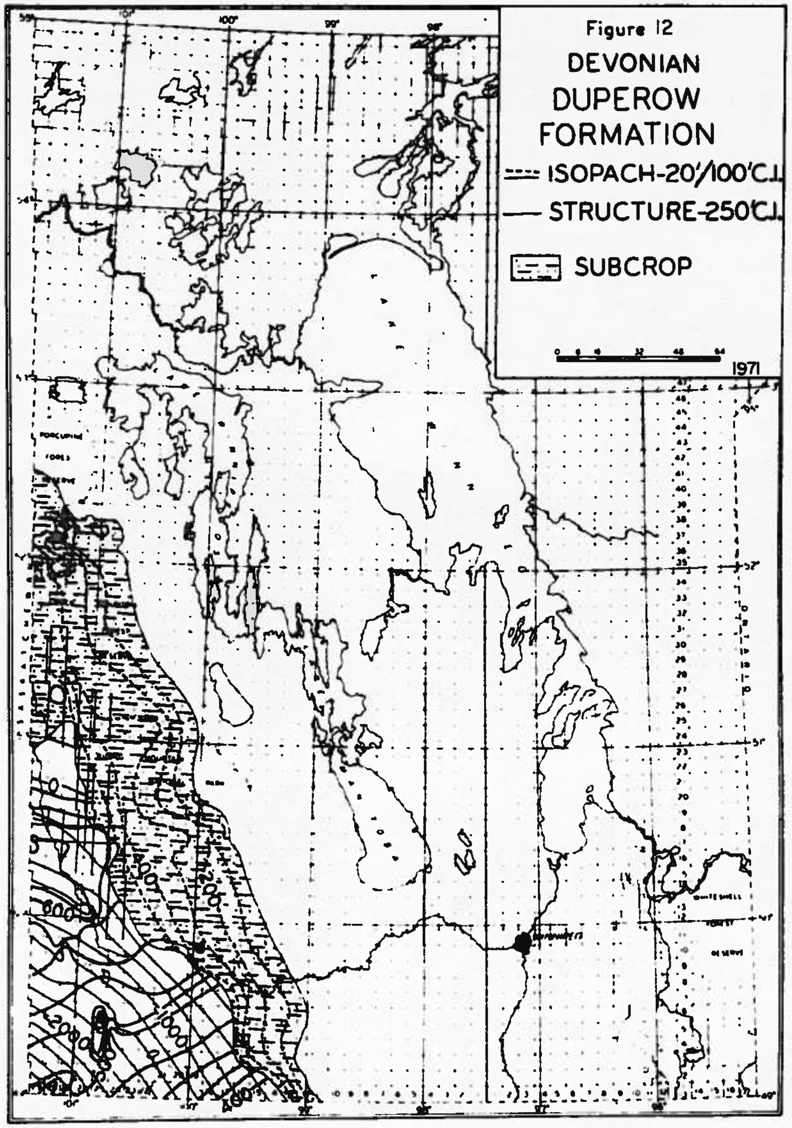
The isopach map (Figure 13) shows an irregular pattern with no evidence of any significant depositional trends; this is suggestive of a biostromal build-up under stabilized tectonic conditions near the end of the major Devonian depositional cycle. The complex of small, sharply-defined structural lows along the Birdtail-Waskada Axis is the same as noted for the Duperow; however, no isopach thicks are associated with any of these features, indicating that no salt solution occurred during Birdbear time.

Lyleton Formation (Torquay Member of the Three Forks Group)

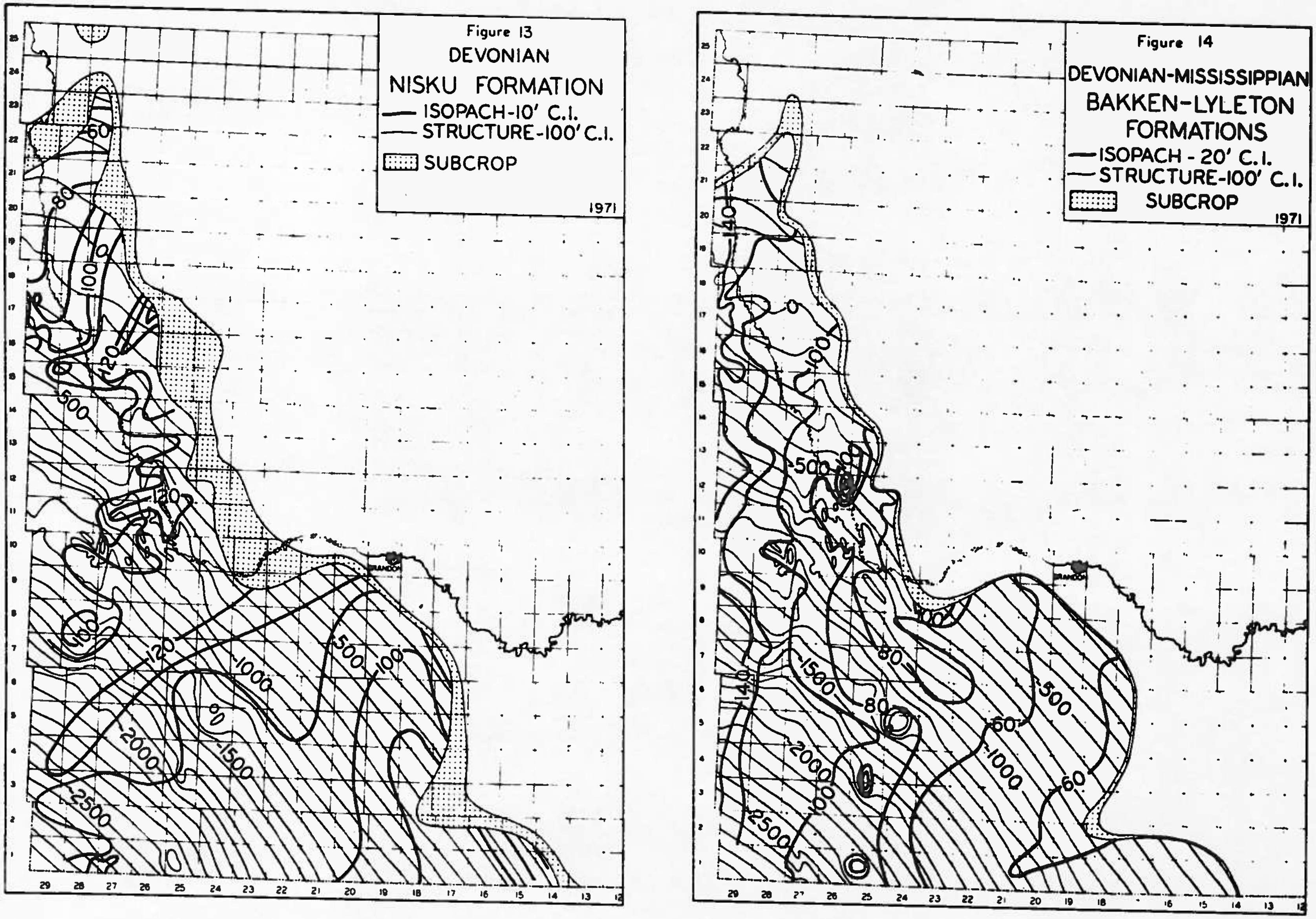
The Lyleton consists predominantly of red shale and dolomitic shale with some development of green, grey, and purplish phases. Breccia interbeds of shale and dolomite are common and suggest a number of minor erosional intervals during Lyleton time, as noted by Christopher (1961) in Saskatchewan. The contact with the overlying Mississippian Bakken Formation is unconformable, although the break is difficult to pick in logs or in samples. Christopher has shown that the upper member of the Three Forks—the Big Valley Member—is truncated in eastern Saskatchewan. In addition, the overlying Bakken shows onlap to the east so that the Lower Bakken pinches out in eastern Saskatchewan, and the Middle Bakken siltstone rests directly on eroded Lyleton (Torquay) beds in eastern Saskatchewan and Manitoba.

Because of the difficulty in picking the break between the Lyleton and Bakken, the combined Bakken-Lyleton interval has been included in the isopach-structure contour map (Figure 14). A prominent north-south isopach trend is evident, with a fairly rapid thinning towards the east, due to a combination of depositional thinning, intraformational erosion, and pre-Bakken truncation; the pattern appears transitional between that shown by the Devonian strata (related to the Elk Point Basin) and that shown by Mississippian strata (related to the Williston Basin). Also prominent on the isopach map are the series of isopach thicks along the Prairie Formation salt edge (i.e., Birdtail-Waskada





Figures 11,12: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.



Figures 13,14: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.

Axis); these are indicative of a period of salt solution during Bakken-Lyleton time. The southerly features coincide with structural highs, indicating later salt solution in adjacent areas; however, there is no evidence of structural deformation associated with the most northerly isopach thick, indicating that there has been no further salt solution in this area.

The marked irregularity of the subcrop belt is a result of the easily eroded nature of the Bakken-Lyleton shales, combined with the local facies development of a soft recessive black shale in the lower part of the overlying Lodgepole Formation, in the areas of the two main subcrop re-entrants.

MISSISSIPPIAN

Bakken Formation

Bakken strata, in Manitoba, consist of a basal Middle Bakken pyritic and argillaceous siltstone to fine sandstone, 10 to 30 feet thick, and an Upper Bakken highly organic and radioactive shale 10 to 20 feet thick. As noted previously, the shale beds of the Lower Bakken do not extend as far east as Manitoba, although they do occur locally near Waskada (tp. 1, rge. 25WPM) where they appear to have been deposited in an area in which salt solution occurred during Lower Bakken time. In places (e.g. St. Lazare area, tp. 17, rge. 28WPM) the Middle Bakken becomes somewhat coarser grained and cleaner; patchy oil staining has been noted but there has been no commercial production.

The Bakken apparently represents the basal transgressive deposit of the next major depositional sequence, following the period of late Devonian regression and erosion.

Lodgepole Formation

The Bakken is overlain conformably by the limestones and calcareous shales of the Lodgepole Formation. Because of the limited extent of Lodgepole and younger Mississippian strata in Manitoba, no isopach maps are included; rather, a subcrop-structure contour map (Figure 15) is used to show the configuration of the subcrop belts and their relation to oil occurrence. Details of Mississippian stratigraphy and oil accumulation have been presented previously by the writer (McCabe, 1959, 1963); new drilling data since that time have not changed the interpretation appreciably. The following, therefore, is only a brief review of some of the major features of Mississippian stratigraphy and oil accumulation.

Lodgepole strata in Manitoba are characterized, in the lower part, by marked lateral facies changes from clean limestones in the east to calcareous shales and argillaceous limestones in the west. The axis of maximum argillaceous content trends north-south in the vicinity of ranges 27 to 28WPM; farther west, in Saskatchewan, the lower Lodgepole grades back to a clean limestone. These facies changes appear to be due to minor differential subsidence with resultant entrapment of fine terrigeneous detritus along this north-south axis (approximately coincident with the Birdtail-Waskada Axis).

Two small highly anomalous areas of black shale (Routledge Shale) occur within the lower Lodgepole in the eastern limestone facies; the two areas are centred around Virden and Boissevain. Here, the Bakken black shale is overlain directly by up to 90 feet of similar but generally less radioactive black to dark brown shales. Because of the presence of the soft recessive weathering shales two prominent re-entrants have been developed in the Mississippian escarpment, leaving a large remnant paleotopographic high in the area southwest of Brandon (Figures 15, 16).

The upper part of the Lodgepole sequence consists of cyclically interbedded limestones and calcareous shales showing relatively minor lateral facies variation. The cyclical sequences in the lower part of this section have been named the Virden and Whitewater Lake Members; these beds comprise the reservoir strata for Lodgepole oil production in Manitoba. The lower parts of both members consist of interbedded porous oolitic limestones and thin calcareous shales; the upper parts are crinoidal fossil-fragmental limestone. Although facies changes in these strata are not as marked as in the lower Lodgepole, there is a westward decrease in grain size of the calcarenite beds and an increase in argillaceous content, which is reflected by a westward decrease in permeability and porosity of these reservoir beds.

Mississippian strata in the Williston Basin form an uniquely favourable environment for oil formation and entrapment. In the central part of the Williston Basin, Lodgepole and Mission Canyon strata consist of dark highly organic (bituminous) basinal limestones which provide excellent source beds for petroleum. The shales of the underlying Bakken and Lyleton Formations form an effective seat seal, and the overlying and up-dip equivalents of the Lodgepole and Mission Canyon basinal limestones consist of porous fragmental limestones which provide excellent reservoir beds. Truncation of Mississippian strata at the pre-Jurassic unconformity, and capping by the relatively impermeable Watrous or Amaranth red beds, combined with sealing of the subcrop by secondary dolomitization and anhydritization associated with the red beds, has provided an excellent cap rock. Furthermore, greater differential uplift and erosion on the northeastern flank of the Williston Basin has resulted in exposure, at the erosion surface, of a relatively deep basin-margin facies, one comprising the optimum interbedding of porous and non-porous strata; this in turn has resulted in the formation of a maximum number of stratigraphic truncation traps.

Localization of Lodgepole oil accumulation in the Virden area of Manitoba is directly attributable to the greater uplift and erosion in this area. This has resulted in a discordance between the subcrop and structure contour trends so that the subcrop belt is seen to rise structurally to the northwest (Figure 15). Since the Virden-Whitewater Lake reservoir beds show a westward decrease in porosity, oil has migrated up-dip (northwest) along the subcrop belt as far as the Virden area, where further migration was prevented because of the westward decrease in porosity; the numerous structural lows in this area also were effective in controlling or modifying oil accumulation. Reservoir porosity, in addition to being controlled by regional facies changes, has also been éffected by leaching during the period of pre-Jurassic erosion, and by secondary dolomitization and anhydritization associated with deposition of the overlying Amaranth red beds and evaporites. Because of the complexity of the structure and porosity variations, development of the field areas has been a slow and uncertain process.

Oil accumulation in the Daly area (vic. tp. 10, rge. 28WPM) occurs in strata approximately correlative with the upper producing beds of the Virden area, but results from down-dip entrapment due to the presence of several large structural (salt collapse?) lows that prevented further up-dip migration to the subcrop belt.

Mission Canyon Formation

Mission Canyon strata conformably overlie the Lodgepole beds, and consist of fossil-fragmental, algal, oolitic, and pelletoid limestones. This virtually basin-wide change from shaly deposits to clean, coarse-grained calcarenites indicates a major tectonic and environmental change, probably resulting from a relative stabilization of the tectonic framework and initiation of the regressive phase of the Mississippian depositional cycle.

The upper part of the Mission Canyon sequence shows a cylical interbedding of limestones and basin-margin type evaporites (anhydrite) with, in general, each younger evaporite showing a progressively greater basinward recession. Thin argillaceous and sandy marker beds are associated with the evaporites. By late Mississippian (Charles) time the cyclic evaporites had regressed to the central part of the Williston Basin and the degree of restriction had increased to the point where halite became a prominent constituent of the evaporites. Madison deposition ended with complete recession of seas from the Williston Basin area resulting in deposition of thick central basin halites and subsequent, relatively minor, erosion prior to commencement of the next main depositional sequence, initiated by the red beds of the upper Mississippian Big Snowy Group.

In Manitoba, only the lower part of the Mission Canyon sequence has been preserved; these beds have been designated as the MC-1 (limestone), MC-2 (evaporite) and MC-3 (limestone) Members. The uppermost Mississippian strata in Manitoba consist of anhydritic and dolomitic evaporites and have been referred to as the "Charles Evaporites"; they are not correlative with the type Charles Formation but lithologically belong to the Charles evaporite facies. The MC-1 and MC-2 Members together correlate with the Tilston Beds of Saskatchewan terminology, and the MC-3 and Charles correlate with the lower part of the Frobisher-Alida Beds.

The Mission Canyon subcrop units (Figure 15) show a general rise to the southeast, in direct contrast to the Lodgepole reservoir beds. However, no lateral porosity pinchouts or transcurrent structural or paleotopographic trends are present along the subcrop belt to localize oil accumulation. This probably accounts for the sparsity and small size of Mission Canyon oil accumulations in southwestern Manitoba (Figure 15). The oil would have tended to migrate through the Manitoba portion of the subcrop belt into North Dakota. By contrast, in Saskatchewan, the subcrop and structure contour trends are essentially parallel, and numerous gentle northeast-trending structural and/or topographic features are present and have resulted in the formation of numerous productive traps.

Oil accumulation in the Waskada area (vic. tp. 1, rge. 25WPM) is the only occurrence of its type in Manitoba. Accumulation has been localized on the flank of a truncated "sombrero-type" structural high, which apparently is the result of multiple-stage salt solution (Swenson, 1967). The window of Lodgepole in township 4, range 25WPM also represents a similar truncated sombrero-type structure, but no oil shows have been encountered to date.

PRE-MESOZOIC EROSION SURFACE

As noted previously, in descriptions of the individual formations, the Manitoba portion of the Williston Basin has apparently undergone relatively greater subsidence during periods of deposition, and relatively greater uplift during periods of erosion. This possibly reflects the different tectonic behaviour of the Superior crustal block, which underlies the Manitoba portion of the basin. Furthermore, the apparent boundary zone between the Superior and Churchill crustal blocks—the Birdtail-Waskada Axis—has been a zone of significant though minor structural and stratigraphic disturbance as shown by the occurrence of numerous structure, subcrop, and isopach anomalies (Figures 8 to 16).

Because of the greater uplift and deeper erosion in the Manitoba portion of the basin, a relatively thick, almost basinal sequence of Paleozoic strata is exposed in places at the pre-Jurassic erosion surface (Figure 16), and because of the general divergence of isopach and outcrop trends, most outcrop belts show a high degree of isopach and lithofacies change along the belt, from thin shelf facies to thick near-basin facies. Consequently, the maximum possible amount of stratigraphic data are obtainable from the outcrop belt.

The pre-Jurassic erosion surface (Figures 15, 16) is generally rather uniform, with a few major exceptions:

(i) Cuestas, scarps, and re-entrants caused by recessive-weathering shales. These are recognizable only along the edge of the Mississippian and along the subcrop of the Virden-Whitewater Lake beds, where close well control is available.

(ii) A major east-west trending channel south of Winnipeg (vic. tp. 3), with relief of more than 500 feet. Jurassic red beds and evaporites fill the channel and probably overlap as far east as the Precambrian shield.

(iii) Small, sharply-defined pre-Cretaceous channels, such as the Cretaceous outlier near Arborg (tp. 24, rge. 1WPM).

(iv) A local Duperow paleotopographic high south of Riding Mountain National Park (relief 200 feet), and a Dawson Bay high at Portage la Prairie (relief 150 feet). No specific control for these features is known.

(v) Structural-paleotopographic irregularities north of Riding Mountain National Park. These probably reflect a combination of salt collapse and Winnipegosis reef development.

(vi) The Lake St. Martin structure (vic. tp. 33, rge. 8WPM).

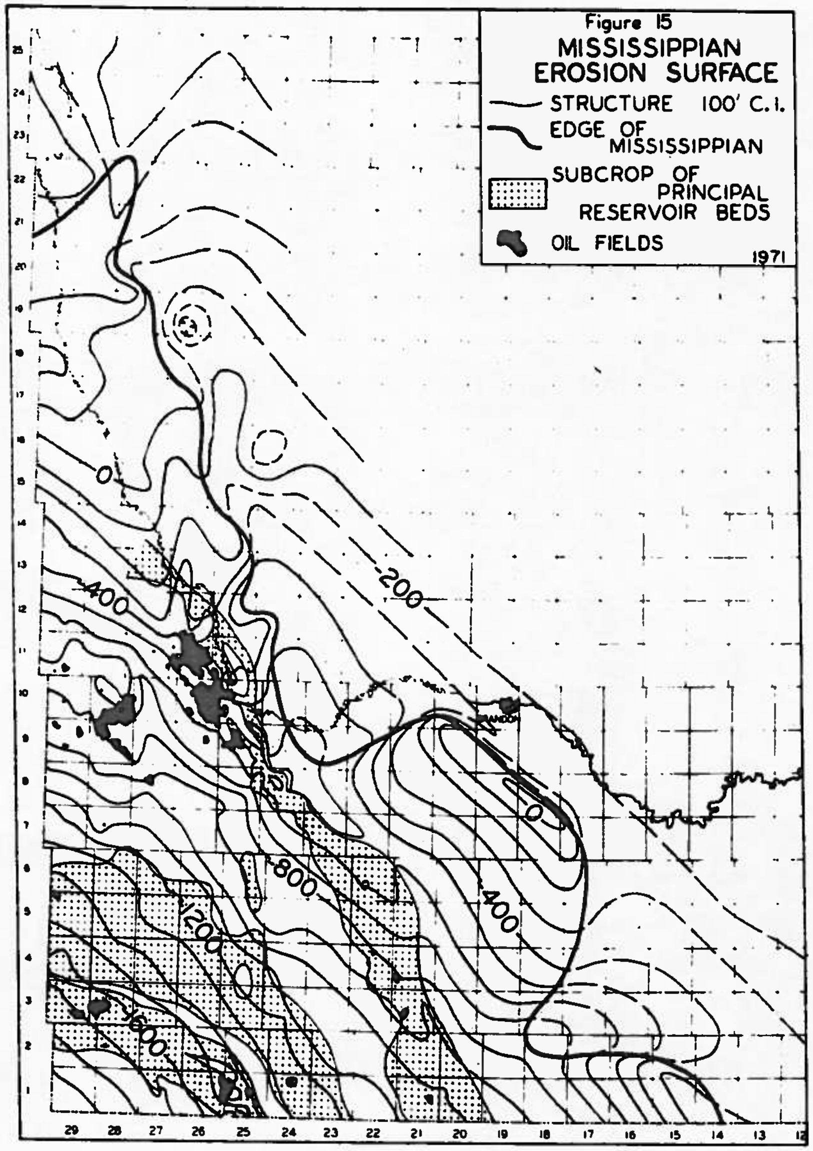
(vii) The Hartney structure (vic. tp. 5, rge. 24WPM).

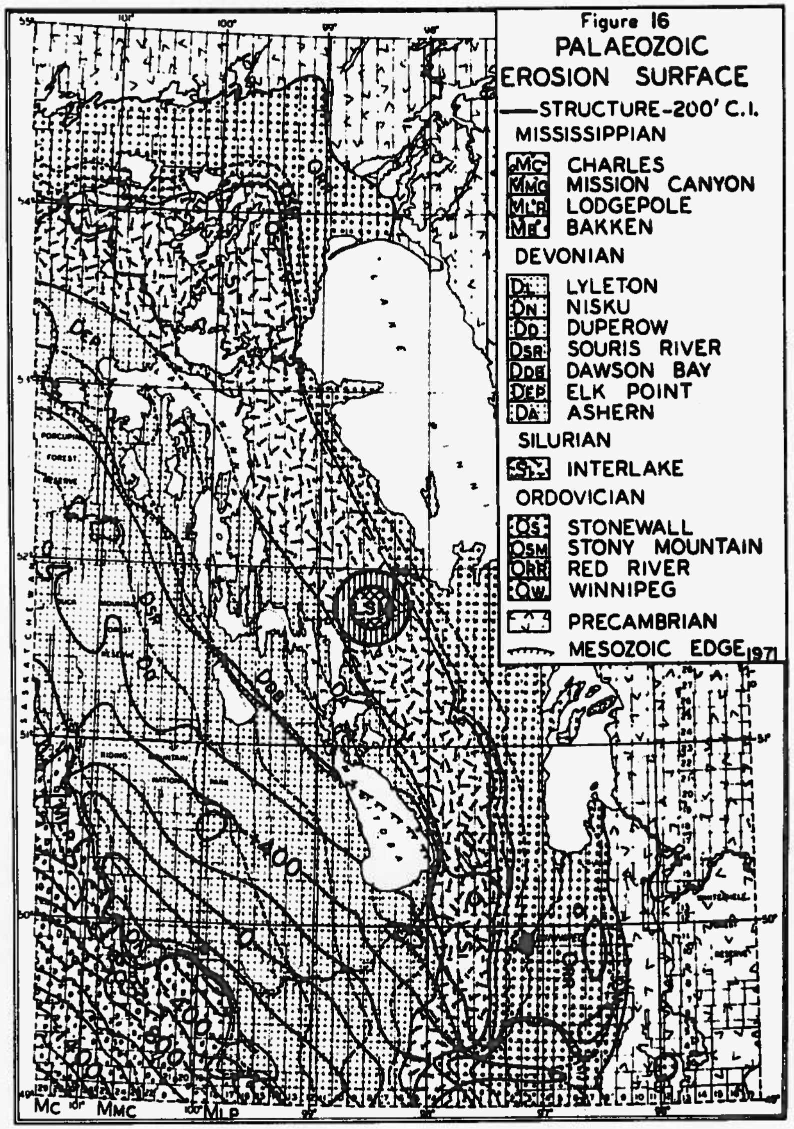
The *Lake St. Martin structure* is the most prominent feature shown on the Paleozoic subcrop/outcrop map (LSM, Figures 1 to 6, 16). A preliminary Mines Branch report on this feature (McCabe and Bannatyne, 1970a) gives all presently known data. The feature is a crypto-explosion crater, and consists of a crater or hole 14 miles in diameter and more than 1,000 feet deep, filled with an extremely complex sequence of breccias and volcanic-like rocks, including some carbonate breccias and fault blocks of probable Devonian strata. A central core, 2 to 3 miles in diameter, consisting of highly shock-metamorphosed Precambrian gneiss has been uplifted by at least 700 feet, and is exposed in the centre of the crater. The structure is approximately Permian in age (200-250 m.y.) and probably was formed when the area was uplifted and undergoing subaerial erosion. The presence of Devonian (?) rocks within the crater indicates that only a moderate amount of erosion had taken place at the time of crater formation. The upper part of the crater structure was truncated by later pre-Jurassic erosion, but subsequent burial by Amaranth strata has protected the crater from further erosion.

Beyond the crater rim is a structurally uplifted belt extending for about 14 miles. At the crater rim lower Paleozoic and Precambrian rocks have been uplifted by 700 feet or more and are exposed in outcrop near The Narrows of Lake St. Martin.

The origin of the crater structure, and of similar structures in Canada and around the world, is a subject of considerable controversy. Present theories suggest a meteorite impact origin, an explosive volcanic origin, or a composite origin with meteorite impact triggering subsequent volcanism. Data are presently insufficient to resolve the problem, but the Lake St. Martin structure undoubtedly provides one of the best preserved craters of this type and may eventually provide the answers to this problem.

The *Hartney Structure* is located in township 5, range 24WPM; the area of disturbance is poorly defined by a few deep oil exploration test holes, but probably is not more than 6 to 8 miles in diameter. The most complex structure involves the middle and upper Paleozoic strata, from basal Devonian





Figures 15,16: A series of Isopach-Structure contour maps for Paleozoic formations of southwestern Manitoba.

through Mississippian. Some structural anomalies are also present in the overlying Jurassic strata, but there is little evidence of deformation in pre-Devonian or post-Jurassic strata, except for the previously noted thickening of the Red River strata in the Hartney 1-29-5-24 well, with the resultant structural low on the Precambrian basement.

In the centre of the structure (Hartney 16-33-5-24) the top of the Paleozoic is 600 feet below regional elevation; the entire Mississippian section is missing and is replaced by a sequence of Jurassic (?) sands and shales showing a high degree of deformation and brecciation. Parts of the upper Devonian section, down to the Dawson Bay, appear to be missing, apparently due to normal or gravity-type faulting; below this, the stratigraphic succession appears normal, although all units down to Precambrian seem slightly high. Wells flanking the hole show the Paleozoic surface to be about 250 feet structurally high, and intensely brecciated (polymict carbonate breccias) in the upper part so that stratigraphic correlations are impossible; mechanical logs suggest repetition of section, presumably by reverse or thrust faulting.

The origin of the Hartney Structure is uncertain, but the intense brecciation, the apparent central "hole", the uplifted "rim", and the limitation of the disturbance to the stratigraphic interval from Devonian to Jurassic, all suggest a close similarity to the crypto-explosion craters, such as the Lake St. Martin structure. Other workers (e.g. Haites and Van Hees, 1962) have suggested that the Hartney structure is due to a major northeast trending transcurrent fault.

According to the writer's interpretation, the age of the structure is probably post-Mississippian–pre-Jurassic, as suggested by the lack of mixing of Paleozoic carbonates and Jurassic shales. The anomalous nature of the Jurassic (?) section probably results from penecontemporaneous slump faulting.

One other feature which has been noted at the pre-Jurassic erosion surface, is incipient development of a karst topography. Two holes drilled near the limit of Mesozoic cover, as part of the Mines Branch stratigraphic core hole programme, intersected extreme cavernous porosity in the near-surface carbonates of the Souris River Formation. Also, in the Mafeking Quarry of Inland Cement Industries (tp. 44, rge. 25WPM), approximately a dozen large solution channels up to 10 feet by 30 feet and of unknown length, have been uncovered; these channels are filled almost entirely by fine clean quartz sand and clay, probably of Cretaceous age and related to the basal Cretaceous Swan River sands. Such features are evidence of the extensive underground solution that occurred during the post-Paleozoic–pre-Mesozoic erosion interval.

MESOZOIC

With the one exception noted below the writer knows of no recent studies of the Mesozoic strata of southwestern Manitoba (see Table I for list of Mesozoic formations). No significant oil shows have been reported in these strata, so there has been no economic incentive for such studies, other than the brief period of interest in 1965-1966 when the oil shale potential of the Favel and Ashville Formations was investigated (Bannatyne, 1970, p. 44). The principal interest has been in the field of industrial minerals, and the recent study by Bannatyne (op. cit.) presents a general review of the entire Mesozoic sequence, as well as a series of isopach-structure contour maps incorporating essentially all available subsurface oil well data. New information presented in the study includes identification of a new subsurface stratigraphic unit occurring between the Pembina and Boyne Members of the Vermilion River Formation; this unit has been correlated with the Gammon Ferruginous Member of North Dakota. Also, Bannatyne has shown that the contact between the Odanah and Millwood Members of the Riding Mountain Formation follows a well defined stratigraphic marker, rather than being a facies type of contact.

For further information on Jurassic stratigraphy, the reader is referred to Stott (1955), and for Cretaceous stratigraphy, the principal reference is Wickenden (1945). No attempt will be made to review data covered in the above reports; however, a generalized discussion will be presented for Jurassic and lower Cretaceous strata, based on preliminary subsurface correlations by the writer, utilizing the large amount of subsurface data obtained subsequent to the reports by Stott and Wickenden.

JURASSIC

Amaranth Formation (Watrous Formation)

The Amaranth Formation comprises the basal unit of the Mesozoic sequence, and is believed to be of Jurassic or Jura-Triassic age, although no direct faunal evidence is yet available to prove this. The Amaranth was laid down on a deeply eroded Paleozoic surface from which up to 2,000 or more feet of Paleozoic strata probably had been eroded. In southeastern Manitoba, Amaranth beds occur in a deep erosional channel and probably rest directly on Precambrian basement, indicating truncation of the entire Paleozoic section.

The Amaranth consists of two members; the lower member is a red bed unit, of sandy argillaceous siltstone or shale, ranging up to 130 feet thick. The isopach of this unit reflects closely the topography of the pre-Amaranth erosion surface, as described previously. Local development of a sandy facies in the basal part of the red beds occurs in the southwestern corner of the Province, and oil shows have been reported. Further tests, however, did not yield commercial production, although such production is obtained a short distance south of the border, in the "Spearfish" beds of North Dakota.

The upper member of the Amaranth, in the subsurface, consists of interbedded anhydrite and shale, with minor dolomite. Near the outcrop belt the anhydrite has been largely converted to gypsum, and several mining and quarrying operations have utilized the basal evaporite bed, the thickest and purest of the three main evaporite beds in the Amaranth. The upper Amaranth shows a general southwestward thickening, from about 25 feet at the north end of the outcrop belt to 175 feet in the southwest corner of the Province. Thinning of the evaporite occurs over some of the larger pre-Amaranth paleotopographic highs, particularly in the area north of Virden where the entire Amaranth section pinches out.

Reston Formation

The Reston consists of interbedded limestone, dolomite, shale, and minor calcareous sandstone. Stott (1955) indicated that the contact between the Reston and the underlying Amaranth was unconformable; recent data, however, show no appreciable evidence of erosion or truncation, so the unconformity, if present, is slight. The Reston, in part, passes laterally into the shales of the overlying Melita Formation. This could possibly be due to pre-Melita erosion, but more likely is the result of a facies change from limestone to shale. In either case, apparent changes in thickness of the Reston of up to 80 feet are evident over short distances, with little change in overall thickness of the Reston-Lower Melita interval. The reston thins to the north, pinching out north of the Virden area because of both depositional (or erosional ?) thinning and overlap on the previously noted major paleotopographic high.

Melita Formation

Stott (op. cit.) divided the Melita into upper and lower members; the Lower Melita consists of a highly variable sequence of sand, calcareous sand, and shale, commonly varicolored. The sand content shows a marked increase to the north, and north of the Daly area mechanical logs for some wells indicate 70 per cent or more clean sand. In this same area (vic. Owen McAuley 12-2-15-29) pre-Cretaceous erosion has removed most of the Upper Melita so that the highly variable Swan River sands rest almost directly on the highly variable Lower Melita sands. Separation of the two units becomes virtually impossible, especially with the generally poor quality of the available well samples. The Swan River Formation in the type area may possibly include both Jurassic (Lower Melita) and Cretaceous sands. The Lower Melita isopach (Bannatyne, 1970, Figure 7, p. 18) shows a general though irregular thinning to the west.

The Upper Melita is distinguished from the underlying strata by a marked decrease in sandy interbeds and a much less variable lithology. Mechanical log markers are correlatable over large areas, indicating a much more stable environment of deposition. Lithologically, the Upper Melita consists of slightly calcareous and silty shales, commonly greenish to brownish grey, although variegated shales are present in some areas. Towards the top of the unit, interbeds of fossiliferous and sandy limestone occur as prominent marker beds. The Upper Melita shows a somewhat anomalous isopach pattern with a rather uniform thickening to the northwest, from 200 feet in the Turtle Mountain area to 300 feet in the Daly area. Pre-Cretaceous truncation occurs northeast of Brandon, where Upper Melita beds are unconformably overlain by Cretaceous sands and shales; in addition, two areas of local erosional thinning of Upper Melita are evident in the area south of Pierson (vic. tp. 2, rge. 29WPM), and in an area trending east and north between Waskada and Souris (Bannatyne, 1970, Figure 12, p. 23), where deeply incised pre-Cretaceous channels have eroded the upper part of the Melita, removing as much as 60 feet of Melita strata. Another more poorly defined channel occurs in the Treherne area (vic. tp. 8, rge. 9WPM). Data are not sufficient to completely define these channels.

Waskada Formation

Throughout most of the southwestern corner of the Province, southwest of Brandon, the Waskada Formation overlies the Melita Formation with apparent conformity, and is in turn overlain with marked unconformity by the Lower Cretaceous Swan River Group. Locally, in the vicinity of Brandon and Virden, the Swan River pinches out and the Waskada beds are overlain directly by Lower Ashville shales. Maximum thickness of the Waskada is about 160 feet in the southwest corner of the Province; thickness variations are extreme, with relief in the vicinity of the previously described pre-Cretaceous channels resulting in local thickness variations of as much as 250 to 300 feet.

The Waskada consists of interbedded shales, fine-grained sandstones, and minor calcareous sandstones; facies changes are rapid but some lateral correlation is possible. Because the log response and lithology of the Waskada are similar to the overlying Swan River, the contact between the two units is difficult to pick, and, as Stott pointed out, poses a major stratigraphic problem. Lithologic data generally are too poor to assist materially in determining the contact.

CRETACEOUS

With the exception of the Swan River Group and the Ashville Sand, Cretaceous sediments consist of a sequence of siliceous, bentonitic, and carbonaceous shales with two marker beds of calcareous shale and argillaceous limestone (Boyne and Favel). Most of the strata are comparatively well exposed in outcrops along the Manitoba Escarpment and in the uplands to the west; detailed descriptions have been reported by Wickenden (1945), and a summary, including subsurface stratigraphic maps, has been presented by Bannatyne (1970). A general review and guide to the outcrop sections is included by McCabe and Bannatyne (1970b). Further discussion will be limited to the Swan River Group and the Ashville Sand, for which considerable new data are available.

Swan River Group

The Swan River Group comprises a highly variable sequence of fine to coarse sandstone, pyritic sandstone, shale, and lignite. It overlies the Jurassic strata with slight angular unconformity and pronounced erosional channelling. To the north, in the Swan River area, most if not all of the Jurassic strata have been eroded and Swan River sands apparently lie directly on eroded Paleozoic strata; it is possible, however, that the lower part of the Swan River may include some Jurassic sands.

Marked isopach variations are evident in addition to the previously described channelling. The Swan River thins to the northeast, from a maximum of 400 feet in the channel south of Pierson, to a pinchout in an east-west belt extending from about township 7 to township 10. North of township 10 and west of range 20WPM, the sand reappears and thickens to the north to a maximum of about 330 feet in the Swan River area; thickness estimates in this area, however, are uncertain because of the previously noted difficulty in distinguishing between the Swan River sands and the underlying Jurassic sands.

The presence of a number of Cretaceous outliers should be noted. These occur in sharply defined channels cut into earlier Jurassic or Paleozoic strata. The best known channel is at Arborg (vic. tp. 24, rge. 1WPM), where kaolinitic shales and siltstones occur in a channel averaging 300 feet wide and more than 120 feet deep, eroded into Upper Ordovician strata. A second channel is cut into Jurassic strata near Ste. Rose du Lac, where the Swan River clays are quarried for brick clay (Bannatyne, this volume).

Price (1963) has suggested that, in the Swan River area, the stratigraphic position of the top of the Swan River rises sharply, with the upper Swan River strata being equivalent to the Ashville shales to the southwest. Correlation of structure test holes a short distance south of Swan River shows little evidence of such transgression, although several wells did intersect a "stray" sand within the lower part of the Ashville, in a position roughly equivalent to the Ashville Sand of southern Manitoba or the Viking Formation of Saskatchewan. Considerable structural disturbance is evident in the Swan River area, as shown by repetition and omission of marker beds, etc.; this may be due to slump faulting and/or ice thrusting near the Manitoba Escarpment.

Ashville Sand

The Swan River is conformably overlain by the Ashville Formation. The Ashville Sand occurs within the lower part of the Ashville Formation, approximately half way between the "Fish Scales Marker" and the top of the Swan River. It appears to be directly correlatable with the Viking Formation of eastern Saskatchewan. Although sample data are very poor, the unit appears to consist of fine to coarse, well sorted and relatively clean sand. Thickness variations are highly erratic, but the isopach pattern shows a general thickening towards the southwest, to a maximum of about 110 feet. However, southwest of an irregular line from approximately township 12, range 29WPM to township 2, range 12WPM, the Ashville sand pinches out abruptly, apparently by facies change to

Ashville shale. To the northeast, the unit thins to a relatively uniform blanket sand, commonly less than 10 feet thick. Near the southwestern limit of the unit, where close well control is available in the Virden oil fields, thickness changes of as much as 70 feet occur in distances of less than one-quarter mile.

Much more detailed work is necessary to determine the origin of the Ashville Sand, but from the presently available isopach and lithologic data, the sand body appears to be a shoreline-delta complex with a source of sand to the northeast. The trend of the sand body is subparallel to the isopach trend of the Lower Ashville (Bannatyne, 1970, Fig. 19).

TERTIARY

Boissevain and Turtle Mountain Formations

These strata consist of interbedded sandstone, shale and lignite beds, attaining a maximum thickness of approximately 150 feet. The outcrop area, on Turtle Mountain, comprises an isolated outlier of the Third Prairie Level, and occurs about 40 miles northeast of the main Missouri Couteau. Geological data were sparse until recent sidewall sampling was carried out jointly by the Geological Survey of Canada and the Manitoba Mines Branch; this provided a fairly complete lithologic sequence. All of these data have been presented by Bannatyne (1970). In addition, the Mines Branch is presently carrying out a core hole programme to sample the kaolinitic clay and lignite beds of the Turtle Mountain area and to provide additional basic lithologic data for more detailed stratigraphic studies.

REMARKS

The foregoing discussion of the sedimentary rocks of southwestern Manitoba has attempted to outline briefly the present state of knowledge and to summarize the more recent geological data. It has also attempted to set a regional framework for the following papers, and to point out some of the remaining stratigraphic problems. Hopefully, the stratigraphic core hole programme recently undertaken by the Mines Branch will supply some of the basic data necessary to answer these problems.

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