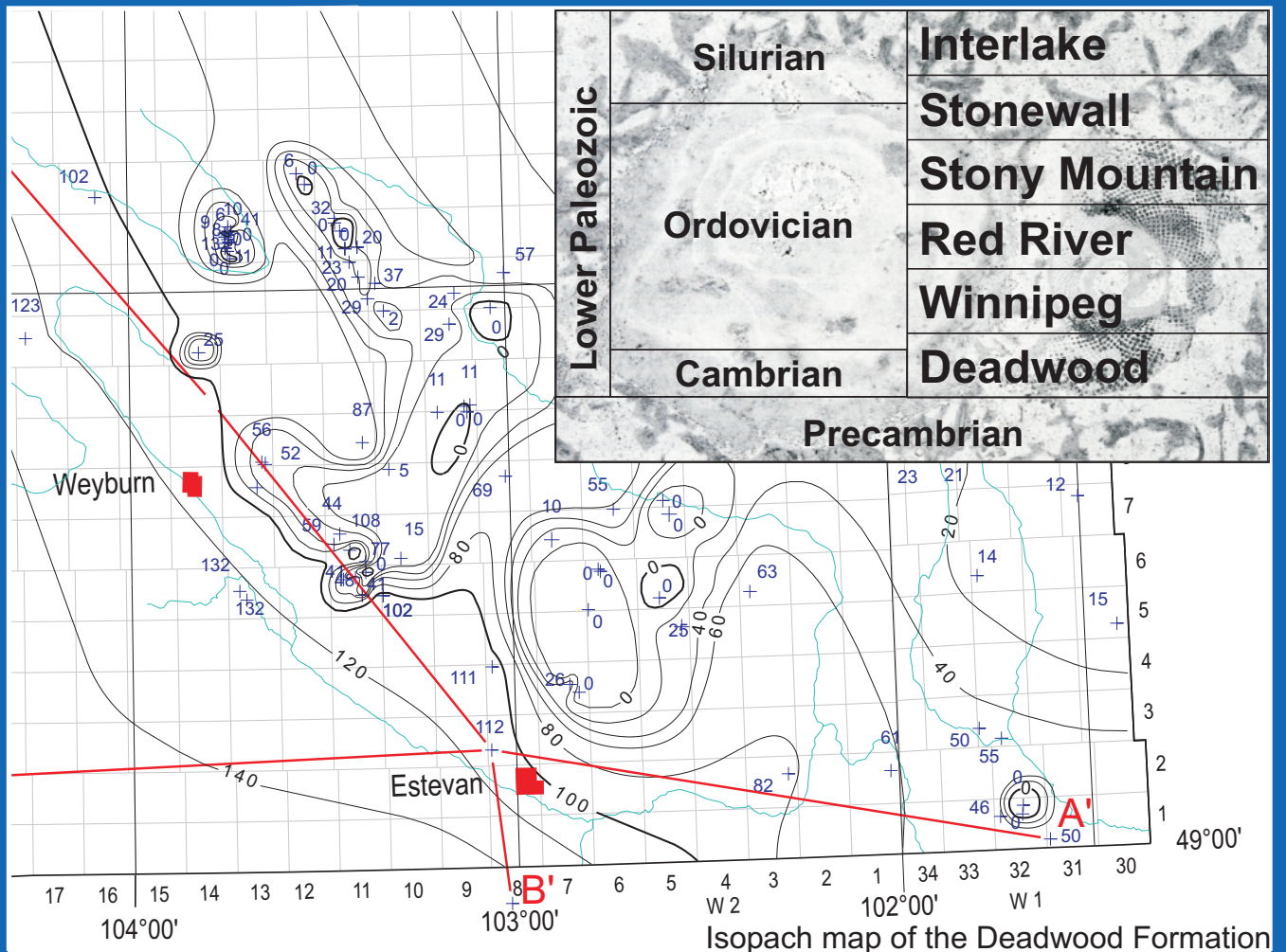




Lower Paleozoic Map Series – Saskatchewan

by

L.K. Kreis, F.M. Haidl, A.R. Nimegeers,
K.E. Ashton, R.O. Maxeiner, and J. Coolican





Saskatchewan
Industry and
Resources

Miscellaneous Report 2004-8

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Cover:

Isopach map of the Deadwood Formation in southeastern Saskatchewan illustrating Deadwood thins which commonly overlie highs on the Precambrian surface. Stratigraphic intervals mapped as part of this project are superimposed on a photograph of Ordovician Tyndall Stone displaying *Receptaculites* and stromatoporoid fossils.

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Foreword

Work toward compiling a full suite of structure and isopach maps of Lower Paleozoic strata in Saskatchewan and spreadsheets of their supporting data was initiated in 1993, and the first preliminary Stonewall Formation map sheet was published in the Saskatchewan Geological Survey's 1994 Summary of Investigations. The preliminary Interlake map sheet and regional cross section sheet were published in the 1995 Summary of Investigations.

In 2000, the Precambrian, Deadwood, Winnipeg, and Red River map sheets (Sheets 1 to 4), were released as Saskatchewan Energy and Mines Open File Report 2000-2. This CD contains digital versions of those map sheets with only minor editorial changes.

The Stony Mountain, Stonewall, and Interlake contour maps included on this CD (Sheets 5 to 7) have been updated using data from most off-confidential wells available to January 2000 and from selected, more recently drilled, wells. The text and some figures for these map sheets incorporate information from wells that were off confidential as of July 31, 2003. The regional cross-section sheet (Sheet 8) has been modified to include a reference list; other minor editorial changes have also been made.

The original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. An interactive ESRI ArcReader Project included in this publication allows users to overlay contours, well information, geophysical maps, and other data with Saskatchewan cultural data (borders, cities, rivers, etc.).

Appendix A includes an Excel spreadsheet that incorporates stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian for wells off confidential as of July 31, 2003. Appendix B includes a publication on Lower Paleozoic anhydrites in the Saskatchewan Weyburn Project area together with the stratigraphic data used in the study. Included in the publication are maps of seven anhydrite units, two cross sections, and a description and interpretation of each anhydrite unit. The Saskatchewan Stratigraphic Correlation Chart and other reference material are included as Appendix C.

Detailed instructions explaining how to access various components of this CD are included.

The production of this Lower Paleozoic Map Series CD is an important milestone in the development of an integrated stratigraphic framework of the province's Phanerozoic sedimentary rock package. Contained data have recently been and continue to be incorporated into major regional basement-to-near-surface mapping projects such as the Petroleum Technology Research Centre's (PTRC's) *Weyburn CO₂ Monitoring and Storage Project*, the NRCan-Manitoba-Saskatchewan Targeted Geoscience Initiative (Round 2) *Williston Basin Architecture and Hydrocarbon Potential Project*, and PTRC's *Stratigraphic and Hydrogeological Framework of Western Saskatchewan Project*. Province-wide completion and subsequent comprehensive integration of these collaborative subsurface mapping projects is expected in 2006, and will form a reliable foundation for further research, and for exploration and development of hydrocarbons, potash and other geological resources in southern and central Saskatchewan.

*Chris Gilboy
Director Petroleum Geology Branch
Saskatchewan Industry and Resources*

March 2005

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Sheet 1 – Geology of the Precambrian Basement and Phanerozoic Strata in Saskatchewan

L.K. Kreis, K.E. Ashton, and R.O. Maxeiner

Kreis, L.K., Ashton, K.E., and Maxeiner, R.O. (2004): Geology of the Precambrian basement and Phanerozoic strata in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 1 of 8.

Introduction

Depth and thickness values used in the construction of Precambrian structure and Phanerozoic isopach maps shown here were largely derived from geophysical logs run in boreholes drilled to the Precambrian below the Phanerozoic cover south of the exposed Precambrian Shield edge. Most of these boreholes were licensed for oil and gas exploration and the data collected are accessed through the Well Information System (WIS). Others, drilled for metallic minerals and diamond exploration, yielded values that were derived strictly from continuous core. Information collected from base metal and diamond exploration reside in the Mineral Assessment files. Data from a total of 346 Precambrian borehole penetrations were used in the construction of these maps.

The sub-Phanerozoic Precambrian basement in Saskatchewan largely consists of meta-igneous and metasedimentary rocks of the Archean Rae, Hearne, Sask, and ?Wyoming cratons; the Paleoproterozoic (~1.9 to 1.8 Ga) Reindeer Zone; the Churchill-Superior Boundary Zone (here renamed to Superior-Reindeer Boundary Zone); and the unmetamorphosed Swift Current Anorogenic Province (~1.7 Ga). In the southern two-thirds of Saskatchewan, sediments ranging in age from Middle Cambrian to Cretaceous unconformably overlie the basement surface. The southern edge of the exposed Precambrian Shield shown on these maps represents the northern boundary of pre-Quaternary sediments in Saskatchewan. Quaternary sediments are found both north and south of this boundary.

Precambrian Surface (Precambrian Structure Map)

The Precambrian unconformity dips to the southwest at approximately 2.8 to 4.8 m/km until it reaches the northern margin of the present-day structural Williston Basin (approximately represented by the -1500 m contour), the configuration of which is largely the result of Laramide deformation. South of the -1500 m contour, the dip of the unconformity steepens from about 4.5 m/km to about 15.0 m/km at the Canada/U.S.A. border near Estevan. The regionally uniform slope is disrupted in the southwest, where, south of latitude 52°N to latitude 50°N, the dip of the unconformity changes to approximately 1.6 m/km south. South of latitude 51°N, the strike of the unconformity, near the Alberta-Saskatchewan border, swings to north-south and the dip is shallow to the east. In the southwestern corner of the map area, the unconformity strikes northwest-southeast and dips 6.6 m/km to the northeast, creating a shallow east-plunging synclinal feature between Swift Current and the southwestern corner of the province. The region in which the unconformity is essentially sub-horizontal forms the Swift Current Platform and has exhibited repeated tectonic movement through Phanerozoic time. Basement highs, particularly numerous in southeastern Saskatchewan, reflect the topography of the Precambrian surface prior to deposition of overlying sediments and episodic reactivation of basement structures during Phanerozoic time.

Precambrian Geology

In the past, partitioning of the sub-Phanerozoic Precambrian basement of Saskatchewan into geologically similar regions has been based on southward extrapolation of lithotectonic domains in the exposed shield, aeromagnetic and gravity data sets, and limited lithological and geochronological information from Precambrian rocks encountered during the drilling of hydrocarbon and mineral exploration wells (*e.g.*, Thomas *et al.*, 1987; Hoffman, 1989; Burwash *et al.*, 1993; Jones *et al.*, 1993; Nelson *et al.*, 1993; Miles *et al.*, 1997). New interpretations of the geology of the exposed shield, resulting from recent mapping, the NATMAP (*e.g.*, Syme *et al.*, 1998) and LITHOPROBE (*e.g.*, Clowes, 1997) initiatives, and upgrading of the geophysical database, have led to a re-evaluation of the Precambrian basement in southern Saskatchewan. Interpretations of the sub-Phanerozoic Precambrian geology of southern Alberta (*e.g.*, Ross *et al.*, 1995) and the northern United States (*e.g.*, Baird *et al.*, 1996) have also provided a regional framework within which to integrate the Saskatchewan component of the Precambrian basement.

In this study, subdivision of the sub-Phanerozoic Precambrian Shield was primarily based on interpretation of total field and first vertical derivative aeromagnetic maps. Several magnetic domains were recognized (see [Figure 1a](#)), the boundaries between them delineated by large changes in overall aeromagnetic intensity, sharp truncations of aeromagnetic trends, and/or extrapolation of domain boundaries from the exposed shield. While magnetic domain boundaries generally follow the structural grain of the aeromagnetic map, they crosscut in some places where they

are delineating areas of differing intensity. The gravity map (Figure 1b) was used as a further means to interpret the Precambrian geology, and is shown with an overlay of the magnetic domains and major crustal subdivisions.

Most major tectonic elements known in the exposed Precambrian Shield can be traced with a high degree of certainty southward below the Phanerozoic cover. The thicker lines show the first-order lithostructural hierarchy that defines major crustal features of the buried and exposed Precambrian, namely the Archean Rae, Hearne, Wyoming, and Sask cratons, the Paleoproterozoic Reindeer Zone, and boundary zones between them. Confidence in this interpretation decreases with distance from the southern edge of the exposed shield. Discussion of the sub-Phanerozoic Precambrian architecture focuses on the main crustal-scale breaks as they are potential zones of Phanerozoic reactivation, an important aspect in Phanerozoic sedimentation and the formation of structural traps for hydrocarbons.

The Wapawekka-Estevan magnetic domain (Figure 1a) is defined by a curvilinear zone of magnetic quiescence that separates the Sask Craton from the Reindeer Zone. It is thought to represent the zone of *ca.* 1.84 to 1.83 Ga collision between the Sask Craton and overthrust juvenile Paleoproterozoic Reindeer Zone (Lewry *et al.*, 1994; Ansdell *et al.*, 1995; Ashton *et al.*, 1996, 1999; Lucas *et al.*, 1993). The largely buried Archean Sask Craton, comprising the Tobin and Humboldt magnetic highs and the Smeaton and Weyburn magnetic lows, crops out in only three small tectonic windows on the exposed shield (*e.g.*, Lewry *et al.*, 1990; Ashton *et al.*, 1996, 1999), but has been seismically profiled in southern Saskatchewan by LITHOPROBE (Lucas *et al.*, 1993). Seismic studies some 50 km south of the Canadian-American border by COCORP (Baird *et al.*, 1996) have revealed a zone of similar seismic character termed the Dakota Block which is considered broadly correlative with the Sask Craton.

The Tabbernor Fault Zone is a long-lived (>1.7 Ga) 'mega-lineament' (Elliott, 1996) that stretches for more than 1000 km from the Northwest Territories into the United States. Its extrapolation south of the exposed shield coincides with the eastern extent of the Wapawekka-Estevan magnetic low, suggesting a genetic relationship. Early ductile deformation is overprinted by a later, long-lived brittle deformation that continues into the Quaternary (Elliott, 1996). West of the Sask Craton and Reindeer Zone, another major crustal-scale discontinuity is marked by a set of west-dipping seismic reflectors (Nelson *et al.*, 1993; Hajnal *et al.*, 1996). It coincides with the >500 km long Reindeer Magnetic Quiet Zone (RMQZ; Burwash *et al.*, 1993), and the ~2000 km long North American Central Plains conductivity anomaly (NACP; Reitzel *et al.*, 1970). Green *et al.* (1985) were the first to correlate the NACP with the RMQZ, although their spatial correspondence is not perfect, possibly due to the wide magnetometer spacing and resulting poor control of the NACP survey (Jones *et al.*, 1993). On the exposed shield, the western edge of all these geophysical elements roughly coincides with the eastern extent of the Wathaman Batholith, which has been interpreted as a 1.86 Ga Andean-type continental arc pluton (*e.g.*, Meyer *et al.*, 1992) intruding the Hearne Craton margin and accreted terranes of the Reindeer Zone. In the north, the RMQZ probably represents a collisional zone between the accreted La Ronge arc and the Hearne Craton. To the south, it is unclear whether the La Ronge and Wathaman domains are continuous, or whether the RMQZ represents a suture between the Sask and Hearne-Wyoming cratons.

The 2800 km long Snowbird Tectonic Zone (STZ) represents the boundary between the Hearne and Rae cratons (Hoffman, 1989). In Saskatchewan, the Rae Craton is made up of the Firebag, Clearwater, and Western Granulite magnetic domains; the Hearne Craton of the Virgin River and the Mudjatik, Makwa, and Battlefords magnetic domains. The STZ appears to have been a long-lived structure in which the effects of two Archean (3.2 Ga and 2.6 Ga; Hanmer *et al.*, 1991), and two Paleoproterozoic compressional tectonic events (1.95 to 1.85 Ga and 1.84 to 1.78 Ga; Hoffman, 1989) have been recognized. In the exposed part of the Precambrian Shield in Saskatchewan, south of the Athabasca Basin, the STZ is fringed along its southeast side by the variably tectonized 1.82 Ga Junction Granite of the Virgin River magnetic high. In the sub-Phanerozoic, the STZ is defined by truncation of the Clearwater magnetic high and by truncation of the 2.0 to 1.9 Ga Taltson magmatic zone farther west in Alberta.

Another zone of possible Phanerozoic reworking is the Superior-Reindeer Boundary Zone, which separates the juvenile Paleoproterozoic rocks of the Reindeer Zone in the west from predominantly Archean gneisses of the Superior Craton in the east. It coincides with a gravity high (Figure 1b), probably due to the presence of ultramafic rocks similar to those exposed along strike in the Thompson Nickel Belt to the northeast (*e.g.*, Baragar and Scoates, 1981).

The southwestern portion of Saskatchewan is the most difficult to interpret as the aeromagnetic pattern there is indistinct. North-northeast-trending anomalies related to the Wollaston Domain of the Hearne Craton can be traced continuously through the Battlefords Domain southward to the bend of the Reindeer Magnetic Quiet Zone. There, the magnetic pattern changes to a more south- and southeast-trending orientation, and is overprinted by weak east-northeasterly trending discontinuities related to the Great Falls Tectonic Zone (GFTZ; O'Neil and Lopez, 1985), an enigmatic, periodically reactivated Precambrian structure (Boerner *et al.*, 1998). Recent interpretations of the sub-Phanerozoic geology in this area are divided on the origin of the GFTZ. Workers favouring a distinct Wyoming Craton (Assiniboia magnetic domain), regard the GFTZ as an ~1.8 Ga suture between it and the Hearne Craton (*e.g.*, Hoffman, 1989; Erslev and Sutter, 1990; Dahl *et al.*, 1999). Others view the two cratons as broadly correlative

and interpret the GFTZ as an intracratonic fault (Boerner *et al.*, 1998). The indistinct nature of the aeromagnetic pattern in the southwest may also result from the presence of ~1.76 Ga anorogenic high-level granitic and extrusive rocks, which together form the Swift Current Anorogenic Province (Collerson *et al.*, 1989).

The GFTZ appears to coincide with the northwestern boundary of Cretaceous and Tertiary exposures between Maple Creek and Swift Current. Northwesterly trending discontinuities, possibly related to the RMQZ, may similarly control the northeastern edge of the Missouri Coteau. A more restricted northwest-trending exposure of Cretaceous and Tertiary rocks in the Grassland National Park is spatially related to an aeromagnetic lineament of unknown origin.

Miles *et al.* (1997) placed emphasis on identifying small-scale aeromagnetic lineaments in their interpretation of the sub-Phanerozoic Precambrian geology. While we also recognize these features, we have excluded them from the present maps as we are unable to adequately interpret them.

Phanerozoic Isopach (Phanerozoic Isopach Map)

The Phanerozoic isopach map shows a north- to northeast-thinning wedge of sediments ranging in age from Cambrian to recent and terminating at the southern margin of the exposed Precambrian Shield. Values at a given well location on this map represent the total thickness of sedimentary material from ground level to the top of the underlying Precambrian basement. Phanerozoic sediments cover the southern two-thirds of Saskatchewan and are part of the Western Canada Sedimentary Basin (WCSB). Precambrian rocks crop out in the northeastern part of the map. The exposed basement-cover contact extends west-northwestward from a point 22 km south of the town of Flin Flon at the Saskatchewan/Manitoba border.

Two distinct depositional-tectonic phases are recognized in the development of the WCSB. An initial passive-margin phase (Cambrian to Middle Jurassic), characterized in Saskatchewan by deposition of a basal clastic sequence and a thick sequence of platform carbonates and evaporites and minor clastics. This was followed by a convergent-margin phase (Middle Jurassic to Eocene) which resulted in foredeep migration and thick accumulations of clastic sediments derived from the ancestral Rocky Mountains formed during the Cordilleran Orogeny (Stott and Aitken, 1993).

The Williston Basin was an actively subsiding basin during much of the Phanerozoic. During Silurian, Mississippian, and Jurassic times, a distinct paleobathymetric control resulted in facies zonation with peritidal shallow-shelf conditions at the margins of the basin to deep-water facies in the centre. In Cambrian to Ordovician time, sedimentation kept pace with subsidence and the patterns of facies distribution are unrelated to the geometry of the Williston Basin. During Devonian and Cretaceous time, the Williston Basin appears to have been a relatively inactive and indistinct part of the WCSB. Detailed discussion of paleotectonic controls on sedimentation in the Williston Basin is presented by Kent (1987).

These factors, along with the complex interplay between faulting and salt-solution effects, have played a critical role in the deposition and distribution of source and reservoir rocks, and the formation of traps for oil and gas in Saskatchewan.

Economic Considerations

To date, all Red River Formation and Winnipeg Formation hydrocarbon production in southeastern Saskatchewan appears to be underpinned by Precambrian basement with measurable positive paleotopographic relief. Producing wells which penetrate the basement invariably show some thinning or complete absence of the overlying Deadwood Formation (Haidl *et al.*, 2000; Kreis and Kent, 2000). The assumption therefore appears reasonable that wells which do not penetrate the Precambrian, but show Red River or Winnipeg hydrocarbon entrapment, are likely to overlie a basement high. The apparent orthogonal arrangement of basement highs recognized from isopach mapping of the Deadwood (Kreis and Kent, 2000; Kreis, 2004) and similar patterns from lineament mapping may prove useful as trend indicators for future plays of this type.

Generally, structural highs on the Precambrian surface show up as structural highs on the top of the Red River (Kreis and Kent, 2000; Kreis and Haidl, 2004) suggesting a genetic relationship. Also, hydrocarbon production is often greater over the structurally highest Red River locations which tend to coincide with relatively higher paleotopographic relief on the basement. Bearing this in mind, the Amerada Crown S AD 13-12-14-24W2 well location, which shows the highest positive relief on the Precambrian basement yet recognized from mapping in southeastern Saskatchewan, is highly prospective (Kreis and Kent, 2000).

Data Sources and Other Information

Research by Petroleum Geology Branch staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

This map sheet was originally published as Sheet 1 of 8, Sask. Energy Mines, Open File Report 2000-2, in May 2000 (Version 1.0). It is reproduced here as Version 1.1, with minor editorial changes, as part of Sask. Industry Resources, Misc. Rep. 2004-8 (CD-ROM). Data from most off-confidential wells available to January 2000 were utilized in the construction of the original maps and no additional data have been added to this version. However, an updated Excel spreadsheet that includes stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian (or deepest Paleozoic unit penetrated) for all wells off confidential as of July 31, 2003, is included as [Appendix A](#) in this publication.

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Sheet 2 – Geology of the Middle Cambrian–Lower Ordovician Deadwood Formation in Saskatchewan

L.K. Kreis

Kreis, L.K. (2004): Geology of Middle Cambrian–Lower Ordovician Deadwood Formation in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 2 of 8.

Introduction

Sandstones, siltstones, shales, and minor carbonates of the Middle Cambrian Earlie and Upper Cambrian to Lower Ordovician Deadwood formations record the initial marine transgression of the western side of the North American Craton (Precambrian Shield) that submerged the area for the first time after a long period of post-Precambrian erosion. These sedimentary rocks lie with obvious unconformity upon igneous and metamorphic rocks of the Precambrian basement. In the western part of eastern Saskatchewan, the Deadwood Formation is unconformably overlain by sandstones, siltstones, and shales of the Middle Ordovician Winnipeg Formation (Vigrass, 1971; Slind *et al.*, 1994; LeFever, 1996). Farther east, where the Deadwood reaches its zero limit, it is overstepped by clastic strata of the Winnipeg Formation (Figure 1). It is also locally absent in areas of southeastern Saskatchewan where it overlapped paleotopographic highs on the Precambrian basement. West of the zero edge of the Winnipeg Formation, carbonates of the Upper Ordovician Red River Formation unconformably overlie clastic rocks of the Deadwood Formation (Figure 1). North of the Meadow Lake Escarpment, erosional remnants of the Deadwood/Earlie (from Early Devonian erosion) are unconformably overlain by carbonates, mudstones, and sandstones of the Middle Devonian Meadow Lake Formation (Fuzesy, 1980).

Stratigraphy

In southeastern Alberta, the clastic sequence immediately overlying the Precambrian basement is sub-divided into the Middle Cambrian Earlie and Upper Cambrian to Lower Ordovician Deadwood formations (Pugh, 1971; Slind *et al.*, 1994; LeFever, 1996). There, the lithologically similar Earlie and Deadwood formations are commonly separated by a thin limestone and shale unit called the Pika Formation. Where this unit is not developed, the clastic equivalent, referred to as the “Pika Marker”, defines the top of the Middle Cambrian Earlie Formation. The Pika Formation is not recognized in Saskatchewan; however, attempts to carry the “Pika Marker” from Alberta into Saskatchewan have been made by Paterson (1989) and Slind *et al.* (1994). Hein and Nowlan (1998), argue that the “Pika Marker” becomes less pronounced and acquires a discontinuous distribution eastward into Saskatchewan, and “the distinction between Middle Cambrian and Upper Cambrian successions cannot be recognized either with geophysical logs or with seismic reflections”. Therefore, although Earlie equivalent strata are likely to be present at least in western Saskatchewan, no attempt is made to show their distribution on this map sheet due to the difficulty in their recognition. The isopach map depicts the combined thickness of Deadwood and Earlie formations in Saskatchewan and the entire sequence is referred to as the Deadwood Formation (Figure 2).

The lithological descriptions given below are based on those of Pugh (1971) and Slind *et al.* (1994).

Basal Sandstone Unit

The basal sandstone is an informal unit which unconformably overlies and infills the irregular paleotopography of the underlying Precambrian basement over much of southern Saskatchewan. It consists mainly of well-rounded, poorly sorted, coarse-grained to locally pebbly quartz, which is commonly frosted, and is yellowish in colour with pink to reddish-brown (hematitic) staining. Porosity is good to excellent. Deposition occurred upon a Precambrian surface rising eastward, and is therefore diachronous, being Middle Cambrian Earlie-equivalent in the west, and Upper Cambrian Deadwood-equivalent in the east (Slind *et al.*, 1994; Figure 8.8). These sandstones tend to be well developed around Precambrian paleotopographic highs.

The depositional environment of the basal sandstone is difficult to interpret due to a lack of core and fossil evidence. Nevertheless, the fact that the sandstone was deposited upon a highly weathered Precambrian surface of variable relief suggests some of the conglomeratic and coarse-grained material may initially have accumulated in a fluvial continental environment. The commonly frosted nature of the quartz grains points to an aeolian origin. These earlier sediments were probably extensively reworked by an eastward advancing Cambrian sea on a paleotopographically high Precambrian surface, resulting in the generally well winnowed, widely distributed, and diachronous basal sandstone unit.

Earlie Formation

The Middle Cambrian Earlie Formation is made up of glauconitic siltstones interbedded with fine-grained sandstones and shales (Pugh, 1971). It immediately overlies either basal sandstone or, locally, Precambrian basement. It is overlain by a similar sequence of clastics belonging to the Deadwood Formation. The Earlie is overstepped by the Deadwood Formation in an easterly direction (Paterson, 1989; Slind *et al.*, 1994).

Deadwood Formation

The Upper Cambrian–Lower Ordovician Deadwood Formation is characterized mainly by interbedded siltstones, fine-grained sandstones, and shales. The siltstones and sandstones are commonly glauconitic and micaceous and range in colour from white to pale brown, green, pink, and reddish brown. The shales are micaceous, fissile, and usually green to greenish grey but, locally, may be reddish brown to purple. Minor interbeds of pale buff to white micritic limestones are found in southwestern Saskatchewan.

The Earlie and Deadwood formations are interpreted to have been deposited in shallow to moderately deep inshore basins (Slind *et al.*, 1994). In mid-Ordovician time (latest Llanvirnian), a major sea-level fall exposed the Deadwood to erosion for the period between latest Llanvirnian to early Caradocian (LeFever, 1996).

Thickness and Structure **(Deadwood Isopach Map) (Deadwood Structure Map)**

The Deadwood Formation ranges in thickness from zero at its erosional edge in eastern and northern Saskatchewan to more than 500 m near Lloydminster in west-central Saskatchewan. The latter is referred to as the “Lloydminster Embayment” (van Hees, 1964; Slind *et al.*, 1994).

Numerous Deadwood thins in southern Saskatchewan define areas in which the Precambrian surface appears to have been paleotopographically higher than the advancing Deadwood sea. Some of these high areas have been interpreted as monadnocks (Fyson, 1961). Others, such as the large area defined by anomalously thin Deadwood centred around Swift Current (Swift Current High), have been described as structures present in Precambrian time which have been reactivated periodically in post-Cambrian time (Sawatzky *et al.*, 1960). Deadwood thinning may also have occurred as a result of uplift of the Precambrian basement contemporaneously with or shortly after Deadwood but prior to Winnipeg deposition, resulting in the partial removal of Deadwood strata.

In southeastern Saskatchewan, Deadwood thins delineate Precambrian basement highs that may also represent uplifted blocks. Examples include: Workman (Tp. 1, Rge. 32W1), Browning (Tp. 6, Rge. 5W2), Weir Hill (Tp. 6, Rge. 6W2), Midale (Tps. 6 and 7, Rge. 11W2), Hartaven (Tp. 10, Rge. 9W2), Montmartre (Tp. 13, Rge. 11W2), Tyvan (Tp. 13, Rge. 13W2), and Briercrest (Tp. 14, Rge. 24W2). Some of these highs appear to be aligned in northeasterly and northwesterly directions (see [isopach map](#)) that perhaps reflect a stress regime within the underlying basement (Kreis and Kent, 2000). Many Deadwood thins are defined by single well anomalies. This makes precise determination of their areal extent impossible. They show up as “bulls-eyes” on the isopach map (*e.g.*, 16-11-6-20W3, 9-20-12-2W3, and 13-12-14-24W2).

The Deadwood Formation dips gently to the southwest from its northern limits except in the northwest near 54°N, where, north of the Meadow Lake Escarpment, structure contours are deflected in a north-south orientation. The Meadow Lake Escarpment is defined by the northern zero limit of the overlying Red River Formation ([Figure 1](#) and Kreis and Haidl, 2004). Carbonates of the overlying Red River Formation acted as a resistant cap rock that protected the friable clastic strata of the Deadwood/Earlie from sub-Devonian erosion (van Hees, 1958; Haidl, 1989). South of approximately 51°N, structure contours define the northern flank of the present-day structural Williston Basin, the shape of which is attributed to Laramide deformation (Christopher *et al.*, 1971). Subsidence of this basin was initiated in the Early Ordovician (LeFever *et al.*, 1987; LeFever, 1996) and has continued to the present. The Swift Current High, Eastend (Ponteix) Syncline, and Val Marie Arch appear to be smaller structural elements within the Williston Basin. The Val Marie Arch defines the northern limit of the Bowdoin Dome in northeastern Montana.

The Elbow Structure, centred around the Imperial Elbow #1 well (12-25-23-6W3), which shows the top of the Deadwood Formation to be approximately 170 m higher than regional, is interpreted to represent part of the central uplifted area of an astrobleme (Grieve *et al.*, 1998).

Economic Considerations

Currently, no hydrocarbons are produced from the Deadwood in Saskatchewan. Nevertheless, oil staining has been reported in Cambrian sandstones in the Elk Point 3 well in Alberta, and the Deadwood is producing oil from the Newporte Structure in northwestern North Dakota, a few kilometres south of the North Dakota/Saskatchewan border. The Newporte discovery well, E-M Larson #9-11 NESW 9-163N-87W, produced over 1800 m³ of 33.7 API

oil with no water in the first 18 days of production, making it the first significant oil producer from the Cambrian in the Williston Basin. The Deadwood also produces significant volumes of gas in the Antelope Field of North Dakota (e.g., #1-32 Brenna Lacey SWNE of 1-152N-95W has produced over $141 \times 10^3 \text{ m}^3$).

Helium and other inert gases (e.g., nitrogen and carbon dioxide) have been identified in the Deadwood in seven wells in three areas in southwestern Saskatchewan: 1) Swift Current (e.g., 1-9-17-14W3); 2) Battle Creek (e.g., 10-25-3-27W3); and 3) Wood Mountain (e.g., 12-10-5-8W3). Helium has been produced in economic quantities from some of these wells.

To date, all Red River Formation and Winnipeg Formation hydrocarbon production in southeastern Saskatchewan appears to be underpinned by Precambrian basement showing measurable positive paleotopographic relief. Producing wells which penetrate the basement invariably show some thinning or complete absence of the Deadwood Formation (Kreis and Kent, 2000; Haidl *et al.*, 2000). The assumption therefore appears reasonable that wells which do not penetrate the Precambrian, but show Red River or Winnipeg hydrocarbon entrapment, are likely to overlie a basement high. The apparent orthogonal arrangement of basement highs recognized from isopach mapping of the Deadwood (Kreis and Kent, 2000; Kreis, 2004) and similar patterns from lineament mapping may prove useful as trend indicators for future plays of this type.

Data Sources and Other Information

Research by Petroleum Geology Branch staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

This map sheet was originally published as Sheet 2 of 8, Sask. Energy Mines, Open File Report 2000-2, in May 2000 (Version 1.0) and subsequently with minor revisions in October 2001 (Version 1.1). It is reproduced here as Version 1.2, with minor editorial changes, as part of Sask. Industry Resources, Misc. Rep. 2004-8 (CD-ROM). Data from most off-confidential wells available to January 2000 were utilized in the construction of the original maps and no additional data have been added to this version. However, an updated Excel spreadsheet that includes stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian (or deepest Paleozoic unit penetrated) for all wells off confidential as of July 31, 2003, is included as [Appendix A](#) in this publication.

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Sheet 3 – Geology of the Middle Ordovician Winnipeg Formation in Saskatchewan

L.K. Kreis

Kreis, L.K. (2004): Geology of the Middle Ordovician Winnipeg Formation in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 3 of 8.

Introduction

Sandstones, siltstones, and shales of the Winnipeg Formation record the initial deposits of the Middle Ordovician (Trentonian-Early Edenian) transgression which covered most of the North American Craton (Norford *et al.*, 1994). The Winnipeg Formation unconformably overlies the Deadwood ([Figure 1](#)) everywhere except in the northeast where it extends beyond the eastern erosional limits of the Deadwood and rests with marked unconformity upon the Precambrian basement. The northeastern erosional edge of the Winnipeg lies immediately below an eroded cap of resistant Upper Ordovician Red River carbonates which commonly form well-developed cliffs. The northern edge of the Winnipeg owes its present-day position mostly to the Late Silurian-Early Devonian erosional episode that formed the buried, north-facing Meadow Lake Escarpment (Vigrass, 1971; Haidl, 1989).

The nature of the contact between the Winnipeg Formation and the overlying Red River Formation is uncertain. Paterson (1971) and Kendall (1976) interpret this contact to be erosional at least in part at the margins of the Winnipeg depositional basin. Other workers suggest that the Winnipeg/Red River contact is conformable and merely represents a depositional hiatus (Vigrass, 1971; McCabe, 1978; Ellingson and LeFever, 1995; LeFever, 1996). The western limit of the Winnipeg Formation shown on the [isopach map](#) is probably depositional, the Winnipeg having overlapped the underlying eroded Deadwood surface (Vigrass, 1971). The Winnipeg Formation is present well beyond the confines of the Williston Basin, covering parts of Saskatchewan, Montana, Wyoming, Manitoba, North and South Dakota, and Minnesota (Laird, 1956; Ellingson and LeFever, 1995).

Stratigraphy

In the Williston Basin, the Winnipeg Formation consists of three members in ascending order: 1) Black Island Member, 2) Icebox Member, and 3) Roughlock Member.

Black Island Member

The Black Island Member unconformably overlies the Deadwood Formation except in the east where it oversteps the Deadwood Formation and lies directly upon the Precambrian basement. It is conformably overlain by the Icebox Member except on the eastern and northern margins of the Williston Basin where the contact may be unconformable (Paterson, 1971; Kessler, 1991).

The Black Island is characterized by quartz arenites and quartz wackestones with minor black to greenish grey and brown shale and siltstone breaks (Paterson, 1971; LeFever, 1996). Sandstones are commonly bioturbated to massive, but in places are laminated and cross bedded. The quartz grains are generally white to slightly yellowish orange in colour, medium to fine grained, well sorted, highly rounded, frosted, and pitted. Sandstones range in colour from white to yellowish to grey and greenish grey, and brown. The white to yellow sandstones usually contain some kaolin, whereas the grey to brown sandstones get their colour from argillaceous and organic material (Paterson, 1971). Bioturbated sandstones commonly have a burrow-mottled appearance.

Sediments from the Black Island Member probably represent a variety of depositional environments including: fluvial, aeolian, coastal, shoreface, and storm shelf (Kessler, 1991).

Icebox Member

Some controversy exists over the geographical distribution of the Icebox Member. Vigrass (1971), Kessler (1991), and Ellingson and LeFever (1995) contend that the Black Island was overlapped by the Icebox Member during a marine transgression early in Icebox time. Paterson (1971), however, suggests that the Icebox overlies the Black Island Member and is therefore more restricted in areal extent.

Lithologically, the Icebox Member consists predominantly of greenish grey to dark greenish grey, waxy, fossiliferous, bioturbated and fissile shale. Locally, it is oxidized giving it a mottled reddish brown appearance. In

southeastern Saskatchewan, the Icebox is commonly a black fissile and pyritic shale (Paterson, 1971). It contains comminuted arthropod and brachiopod fragments and trace fossils (*i.e.*, burrows). Fine- to medium-grained, argillaceous, quartzose sandstones and minor siltstone beds are present but rare in the extreme southeastern portion of the province. Sandstone interbeds, however, become increasingly common to the north and west (Paterson, 1971).

Sediments from the Icebox Member appear to represent such depositional environments as coastal, shoreface, and inner to middle shelf (Kessler, 1991).

Roughlock Member

The Roughlock Member is poorly developed in Saskatchewan. It is recognized on geophysical logs only in the extreme southeastern portion of Saskatchewan (*e.g.*, Interaction Renata et al Workman 3-27-1-32W1) where it is less than 3 m thick (Ellingson and LeFever, 1995; LeFever, 1996). Conodont data from eastern North Dakota suggest a Middle to Late Edenian age for the Roughlock. It is in conformable and gradational contact with the overlying Red River Formation (Ellingson and LeFever, 1995; LeFever, 1996).

Lithologically, the Roughlock grades upwards from greenish grey limestone-nodule-bearing calcareous shale at the base into interbedded calcareous shale and limestone, nodular limestone, and, finally, clean limestone of the overlying Red River. A few sandstone-interbedded shale bodies occur within the Roughlock in North Dakota (LeFever, 1996).

The Roughlock was probably deposited in shelf and slope depositional environments (Kessler, 1991).

Thickness and Structure (Winnipeg Isopach Map) (Winnipeg Structure Map)

The Winnipeg Formation ranges in thickness from zero at its edges in northern and central Saskatchewan to almost 70 m near the Saskatchewan-North Dakota border in southeastern Saskatchewan. The zero limit is considered to be depositional in western Saskatchewan but erosional in northern Saskatchewan (Vigrass, 1971). The Winnipeg isopach map reflects mainly tectonic subsidence during Winnipeg time and points to a basin centre in northwestern North Dakota (Ellingson and LeFever, 1995; LeFever, 1996). The subsidence accounts for most of the observed regional thickness variations. Initially, Winnipeg sediments infilled the paleotopographic relief of the eroded Deadwood surface. This infilling, post-depositional differential compaction, local faulting, and erosion at the basin margin appear to account for all other thickness variations.

Locally, the Winnipeg thins where it onlaps Precambrian paleotopographic highs, many of which may have been fault controlled (Kreis and Kent, 2000). These areas are well defined on the isopach map of the Deadwood Formation (Kreis, 2004), but are less pronounced on the Winnipeg isopach map. They include: Workman (Tp. 1, Rge. 32W1), Weir Hill (Tp. 6, Rge. 6W2), Midale (Tps. 6 and 7, Rge. 11W2), Hartaven (Tp. 10, Rge. 9W2), Montmartre (Tp. 13, Rge. 11W2), and Tyvan (Tp. 13, Rge. 13W2).

The Imperial Lightning Creek structure (16-7-6-32W1) has no Winnipeg Formation in a location which is expected to have at least 55 m and is interpreted to have been completely removed by faulting (Paterson, 1971; Kendall, 1976; Kreis and Kent, 2000). This well was not used in contouring the structure and isopach maps but is indicated by a green star.

Structurally, the Winnipeg Formation shows the same gentle southwesterly dip as the Deadwood Formation (Kreis, 2004) and Precambrian basement (Kreis *et al.*, 2004), from its northern limit southward to approximately 51°N where it begins to define the northern flank of the structural Williston Basin. The shape of the Williston Basin is attributed to Laramide deformation (Christopher *et al.*, 1971).

Economic Considerations

Sandstones of the Black Island Member are, in places, excellent reservoir rocks with porosity commonly in the 10 to 15% range (Vinopal and Edington, 1998) and permeability up to a few darcies (*e.g.*, Founders et al Hartaven D12-1T-10-9W2).

Gas has been reported as shown from the Winnipeg Formation in Montana (Anderson, 1982) and has been produced in several fields in North Dakota (LeFever, 1996). In April 2000, the Empire et al Browning 8-14-6-6W2 well became the first in Saskatchewan from which commercial production of Winnipeg gas was attempted. The first try at oil production from the Winnipeg Formation was from the Tarragon Forget 11-16-7-7W2 well in 1997. Since then, Winnipeg oil production has been reported from three wells in the Hartaven area (Tp. 10, Rg. 9W2) and four wells from the Midale area (Tps. 6 and 7, Rg. 11W2).

Trapping appears to be in small structurally controlled blocks. Well data demonstrate that these are spatially related to underlying Precambrian paleotopographic highs (Kreis and Kent, 2000). Post-depositional uplift and, perhaps, some compactional draping create closure in these traps. Also, onlapping Winnipeg sandstone against a Precambrian basement high is a likely trap configuration. The Interaction Renata et al Workman 3-27-1-32W1 well appears to demonstrate this onlapping relationship. Significant potential exists for other strati-structural and stratigraphic traps in the Winnipeg Formation. Stratigraphic pinchout of Winnipeg sandstone beneath low-permeability limestones at the base of the Yeoman (Red River) near the western zero edge of the Winnipeg Formation (Figure 2), in combination with even a minor structural component, has the potential to prevent northward migration of oil, possibly creating a more regional strati-structural trap. Also, simple porosity and permeability pinchout updip within Winnipeg sandstones and facies changes, such as the pinchout of sandstones within shales of the Icebox Member, are likely trapping mechanisms.

The Winnipeg Formation in the subsurface has been successfully used for the disposal of waste water from potash mining operations (Simpson and Dennison, 1975). It has also been considered as a source of silica sand and is being studied for use as a hydraulic fracturing sand (Gent, 1993).

Data Sources and Other Information

Research by Petroleum Geology Branch staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

This map sheet was originally published as Sheet 3 of 8, Sask. Energy Mines, Open File Report 2000-2, in May 2000 (Version 1.0) and subsequently with minor revisions in October 2001 (Version 1.1). It is reproduced here as Version 1.2, with minor editorial changes, as part of Sask. Industry Resources, Misc. Rep. 2004-8 (CD-ROM). Data from most off-confidential wells available to January 2000 were utilized in the construction of the original maps and no additional data have been added to this version. However, an updated Excel spreadsheet that includes stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian (or deepest Paleozoic unit penetrated) for all wells off confidential as of July 31, 2003, is included as [Appendix A](#) in this publication.

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Sheet 4 – Geology of Upper Ordovician Red River Strata (Herald and Yeoman formations) in Saskatchewan

L.K. Kreis and F.M. Haidl

Kreis, L.K. and Haidl, F.M. (2004): Geology of Upper Ordovician Red River strata (Herald and Yeoman formations) in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 4 of 8.

Introduction

In Saskatchewan, Red River strata comprise a lower unit of burrow-mottled fossiliferous mudstone/wackestone (with varying degrees of dolomitization) and an upper unit of limestones, dolostones, and minor evaporites (Porter and Fuller, 1959; Kendall, 1976). In southeastern Saskatchewan, the lower unit is defined as the Yeoman Formation; the upper unit is the Herald Formation which is subdivided into the Lake Alma and Coronach members and the Redvers unit (Kendall, 1976). In the remainder of the province, where the Herald and Yeoman formations cannot be differentiated with confidence on geophysical logs, these strata are identified as the Red River Formation. For the purpose of the regional isopach and structure maps on this map sheet, the Herald and Yeoman formations are not differentiated.

Red River strata are Late Ordovician (Edenian, Maysvillian, and early Richmondian) in age (Elias *et al.*, 1988). In most of Saskatchewan they overlie clastic rocks of the Middle to Late Ordovician Winnipeg Formation (Trentonian-early Edenian) with probable disconformity; in western Saskatchewan they unconformably overlie the sandstones, siltstones, and shales of the Deadwood Formation (Cambrian-Early Ordovician).

Upper Ordovician rocks in western North America are remnants of strata deposited in warm shallow seas that covered much of the North American Craton. In the Williston Basin area, they are characterized by repetition of carbonate and evaporite lithologies. Several different interpretations of these Red River carbonate-evaporite sequences have been published: 1) cycles begin with marine carbonates and culminate with basin-centred evaporites, the product of gradual changes from normal basin salinity to hypersaline conditions (*e.g.*, Kendall, 1976; Kohm and Loudon, 1978; Longman *et al.*, 1983); 2) in addition to a brining-upward control on sedimentation, a shoaling- or shallowing-upward component to the cycles is suggested by higher energy facies such as fossiliferous, coated-grain and/or peloidal packstones/grainstones, and stromatoporoid and microbial rudstones and boundstones that separate burrowed marine carbonates from laminated carbonates in several Red River cores (Longman and Haidl, 1996; Pratt *et al.*, 1996; Haidl *et al.*, 1997; Kreis and Kent, 2000); evidence suggests that frequent short-term periods of subaerial exposure are recorded in the lower Lake Alma in some areas (Kent and Kissling, 1998) and at the top of the Coronach (Kreis and Kent, 2000); 3) progradational “shoaling-upward” processes resulted in deposition of carbonate-evaporite cycles in subtidal to supratidal environments (*e.g.*, Carroll, 1978; Clement, 1985; Ruzyla and Friedman, 1985); and 4) in the Midale area in Saskatchewan, Yeoman strata are characterized by basal open-shelf deposits overlain by cycles of restricted-shelf and mud-mound deposits (Canter, 1998); the upper Yeoman-lower Herald (lowermost Lake Alma) strata represent a shoaling-upward cycle beginning with normal marine subtidal carbonates and ending with intertidal and intermittently supratidal carbonate facies; evaporite deposition is associated with a new sequence (Canter, 1998).

Stratigraphy

The detailed stratigraphic nomenclature adopted in southeastern Saskatchewan (Figure 1) reflects the interpretation that the cyclic sedimentation which characterizes the Red River succession is related primarily to three brining-upward sequences (Kendall, 1976). The Yeoman and the Lake Alma represent the earliest cycle, the Coronach Member encompasses the second cycle, and the Redvers unit represents the third cycle, which is incomplete in Saskatchewan.

Yeoman Formation

The Yeoman Formation is composed primarily of burrow-mottled fossiliferous lime mudstones and wackestones which have undergone varying degrees of dolomitization (*e.g.*, Kendall, 1976, 1977, 1984, 1985; Kohm and Loudon, 1978; Longman *et al.*, 1983, 1984; Longman and Haidl, 1996; Canter, 1998). The burrows are characterized by small cylindrical burrows within much larger burrow mottles which are *Thalassinoides*-like. Kendall (1976, 1977), Zenger and LeMone (1995), and Zenger (1996) attribute these structures to two generations of burrowers, with the smaller burrows formed by organisms reworking the original larger burrow. Kissling (1999) interprets these trace fossils as the dwelling burrows of filter-feeders in which the larger burrow mottles “represent

the coherent walls of the small burrows”. *Palaeophycus* and *Planolites* trace fossils have also been identified (Canter, 1998).

Tabulate corals and solitary and colonial rugose corals, cephalopods, brachiopods, bryozoans, echinoderms, stromatoporoids, and gastropods are the most commonly observed macrofossils in core (Brindle, 1960; Kendall, 1976; Pratt *et al.* 1996; Haidl *et al.*, 1997). The micro-alga *Gloeocapsomorpha prisca*, of probable cyanobacterial origin (Foster *et al.*, 1989; Stasiuk and Osadetz, 1990; Stasiuk, 1991; Stasiuk *et al.*, 1993), is the primary component of organic-rich kerogenites (kukersites) which are preserved as thin but widespread layers in the upper one-third of the Yeoman. Two distinct organic facies have been identified in southeastern Saskatchewan: 1) centimetre-scale (1 to 25 cm) beds of layered stromatolitic *G. prisca* and 2) thicker (1 to 2 m) beds with abundant disseminated, and other algal-derived material (Fowler *et al.*, 1998). These rocks are the source of Ordovician-produced oil in Saskatchewan (Kendall, 1976; Brooks *et al.*, 1987; Osadetz *et al.*, 1992; Osadetz and Snowdon, 1995; Fowler *et al.*, 1998).

Rocks of the Yeoman Formation have a maximum thickness of more than 135 m in the southeastern corner of Saskatchewan. These strata are interpreted as having been deposited in marine-shelf environments that ranged from aerobic to dysaerobic (Kendall, 1976, 1985; Stasiuk and Osadetz, 1990; Canter, 1998).

Herald/Yeoman Contact

The contact between the Yeoman and the overlying Herald (Lake Alma Member) is difficult to pick both in core and on geophysical logs. In core, strata between the burrow-mottled rocks typical of the upper Yeoman and the laminated to thinly bedded dolostones which characterize the lower Lake Alma are of variable lithologies. This transitional unit is thin (<1 m to 8 m) and composed of poorly mottled, irregularly bedded lime mudstones (with variable dolomitization) with interbeds of fossiliferous and/or peloidal wackestone/packstone/grainstone (Kendall, 1976; Longman and Haidl, 1996; Haidl *et al.*, 1997; Kissling, 1997; Kreis and Kent, 2000). Coated grains are also present in several cores. A reefal sequence is documented in the LVR et al Steelman 7-28-4-4W2 well where this interval is 8 m thick and includes a stromatoporoid dolerudstone and a microbial doloboundstone (Pratt *et al.*, 1996; Haidl *et al.*, 1997); similar facies are present in cores from the Midale and Weir Hill areas.

On geophysical logs, the contact between the Lake Alma and Yeoman is picked at the top of “clean” carbonates, indicated by a shift to higher gamma readings which characterize basal beds of the Lake Alma Member. However, the increase in gamma radiation is never large and is also variable, making consistent picks difficult. The top of the Yeoman also coincides with the top of a high-porosity interval on logs in many wells. Log-core correlations suggest that the higher gamma-ray response which marks the base of the Lake Alma on geophysical logs often coincides with a distinctive bioturbated (dolo)wackestone, commonly containing oncolites and characterized by abundant anastomosing bituminous solution partings (A.C. Kendall, pers. comm., 1996).

Herald Formation

Herald strata are more than 38 m thick in the vicinity of Lake Alma (Tp.1, Rge.17W2) where the Lake Alma Member reaches maximum thickness. This unit thins to the north, west, and east, due largely to diminishing thicknesses of the Coronach and Lake Alma anhydrites.

Lake Alma Member

Above the transitional beds, the lower unit of the Lake Alma Member is composed of laminated to bedded, commonly slightly argillaceous, dolomudstones and calcareous dolomudstones. Interbedded with the dolomudstones in the extreme eastern part of Saskatchewan (Rge. 2W2 and eastward) are beds of coated-grain dolostone which may have originated as oolitic grainstones (Kent, 1960; Kendall, 1976; Haidl *et al.*, 1997; Kent and Haidl, 1999; Kreis and Kent, 2000).

The Lake Alma anhydrite, the upper unit of the Lake Alma Member, is composed of nodular, bedded, and laminated anhydrite with interbeds of dolomudstone (commonly anhydritic). This is the most widespread of the Lower Paleozoic evaporite units. It extends from the basin centre in North Dakota as far north as Tp. 33, as far west as Rge. 10W3 and into Manitoba to the east (Kent, 1960; Kendall, 1976; Norford *et al.*, 1994; Longman and Haidl, 1996). General distribution of the Lake Alma and Coronach anhydrite units in Saskatchewan is shown on Red River isopach and structure maps; thickness variations in selected areas are illustrated in Kreis *et al.* (2004b) and Nimegeers and Haidl (2004).

Coronach Member

Where fully developed, the Coronach Member comprises: 1) a basal slightly argillaceous dolomudstone, locally with scattered quartz grains; 2) a fossiliferous, commonly burrowed, wackestone or dolowackestone; 3) slightly argillaceous laminated dolomudstones (locally lime mudstones); and 4) the Coronach anhydrite (Kendall, 1976). The basin-centred anhydrite unit is areally less widespread than the Lake Alma anhydrite, extending north to Tp. 11 in south-central Saskatchewan.

Redvers Unit

The Redvers unit is composed of a basal argillaceous dolomudstone bed and an upper laminated dolomudstone or lime mudstone. This unit is mapped with confidence only where an argillaceous marker bed separates it from the overlying Stony Mountain carbonates.

Structure and Thickness (Red River Structure Map) (Red River Isopach Map)

From its northern subcrop edge to 51°30'N latitude the Red River dips gently to the southwest. South of that latitude, structure contours define the northern flank of the Williston Basin. Subsidence of this basin was initiated during the Early to Middle Ordovician and continued episodically through geological time, principally during the Silurian, Devonian, Mississippian, and Jurassic periods. Its present-day shape reflects modification during Laramide deformation (Christopher *et al.*, 1971). Within the basin, local structural anomalies such as the Swift Current High, Eastend Syncline, Battle Creek High, and Val Marie Arch in the southwest (Christopher *et al.*, 1971) and those in the Briercrest (Tp. 14, Rge. 24W2), Tyvan (Tp. 13, Rge. 13), Montmartre (Tps. 12 and 13, Rge. 11W2), Hartaven (Tp. 10, Rge. 9W2), Midale (Tps. 6 and 7, Rge. 11W2), and Weir Hill (Tp. 6, Rge. 6W2) areas in the southeast originate in the Precambrian basement and are commonly associated with anomalously thin Deadwood strata (*cf.*, Haidl *et al.*, 2000; Kreis and Kent, 2000; Kreis, 2004a; Kreis *et al.*, 2004b). Episodic movement of basement blocks has been proposed by several authors (*e.g.*, Christopher *et al.*, 1971; Kent, 1972, 1974, 1987; Potter and St. Onge, 1991; Kissling, 1997).

Red River rocks attain a maximum thickness of 167 m in the southeastern corner of Saskatchewan. The northern erosional edge of these strata coincides with the southern edge of the Precambrian Shield in the outcrop belt in eastern Saskatchewan and the Meadow Lake Escarpment in west-central Saskatchewan. Distribution of Red River strata suggests the existence of an ancestral Williston Basin with a depocentre east of the centre of the present-day Williston Basin. Paleotopography related to basement structures influenced local depositional patterns (*e.g.*, Workman area, Tp. 1, Rge. 32W1; Haidl *et al.*, 2000; Kreis and Kent, 2000). Evidence of faulting is present in core from the Cherokee et al Workman 2-34-1-32W1 well (Haidl, 1995; Kreis and Kent, 2000). Faulting is recognized as the probable cause of an anomalous sequence with 216 m of Red River strata and no Winnipeg rocks in the Imperial Lightning Creek 16-7-6-32W1 well. The local thinning of Yeoman strata in the Cominco SR1 drill hole (11-12-57-8W2), near the southern edge of the Paleozoic outcrop belt, may be related to movement associated with the Tabernor Fault Zone; this movement is documented by a tectonic breccia zone in a core of the Yeoman Formation (Elliot, 1995).

Economic Considerations

Hydrocarbons

Production of $1.4 \times 10^3 \text{ m}^3$ (8.8×10^3 bbl) of oil from Herald and Yeoman reservoirs in 157 wells (to December 1999) and numerous hydrocarbon shows in drillstem tests and cores attest to the economic potential of Red River strata in Saskatchewan (see above, [Figure 2](#), hydrocarbon show map).

The discovery in December 1995 of prolific Red River reservoirs below producing Mississippian strata in the northeastern corner of the Midale Pool (Tps. 6 and 7, Rge. 11W2) was the catalyst for exploration programs that, in the following four years, resulted in the licensing of more than 280 wells targeting the Red River or deeper, the discovery of oil in the Winnipeg Formation, production from new Devonian Birdbear and Duperow reservoirs, and an expansion of the Red River producing area. The discovery well, Berkley et al Midale 4-2-7-11W2, has produced $65\,935 \text{ m}^3$ of oil (to December 1999). Most Red River oil discovered to date is trapped in small fault-bounded closures associated with Precambrian highs, some of which are clustered together resulting in multiple oil pools within an area, as at Midale in Tps. 6 and 7, Rge. 11W2 (Canter, 1998; Haidl *et al.*, 2000) and Minton, at Tp. 3, Rge. 21W2 (Potter and St. Onge, 1991). Structural anomalies such as those in the Briercrest (Tp. 14, Rge. 24W2) and Workman (Tp. 1, Rge. 32W1) areas warrant further consideration as potential hydrocarbon exploration targets (Kreis and Kent, 2000).

The primary control on reservoir quality is dolomitization. The complexity of dolomitization patterns indicates that more than one phase of dolomitization commonly occurred and that different factors may have controlled this process at any given time or place (e.g., Derby and Kilpatrick, 1985; Haidl, 1990, 1995; Kissling, 1997; Kent and Haidl, 1999). Major factors include: 1) gravity-driven seepage of dense magnesium-rich brines associated with deposition of the Lake Alma anhydrite ("C" anhydrite); 2) downward movement of brines generated during and following Silurian Interlake deposition; 3) movement of formation waters toward the overlying evaporite basin (Elk Point) during deposition of the Prairie Evaporite; 4) movement of brines associated with episodic dissolution of the Devonian Prairie Evaporite; 5) solution-cannibalization of magnesium ions from Mg-rich calcite sediments and subsequent precipitation of dolomite crystals at other locales; 6) initial higher porosity and permeability of burrows and some interbeds in the Yeoman which may have resulted in preferential fluid flow and subsequent dolomitization; 7) the presence of organic material and, in particular, of *Gloeocapsomorpha prisca*, may have facilitated dolomitization; and 8) fractures created by movement of basement blocks may have provided access to dolomitizing fluids, some of which may have been hydrothermal (e.g., Thomas, 1968; Kendall, 1976, 1977, 1984, 1985, 1989; Kohm and Loudon, 1978, 1982, 1988; Carroll, 1978; Longman *et al.*, 1983, 1984; Neese, 1985; Potter and St. Onge, 1991; Fox, 1993; Fisher and Hendricks, 1995; Longman and Haidl, 1996; Kissling, 1997, 1999; Zenger, 1996; Zimmer, 1997; Canter, 1998; Kent and Haidl, 1999).

Geochemical studies indicate that oil produced from the Red River in Saskatchewan is sourced from kukersitic beds in Ordovician carbonates in Saskatchewan, North Dakota, and Montana (Brooks *et al.*, 1987; Osadetz *et al.*, 1992; Osadetz and Snowdon, 1995; Fowler *et al.*, 1998). In the Midale area, API gravity values of Red River oils range from 26° to 42°, reflecting a wide range of maturity of the source rocks from which the oils were derived (Fowler *et al.*, 1998). The lower API oils are interpreted as being locally sourced from beds containing disseminated *G. prisca* which have lower Tmax values and lower Hydrogen Indices compared with the stromatolitic kukersites. Long distance migration (from >50 km south of Midale) is implied for the higher gravity, high maturity oils. Oils with intermediate maturity "appear to be mixtures of the high and low maturity end members" (Fowler *et al.*, 1998; Li *et al.*, 1998). Numerical modelling indicates that these kukersites have generated a much larger volume of oil than that yet discovered (Burrus *et al.*, 1995). Models suggest that much of this oil migrated updip into southeastern Saskatchewan prior to Late Eocene time, before the development of closure on the present-day Nesson Anticline in northwest North Dakota (Burrus *et al.*, 1995).

An analysis of an oil stain in Herald carbonates in the Esso Tribune 2-8-3-14W2 well indicates a non-kukersitic source rock. Based on Saturate Fraction Gas Chromatograms, the composition of oil from stains in the Tribune well and in Interlake dolostones in the Mobil Sinc Roy N Redvers 5-33-8-32W1 well (Haidl *et al.*, 1996) resembles that of oil produced from the Deadwood Formation in the Newporte Pool, northern North Dakota. Characteristics of the Newporte oil suggest derivation from a lacustrine source, as yet unidentified (Fowler *et al.*, 1998).

Keys to new discoveries of hydrocarbons in Lower Paleozoic rocks include: 1) an understanding of the tectonic framework of the Precambrian basement and controls exercised by it on the overlying sedimentary sequence, particularly with respect to depositional facies, formation of structural closures, and migration of dolomitizing fluids and hydrocarbons (e.g., Kent, 1972; Haidl, 1990; Kissling, 1997; Kreis and Kent, 2000); evidence of basement tectonism is derived from seismic, gravity and aeromagnetic data, lineament-trend analysis, surface-drainage patterns, heat-flow data, and thickness and facies distribution of individual Phanerozoic units; 2) knowledge of the distribution and maturation history of potential source rocks and the migration pathways of oil generated by them; and 3) the development of dolomitization models for existing pools and application of these models to exploration strategies.

Building Stone and Aggregate

Burrow-mottled upper Yeoman dolostones are currently quarried near Deschambault Lake as a source of rough building stone ("Tyndall Stone" equivalent). Building stone investigations have shown that Saskatchewan Red River dolostones have a dense microcrystalline texture, high compressive strength, and low moisture absorption capacity making them suitable for use as polished "marble" tiles and panels (Pearce and Guliov, 1996). In the McNally Lake area near the Manitoba border, Yeoman dolostones are quarried and crushed for use as aggregate.

Data Sources and Other Information

Research by Petroleum Geology Branch staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

This map sheet was originally published as Sheet 4 of 8, Sask. Energy Mines, Open File Report 2000-2, in May 2000 (Version 1.0) and subsequently with minor revisions in October 2001 (Version 1.1). It is reproduced here as Version 1.2, with minor editorial changes, as part of Sask. Industry Resources, Misc. Rep. 2004-8 (CD-ROM). Data from most off-confidential wells available to January 2000 were utilized in the construction of the original maps and no additional data have been added to this version. However, an updated Excel spreadsheet that includes stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian (or deepest Paleozoic unit penetrated) for all wells off confidential as of July 31, 2003, is included as [Appendix A](#) in this publication.

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Sheet 5 – Geology of Upper Ordovician Stony Mountain Formation in Saskatchewan

L.K. Kreis, F.M. Haidl, and A.R. Nimegeers

Kreis, L.K., Haidl, F.M., and Nimegeers, A.R. (2004): Geology of the Upper Ordovician Stony Mountain Formation in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 5 of 8.

Introduction

The Stony Mountain Formation forms part of the package of carbonate and evaporite strata that characterize Upper Ordovician and Lower Silurian rocks in the Williston Basin area. It is Late Ordovician (Richmondian) in age (Elias, 1983; Elias *et al.*, 1988; Nowlan and Haidl, 2001).

Present-day distribution of Stony Mountain strata is primarily a product of facies changes and depositional thickening toward the centre of an ancestral Williston Basin. Erosional truncation associated for the most part with the sub-Middle Devonian unconformity is responsible for removal of section beyond the northern and western edges of the Stonewall Formation. Data are available from 655 wells for which geophysical logs record penetration of the Stony Mountain Formation (to July 31, 2003), and from 23 cores taken from holes drilled during base-metal and diamond exploration programs.

Stratigraphy

In eastern Saskatchewan, the Stony Mountain Formation comprises three members, which are, from youngest to oldest: 1) the Hartaven Member composed of slightly argillaceous to argillaceous fossiliferous mudstone/wackestone, with varying degrees of dolomitization; 2) the Gunn Member composed of fossiliferous interbedded very argillaceous dolomitic limestone and dolomitic mudstone; and 3) the Gunton Member composed primarily of nodular, commonly nonfossiliferous, dolomudstones. In southeastern Saskatchewan, the Gunton nodular carbonates are overlain by laminated dolomudstones and capped by a thin anhydrite bed, the Gunton anhydrite (Kendall, 1976). Beyond the depositional edge of the Gunn Member, the Hartaven and Gunton members cannot be distinguished on geophysical logs (Kendall, 1976; Norford *et al.*, 1994); therefore, in the remainder of the province the Stony Mountain is undifferentiated.

The lower and upper contacts of the Stony Mountain are defined by argillaceous marker beds that have higher gamma-ray log responses than have been recorded from adjacent beds (Kendall, 1976). The marker bed that defines the base of the Stony Mountain, however, loses its distinctive gamma-ray signature in the western and northern portions of map area necessitating the use of neutron, density, and sonic log responses to correlate lithological units, albeit with a lower level of confidence than correlations based on gamma-ray responses (Figure 2). Similarly, the marker bed at the base of the overlying Stonewall Formation loses its characteristic gamma-ray response in portions of the northern map area, making correlations more difficult.

Conodont and isotope data from two cores in southeastern Saskatchewan (Imperial Hartaven 2-11-10-9W2; CDR Shell FPC Oungre 15-9-2-14W2) indicate that a major marine transgression occurred at the base of the Stony Mountain (Nowlan and Haidl, 2001; Fanton *et al.*, 2002). The interpretation that the Transcontinental Arch was submerged at this time and that argillaceous material from the Taconic Orogen was deposited in the Williston Basin area (Osadetz and Haidl, 1989) is supported by ENd data (Fanton *et al.*, 2002). Preliminary interpretation of conodont data from the Imperial Hartaven core suggests subsequent shallowing and deepening events within the Stony Mountain (Nowlan and Haidl, 2001). Further detailed research, similar to that undertaken in Red River strata (Haidl *et al.*, 2003), is required to determine if transgressive/regressive sequences can be defined in the Stony Mountain based on Sm/Nd ratios and conodont paleoecology.

Structure and Thickness (Stony Mountain Structure Map) (Stony Mountain Isopach Map)

In general, structure contours on top of the Stony Mountain Formation reflect the structure of the Precambrian basement (Kreis *et al.*, 2004a). Stony Mountain strata dip gently to the southwest from their northern edge to approximately 51°30'N Latitude where contours begin to define the northern flank of the structural Williston Basin. Subsidence of this basin was initiated during the Early to Middle Ordovician and continued episodically through geological time, principally during the Silurian, Devonian, Mississippian, and Jurassic periods. The basin's present-day shape reflects modification during Laramide deformation (Christopher *et al.*, 1971). Within the basin, many local structures defined on the Stony Mountain structure map also indicate the presence of features in the

Precambrian basement. These include the Swift Current High, Eastend Syncline, Battle Creek High, and Val Marie Arch in the southwest (Christopher *et al.*, 1971) and many smaller structures in the southeast, including Briercrest (Tp. 14, Rge. 24W2), Minton (Tps. 3 and 4, Rge. 21W2), Ceylon (Tp. 6, Rge. 19W2), Tyvan (Tp. 13, Rge. 13W2), Montmartre (Tps. 12 and 13, Rge. 11W2), Midale (Tps. 6 and 7, Rge. 11W2), Hartaven (Tp. 10, Rge. 9W2), Bryant-Kingsford (Tps. 4 and 5, Rge. 7W2), and Weir Hill (Tp. 6, Rge. 6W2) (Potter and St. Onge, 1991; Haidl *et al.*, 2000; Kreis and Kent, 2000; Larson *et al.*, 2003). Many of the structural highs are commonly associated with anomalously thin Deadwood strata (Kreis and Kent, 2000; Kreis, 2004).

Thickness of the Stony Mountain ranges from 39 m in southeastern Saskatchewan to zero at the erosional edge. Depositional thickening occurs towards the centre of the Williston Basin. Preserved minimum depositional thickness (*i.e.*, rocks overlain by Stonewall strata) is approximately 22 m. Stony Mountain rocks crop out south of the Precambrian Shield edge in east-central Saskatchewan (Kupsch, 1952; Haidl, 1992; Syme *et al.*, 1998).

Hydrocarbon Potential

To date, no commercial oil reservoirs have been discovered in the Stony Mountain. Several hydrocarbon shows, however, indicate that these rocks have economic potential. In the Nexen Bryant 7-4-5-7W2 well, 28 m of clean oil and 86 m of clean mud were recovered from a drillstem test of the upper 18 m of the Stony Mountain Gunton Member (Larson *et al.*, 2003). A drillstem test that encompassed the lower Stonewall and upper Gunton in the Berkley et al Midale 4-2-7-11W2 well yielded 711 m of oil- and mud-cut water. In the Imperial Halkett 15-7-3-8W2 well, gas- and condensate-cut water was recovered on drillstem tests of the Gunton Member and live oil staining is reported in drill cuttings from this interval (Kendall, 1976). Live oil staining is also reported from the Imp Cdn-Sup Stoughton 3-27-8-8W2 well (Kendall, 1976). These four wells are within the area of the best development of Gunton porosity as outlined by Kendall (1976) from approximately Rge. 12 at the international border northeastward to Tp. 8, Rge. 8 eastward to Tp. 9 at the Manitoba boundary. Just north of this area, in the Founders et al Hartaven D12-1T-10-9W2 well, oil staining is recorded in the description of drill cuttings from the upper Stony Mountain.

Hydrocarbons have also been detected in the Stony Mountain in the Lake Alma-Minton-Ceylon area. In the Penn West Ceylon 1-5-6-19W2 well, the upper 4 m of the Gunton were perforated and subsequent swabbing operations recovered a small volume of oil; a geochemical analysis of this oil is on file with Saskatchewan Industry and Resources. This well is located over a structural high in the Precambrian basement (Campbell *et al.*, 1995), suggesting that reactivation of basement structures may be responsible for the fracturing and brecciation of the upper Gunton that is observed in core and also indicated on geophysical logs. Minor oil staining is reported in drill cuttings from the Gunton Member in several wells in the Minton area. Oil-cut mud was recovered from this interval in Dome Tenneco Glasnevin 4-3-8-23W2 and gas- and water-cut mud was recovered from a drillstem test of the lower Stonewall-Gunton interval in Imperial Hummingbird 6-13-2-19W2 (Haidl, 1995).

Data Sources and Other Information

Research by Petroleum Geology staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

Data from most off-confidential wells available to January 2000 and from selected, more recently drilled wells were utilized in the construction of these maps. The text incorporates information from wells off confidential as of July 31, 2003. An Excel spreadsheet that includes stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian (or deepest Paleozoic unit penetrated) for all wells off confidential as of July 31, 2003, is included as [Appendix A](#) on the accompanying CD-ROM.

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Sheet 6 – Geology of the Upper Ordovician-Silurian Stonewall Formation in Saskatchewan

L.K. Kreis, F.M. Haidl, and A.R. Nimegeers

Kreis, L.K., Haidl, F.M., and Nimegeers, A.R. (2004): Geology of the Upper Ordovician-Silurian Stonewall Formation in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 6 of 8.

Introduction

The rocks of the Stonewall Formation are part of a carbonate-evaporite sequence that was deposited in shallow, warm seas which covered much of the North American Craton during most of the Late Ordovician and Early Silurian (*e.g.*, Porter and Fuller, 1959; Osadetz and Haidl, 1989; Norford *et al.*, 1994). Present-day distribution of Stonewall strata is predominantly a product of facies changes and depositional thickening toward the centre of the ancestral Williston Basin. Erosional truncation associated primarily with the sub-Middle Devonian unconformity is responsible for removal of section beyond the northern and western edges of the Interlake Formation.

The Stonewall Formation crops out in east-central Saskatchewan with the best exposures found along the southeastern shore of Cross Bay in Namew Lake (Haidl, 1992; Syme *et al.*, 1998). In the remainder of southern Saskatchewan, these rocks are restricted to the subsurface. Data are available from 647 wells for which geophysical logs record penetration of the Stonewall Formation (to July 31, 2003), and from 21 cores taken from holes drilled during base-metal and diamond exploration programs.

Stratigraphy

The Stonewall Formation in the Williston Basin area is characterized by the following lithologies: 1) argillaceous dolomudstone and dolomitic shale marker beds with varying proportions of quartzose sand; 2) fossiliferous burrowed dolomudstone/wackestone; 3) dolomudstone, commonly laminated; and, in the central portion of the basin; and 4) anhydrite (Porter and Fuller, 1959; Kent, 1960; Kendall, 1976; Norford *et al.*, 1998; Nowlan and Haidl, 1999). The marker beds, characterized by higher gamma-ray responses than have been recorded from adjacent carbonates and anhydrites, facilitate subsurface correlation of beds on geophysical logs (Figure 1 and Figure 2).

The boundary between the Stonewall Formation and the underlying Stony Mountain Formation is placed at the base of a marker bed which, over most of Saskatchewan, is well defined both in core and on gamma logs, but which becomes more difficult to correlate in northern and western Saskatchewan owing to diminished argillaceous content (Kendall, 1976; Haidl, 1992). In southeastern Saskatchewan, this marker bed overlies a thin evaporite bed (Gunton anhydrite) at the top of the Stony Mountain (Figure 1). In the rest of the map area, the Stonewall is in contact with Stony Mountain carbonates. The upper boundary of the Stonewall Formation is placed at the contact between overlying Interlake carbonates and a marker bed that is commonly less argillaceous and thicker than marker beds above and below.

The repetition of lithologies within the Stonewall suggests a complex depositional history. Kendall (1976) describes four sedimentary cycles in the cored reference section of the Stonewall Formation in the Imperial Herald 1-31-1-20W2 well. The lowermost cycle comprises four units: 1) a basal argillaceous laminated dolomudstone with quartz grains; 2) bioturbated dolomudstone; 3) argillaceous laminated dolomudstone; and 4) nodular anhydrite with interbeds of laminated argillaceous dolomudstone (lower Stonewall anhydrite). In this well, the upper three cycles differ from the lowest cycle in that their unit 2 is more fossiliferous and they lack anhydrite in their unit 4.

The number, thickness, and completeness of cycles vary but, in general, a similar pattern of sedimentation characterizes Stonewall deposition throughout Saskatchewan. The distribution of the lower Stonewall anhydrite (<3.5 m in thickness) is illustrated on the adjacent isopach and structure maps. The upper Stonewall anhydrite bed (<4 m in thickness), below the upper Stonewall marker (Figure 1), extends farther north than the lower anhydrite, but appears to thin or is absent east of approximately Range 5W2 (see Appendix A, CD-ROM). A thin anhydrite bed (commonly <1 m thick) has been identified at the top of the second oldest cycle, below the lower t-marker bed (t₂) (Figure 2). This medial Stonewall anhydrite has a more restricted areal distribution than the other two Stonewall evaporite units (Nimegeers and Haidl, 2004).

Conodont data from Saskatchewan and Manitoba indicate that the Ordovician-Silurian boundary coincides with the t-marker bed interval in the Stonewall (Norford *et al.*, 1998; Nowlan and Haidl, 1999). In the IMC K-1 Esterhazy

3SWD 16-26-20-33W1 well, Late Ordovician conodonts were recovered from near the top of the upper t-marker bed (t₂, Figure 2) and Early Silurian conodonts from a sample 4 cm above the contact with this upper t-marker. In the Imperial Herald 1-31-1-20W2 well, the upper t-marker bed yielded Early Silurian conodonts; Late Ordovician conodonts were recovered from a sample 22 cm below the base of the upper t-marker (Nowlan and Haidl, 1999). No conodont fauna typical of latest Ordovician age (Gamachian Stage) were recovered from Saskatchewan and Manitoba cores or from Manitoba outcrop samples, suggesting the absence of Gamachian strata in this portion of the Williston Basin. This represents a gap of at least three to five million years between rocks of Ordovician and Silurian ages (Norford *et al.*, 1998; Nowlan and Haidl, 1999). Further research is required to understand the origin of the t-marker beds and their apparently diachronous relationship.

Structure and Thickness **(Stonewall Structure Map) (Stonewall Isopach Map)**

In general, structure contours on top of the Stonewall Formation reflect the structure of the Precambrian surface (Kreis *et al.*, 2004a). In the north, structure contours show a gentle southwesterly dipping surface. In the south, contours define the northern flank of the asymmetrical Williston Basin. Subsidence of this basin was initiated during the Early to Middle Ordovician and continued episodically through geological time, principally during the Silurian, Devonian, Mississippian, and Jurassic periods. Its present-day shape reflects modification during Laramide deformation (Christopher *et al.*, 1971). Within the basin, many local structures defined on the Stonewall structure map also indicate the presence of features in the Precambrian basement. These include the Swift Current High, Eastend Syncline, Battle Creek High, and Val Marie Arch in the southwest (Christopher *et al.*, 1971) and many smaller structures in the southeast, including Briercrest (Tp. 14, Rge. 24W2), Minton (Tps. 3 and 4, Rge. 21W2), Ceylon (Tp. 6, Rge. 19W2), Tyvan (Tp. 13, Rge. 13W2), Montmartre (Tps. 12 and 13, Rge. 11W2), Midale (Tps. 6 and 7, Rge. 11W2), Hartaven (Tp. 10, Rge. 9 W2), Bryant-Kingsford (Tps. 4 and 5, Rge. 7W2), and Weir Hill (Tp. 6, Rge. 6W2) (Potter and St. Onge, 1991; Haidl *et al.*, 2000; Kreis and Kent, 2000; Larson *et al.*, 2003). Many of the structural highs are commonly associated with anomalously thin Deadwood strata (Kreis and Kent, 2000; Kreis *et al.*, 2004a).

Thickness of Stonewall strata ranges from 36 m in southeastern Saskatchewan to zero at the erosional edge. Depositional thickening occurs toward the centre of the Williston Basin. Preserved minimum depositional thickness (*i.e.*, rocks overlain by Interlake strata) ranges from 12 m to 14 m, except in a small area west and southwest of North Battleford where the Stonewall thins to between 6 and 10 m below the Interlake. Interpretation of controls on deposition and erosion of Stonewall strata is hampered by difficulties in correlating marker beds in the Interlake, Stonewall, and Stony Mountain formations in the northern and western parts of the map area, and in those wells for which there are no gamma-ray logs.

Economic Considerations

In the North Dakota portion of the Williston Basin, the Stonewall Formation produces oil and gas from several zones in a number of pools, most of which are associated with local basement structures (*e.g.*, Indian Hill Field, 13 km southwest of Williston, ND; Mayer, 1987). The Stonewall reservoir in the Indian Hill Field consists of preferentially dolomitized, skeletal wackestone interpreted as a shallow-marine bank facies that was deposited over paleotopographic highs (Mayer, 1987).

In Saskatchewan, no hydrocarbons are currently produced from the Stonewall Formation. Five drillstem tests of this formation have, however, yielded minor quantities of hydrocarbons, and oil staining has been observed in drill cuttings from several wells. The majority of recorded shows occur in the Lake Alma-Minton-Hardy area. In the Berkley et al Hardy S DD 2D2-5-4A2-5-5-21W2 well, 473 m of oil-cut mud and 300 m of salt water were recovered from the Stonewall. Wells in the Lake Alma, Hummingbird, and Herald areas yielded oil- and/or gas-cut mud or water on drillstem tests of this formation (Haidl, 1995). Minor oil-staining of drill cuttings is also reported from several wells in the Minton area (Haidl, 1995).

In the Berkley et al Midale 4-2-7-11W2 well, 711 m of oil- and mud-cut water were recovered from a drillstem test that encompassed the lower Stonewall and upper 6 m of the Stony Mountain. Minor oil staining is also reported in drill cuttings from this interval in a number of other wells in the Midale area.

In the Esterhazy-Rocanville area, Stonewall and overlying Interlake strata have sufficient porosity and permeability to be utilized by potash companies for brine disposal. The best porosity over the disposal zone is developed below the lower t-marker.

Data Sources and Other Information

Research by Petroleum Geology staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a

software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

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Sheet 7 – Geology of the Silurian Interlake Formation in Saskatchewan

L.K. Kreis, F.M. Haidl, and A.R. Nimegeers

Kreis, L.K., Haidl, F.M., and Nimegeers, A.R. (2004): Geology of the Silurian Interlake Formation in Saskatchewan; Lower Paleozoic Map Series – Saskatchewan, Sask. Industry Resources, Misc. Rep. 2004-8, CD-ROM, Sheet 7 of 8.

Introduction

The Interlake Formation is a sequence of shallow-water carbonates with minor evaporites that were deposited in an ancestral Williston Basin during Early Silurian (Llandoveryan-Wenlockian) time (*e.g.*, Johnson and Lescinsky, 1986; Magathan, 1987; Osadetz and Haidl, 1989; Norford *et al.*, 1994). These rocks overlie the Stonewall Formation (Upper Ordovician to Lower Silurian) and are unconformably overlain by the argillaceous dolostones of the Ashern Formation (Middle Devonian). Present-day distribution of Interlake strata is predominantly the product of depositional facies changes and thickening toward the centre of the basin, and of erosional truncation associated primarily with the sub-Devonian unconformity.

Data are available from more than 856 wells for which geophysical logs record penetration of the Interlake Formation (to July 31, 2003), and from 19 cores taken from holes drilled during base-metal and diamond exploration programs. An outcrop on the west shore of Cumberland Lake (Pine Island), described by Kupsch (1952), is likely of Interlake strata (Syme *et al.*, 1998).

Stratigraphy

Formal lithostratigraphic units defined by Stearn (1956) in the outcrop belt in Manitoba cannot be extended to the subsurface of Saskatchewan. The informal stratigraphic nomenclature used here is modified from Porter and Fuller (1959), King (1964), Jamieson (1979), and Haidl (1987).

The Interlake is subdivided into: 1) the Lower Interlake, characterized by cyclic sedimentation with abundant argillaceous, commonly arenaceous, basin-wide marker beds, and 2) the Upper Interlake, which in core can be subdivided into two distinct lithologic units, the Taylorton (equivalent to the Upper Interlake of Porter and Fuller, 1959) and the Cedar Lake (equivalent to the Middle Interlake of Porter and Fuller, 1959). However, in Saskatchewan, the contact between these two units is not well expressed on geophysical logs so the Middle and Upper Interlake are combined as the Upper Interlake for subsurface-mapping purposes.

Lower Interlake

The argillaceous marker beds are defined on geophysical logs by higher gamma-ray values than have been recorded from adjacent beds. They are therefore useful for subsurface correlations. The “u” and “u₂” markers subdivide the Lower Interlake into the Strathclair, Fife Lake, and Guernsey units (Figure 2b). The top of the Lower Interlake (top of Guernsey) is placed at the top of the uppermost marker bed in the sequence which in many wells correlates with the “v” marker of Porter and Fuller (1959); however, in much of southeastern Saskatchewan, additional argillaceous marker beds are present above the “v” marker (*e.g.*, Figures 1 and 2b). The base of the Interlake (base of Strathclair) is placed on the uppermost Stonewall marker bed, which is commonly less argillaceous and thicker than marker beds above or below (Kendall, 1976; Kreis *et al.*, 2004b).

Depositional sequences in the Lower Interlake (and Upper Ordovician rocks below it) suggest brining- and/or shallowing-upward cycles with anhydrite beds present at the top of cycles in the basin centre (Kendall, 1976; Norford *et al.*, 1994; Kreis *et al.*, 2004b). Johnson and Lescinsky (1986) propose a combination of Bahamian-bank and topographic-basin models to explain the distribution of facies in transgressive/regressive cycles within the Stonewall and Lower Interlake of the Manitoba outcrop belt. These cycles may be related to glacio-eustatic sea-level changes (Johnson and Lescinsky, 1986).

Strathclair

This unit is composed primarily of interbedded dolomudstone and dolowackestone. Dolomudstones include both fossiliferous burrowed sequences and laminated sequences. Fossils include corals, crinoids, stromatoporoids, and brachiopods (Brindle, 1960; Jamieson, 1979; Jin *et al.*, 1999). The brachiopod, *Virgiana* sp., is common in this interval (especially near the base) in the outcrop area in Manitoba and Saskatchewan (Baillie, 1951; Stearn, 1956;

Haidl, 1992; Jin *et al.*, 1999). It has also been identified in cores from wells in southern Saskatchewan (Jin *et al.*, 1999). The “u” marker bed is the uppermost bed of the Strathclair and consists of dolomudstone with abundant argillaceous, silty, and arenaceous laminae. Localized occurrences of a thin (<3 m) anhydrite bed below the “u” marker have been identified in the Hume-Midale-Hartaven and Wilcox areas, and in a few areas close to the Manitoba-Saskatchewan border (Nimegeers and Haidl, 2004). Magathan (1987) reports that anhydrite is associated with this unit in North Dakota.

Fife Lake

The Fife Lake represents as many as three sequences composed of: 1) basal fossiliferous wackestone, and 2) interbedded skeletal, coated-grain, lithoclast dolowackestone/packstone/grainstone and laminated dolomudstone (commonly stromatolitic). Fossils identified in basal wackestone units include stromatoporoids, brachiopods, and corals (Brindle, 1960; Jamieson, 1979). Argillaceous content increases towards the top of each sequence, but a well-defined marker bed is not always present in the lower two cycles. The uppermost cycle is capped by the “u₂” marker bed that can be traced over most of the Williston Basin. In North Dakota, three cycles have also been identified within this unit. Each cycle, when complete, comprises, in ascending order: 1) basal skeletal turbidites, 2) homogeneous lime mudstones, 3) laminated lime mudstones, and 4) interbedded lime mudstones and anhydrites (Magathan, 1987).

Guernsey

This unit is composed of laminated dolomudstone with interbeds of coated-grain dolopackstone/grainstone and one or more argillaceous marker beds. In North Dakota, anhydrite is also reported (Magathan, 1987).

Upper Interlake

Cedar Lake

The Cedar Lake comprises interbedded fossiliferous dolowackestone/packstone, coated grain and/or lithoclast dolopackstone/grainstone, and dolomudstone. Dolomudstone units are commonly laminated and are interpreted as stromatolitic in many places (Jamieson, 1979; Magathan, 1987; Martindale and Larson, 2003). Fossils include stromatoporoids, brachiopods, corals, crinoids, and gastropods (Brindle, 1960; Jamieson, 1979). Coral-stromatoporoid boundstone units are present in a few cores (*e.g.*, 12-21-2-29W2; Plate 1D, Haidl, 1987). Thin (<2 m) anhydrite beds have been identified in the Cedar Lake on lithodensity logs from a few wells.

Taylorton

The Taylorton is composed primarily of multiple cycles of dolomudstone, coated-grain dolopackstone/grainstone, lithoclast dolowackestone, and lithoclast breccia (conglomerate). The only fossils observed are ostracods, gastropods, algae, and cyanobacteria (Jamieson, 1979; Haidl, 1987). Magathan (1987) also reports fish fragments and charophytes from equivalent strata in North Dakota. Root traces are observed in several cores, (Haidl, 1987; Magathan, 1987; Inden *et al.*, 1998; Martindale and Larson, 2003). Dolomite cementation is common; microstalactitic, isopachous rims and subequant mosaic fabrics are observed in thin section (Haidl, 1987; Magathan, 1987; Martindale and Larson, 2003). Anhydrite cements are also common.

The relationships of lithologies, textures, and fabrics suggest that subaerial exposure occurred at the top of each cycle with subsequent vadose diagenesis and pedogenesis (Haidl, 1987; Magathan, 1987; Inden *et al.*, 1998; Martindale and Larson, 2003), but interpretation of the original depositional environments is difficult due to a paucity of fossils and a complex diagenetic history. Inden *et al.* (1998) and Martindale and Larson (2003) interpret these rocks as shallowing-upward, restricted-marine deposits subjected at the top of each cycle to subaerial exposure, development of paleosols, and diagenetic overprinting. Magathan (1987), on the other hand, interprets these uppermost Interlake strata as freshwater lacustrine, fluvial, and marsh deposits affected by karsting, incipient soil development, and vadose diagenesis.

Structure and Thickness **(Interlake Structure Map) (Interlake Isopach Map)**

In general, structure contours on top of the Interlake Formation reflect the structure of the Precambrian surface (Kreis *et al.*, 2004a). In the north, structure contours show a gentle southwesterly dipping surface. In the south, contours define the northern flank of the asymmetrical Williston Basin. Subsidence of this basin was initiated during the Early to Middle Ordovician and continued episodically through geological time. Its present-day shape reflects modification during Laramide deformation (Christopher *et al.*, 1971). Within the basin, many local

structures defined on the Stonewall structure map also indicate the presence of features in the Precambrian basement. These include the Swift Current High, Eastend Syncline, Battle Creek High, and Val Marie Arch in the southwest (Christopher *et al.*, 1971) and many smaller structures in the southeast, including Minton (Tps. 3 and 4, Rge. 21W2; Potter and St. Onge, 1991), Midale (Tps. 6 and 7, Rge. 11W2; Kreis and Kent, 2000), and Bryant-Kingsford (Tps. 4 and 5, Rge. 7W2; see [Figure 2c](#)). Many of the structural highs are commonly associated with anomalously thin Deadwood strata ([Figure 2c](#); Kreis and Kent, 2000).

Interlake rocks attain a maximum thickness of 216 m in Tp. 1, Rge. 10W2 and thin to zero at the erosional edge. Depositional thickening toward the centre of the Williston Basin is best illustrated on an isopach map of Lower Interlake strata ([Figure 15](#), Porter and Fuller, 1959), which are unaffected by erosion over most of the study area (see also Kreis *et al.*, 2004b). Pre-Middle Devonian uplift and subsequent erosion on the margins of the basin resulted in removal of a much larger volume of Interlake strata on basin margins than in the basin centre.

Many local anomalies of thin Interlake strata occur in areas characterized by episodic movement of Precambrian basement structures (*e.g.*, Bryant-Kingsford area, Larson *et al.*, 2003; Minton-Lake Alma area, Potter and St. Onge, 1991). Paleotopographic relief created by structural movement resulted in depositional thinning and/or increased erosional truncation of strata on highs during the period marked by the sub-Devonian unconformity.

Economic Considerations

Saskatchewan's first commercial Interlake oil reservoir was discovered in October 2001 when oil flowed to surface during a drillstem test of the Upper Interlake in the Nexen Bryant 7-4-5-7W2 well ([Figures 2a](#) and [2b](#)). A twinned well, Nexen Bryant 7-4T-5-7W2, was completed open hole in the Taylorton unit of the Upper Interlake and yielded rates as high as 218 m³/day (1370 BOPD) during production and reservoir limit tests in March 2002 (Larson *et al.*, 2003). To July 31, 2003, this well has produced 17 138.3 m³ of oil and 19 619 m³ of water.

A detailed description of the Bryant Oil Pool is provided by Larson *et al.* (2003). This pool is located on a basement-related, four-way structural closure with a thick oil column ([Figure 2c](#)). Productivity of the Interlake reservoir is attributed to fractures at the top of the Interlake within Taylorton rocks characterized by limited vuggy and intergranular porosity. The fracturing is probably genetically related to reactivation of the underlying basement structure. In addition to Interlake production from Nexen Bryant 7-4T-5-7W2, the discovery well, Nexen Bryant 7-4-5-7W2, has produced 10 301 m³ of oil from Red River and the Nexen Bryant Hz 2D1-4-3B7-4-7-5W2 well has produced 10 584 m³ of oil from the Ratner Member of the Winnipegosis Formation (to July 31, 2003). Oil has also been recovered from drillstem tests of the Frobisher Beds, and Birdbear and Stony Mountain formations.

A second Interlake producer, Nexen Browning DD 3C5-3-4D8-4-6-5, was completed in March 2003. In its first five months on production, it yielded 2811 m³ of oil and 9498.7 m³ of water. The Browning Pool is located on a structural closure which has lower relief than the Bryant structure (Larson *et al.*, 2003).

Prior to the Bryant and Browning discoveries, the best indication of Interlake oil potential was found in the Redvers area. In the MOWS N Redvers 14-19-8-32W1 well, 27.4 m of oil and 30.5 m of oil-cut mud were recovered from a drillstem test (Haidl, 1995). The well was perforated and stimulated, but no production was recorded and the well was subsequently abandoned.

Drillstem tests of the Interlake in four other wells also record the recovery of minor quantities of oil and/or oil-cut mud and/or oil-cut water: Husky Glen Ewen 16-23T-2-1W2, Tidewater Wapella Crown 12-34-14-1W2, Imperial Douglaston 12-6-5-3W2, and Berkley et al Midale 10-29-6-11W2. The Berkley et al Midale well recovered 400 m of oil-cut mud from the Upper Interlake, and neutron/lithodensity logs across the tested interval show anomalous porosity similar to that observed in the Nexen Bryant 7-4-5-7W2 well ([Figure 2b](#)). Geophysical logs from several wells in other areas of southern Saskatchewan (*e.g.*, Tri Link White Bear 3-7-9-1W2 well) also indicate anomalous zones of porosity in the Upper Interlake, but these zones have never been tested. In the Minton area, oil shows in drill cuttings from the Interlake are documented in Larson *et al.* (2003) and Potter and St. Onge (1991). Gas-cut or aerated mud and/or water, and/or sulphurous water have been recovered from this formation in several wells in southern Saskatchewan.

Production in North Dakota and Montana further demonstrates the hydrocarbon potential of Interlake strata in the Williston Basin area. In North Dakota, the Interlake (to August 31, 2003) has produced over $9.5 \times 10^3 \text{ m}^3$ (59.8×10^3 bbl) of oil, much of it from the Upper Interlake (Taylorton equivalent; Inden *et al.*, 1988). In the Outlook Field in Montana, 20 km south of the Minton Pool in Saskatchewan, Interlake production is from a fractured fossiliferous dolostone reservoir immediately below the sub-Devonian unconformity surface, in an interval equivalent to the Cedar Lake.

The source of Interlake oil has not yet been conclusively identified. Oil produced from the Bryant Pool is similar to that from Interlake pools located on the Nesson Anticline in North Dakota and to that extracted from an oil stain in

the Mobil Sinc Roy N Redvers 5-33-8-32W1 core (Larson *et al.*, 2003). These Family D2 oils have isotopic signatures that differ from Winnipegosis D2, oils but which are similar to those from oil produced from the Deadwood Formation in the Newporte Field in North Dakota (Downey, 1996). This suggests that a yet unrecognized source rock may be present in the Deadwood-Birdbear interval in the Williston Basin (Obermajer *et al.*, 1998).

The Interlake Formation is also of economic significance in the Esterhazy-Rocanville potash-mining area where porosity and permeability are sufficient to allow these strata to be used for brine disposal.

Data Sources and Other Information

Research by Petroleum Geology staff and others provided detailed stratigraphic information on Lower Paleozoic strata in the province along with geophysical log picks from which these maps were generated. Original computer contouring, based on interpretation by L.K. Kreis, was done using Personal Computer Mapping System (PCMS), a software program by Zycor Inc. Addition of new data, further modification of contours, and final map preparation utilized AutoCAD Release 12 and 14 software. The acquisition of some software was funded by the Province of Saskatchewan under the Canada-Saskatchewan Partnership Agreement on Mineral Development 1990-95. Base maps were provided by SaskGeomatics Division of Saskatchewan Property Management Corporation. UTM coordinates are in NAD 27, zone 13.

Data from most off-confidential wells available to January 2000 and from selected, more recently drilled wells were utilized in the construction of these maps. The text incorporates information from wells off confidential as of July 31, 2003. An Excel spreadsheet that includes stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian (or deepest Paleozoic unit penetrated) for all wells off confidential as of July 31, 2003, is included as [Appendix A](#) on the accompanying CD-ROM.

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Sheet 8 – Geological Cross Sections, Saskatchewan

L.K. Kreis, F.M. Haidl, and A.R. Nimegeers

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Figure 1 – Interlake Isopach Map

Figure 2 – North-South stratigraphic cross-section B-B'

Figure 3 – Reference Well

Figure 4 – East-West stratigraphic cross-section A-A'

Data Sources and Other Information

Research by Petroleum Geology Branch staff and others provided detailed stratigraphic information on strata in the province along with Lower Paleozoic geophysical log picks used to generate these cross sections as well as the isopach and structure maps on the accompanying CD-ROM; an Excel spreadsheet of Lower Paleozoic stratigraphic data is also included ([Appendix A](#)).

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Appendix A – Geological Tops and Notes

Introduction

Appendix A includes an [Excel spreadsheet](#) that incorporates stratigraphic picks for major units from the top of the Interlake Formation to the top of the Precambrian for 1082 wells that have been off confidential since July 31, 2003. In ascending order, these major stratigraphic units include the Precambrian, Deadwood, Winnipeg, Red River, Stony Mountain, Stonewall and Interlake. In wells where there were no available data to pick a formation top, the abbreviation “ND” has been entered into the appropriate cell to indicate “no data” (in most cases, “ND” indicates that the lowermost formations were not penetrated in a given well; in a few select wells, geophysical logs, cuttings, and/or core data were unavailable over relevant intervals of the well).

Where the quality or amount of data were insufficient to make a stratigraphic pick, the symbol “?” was used to indicate that the presence or absence of the formation is unknown. A pick with a value of “0.0 m” indicates that the formation is absent; it was either eroded or never deposited. The “comments” column of the spreadsheet includes notes about stratigraphic picks and individual wells but should not be considered as comprehensive. Information about other columns in the spreadsheet is provided below.

Well Type

In this column, “PNG” indicates wells licensed under Petroleum and Natural Gas Regulations. These include hydrocarbon exploration and development wells, water disposal wells, and wells drilled on potash leases. This spreadsheet includes data from many potash wells that are not available on commercial databases. Because the Prairie Evaporite portion of these wells is confidential for an indefinite period of time, they are given overall “confidential” status and not released by SIR to other data providers. However, data from these wells from surface to the top of the Prairie Evaporite and from just above the top of the Ashern to total depth are available from SIR’s Subsurface Geodata Section (787-2562; btroyer@ir.gov.sk.ca).

Wells listed as “Non-PNG” include base-metal and diamond exploratory wells which are not licensed under Petroleum and Natural Gas Regulations.

UWI/Borehole Number

A complete UWI is provided for all wells licensed under Petroleum and Natural Gas Regulations. Base-metal and diamond exploratory wells (Non-PNG) either have: 1) a complete UWI, 2) a partial UWI, or 3) a borehole number (*e.g.*, F-66-11). For wells with a partial UWI (*e.g.*, 59-08W2, missing the Section and LSD), an arbitrary number of “99” has been entered where data are lacking in order to maintain consistency in the spreadsheet. Therefore, the UWI 59-08W2 would be listed as 00/99-99-059-08W2/0.

Deepest Formation Picked

The deepest formation picked does not necessarily correspond to the deepest formation penetrated in a given well. In a few cases, the lowermost formations were not picked because the geophysical logs, cuttings, and/or core were of poor quality or data were lacking.

[<link> Stratigraphic Data \(Excel format\)](#)

Appendix B – Lower Paleozoic Anhydrites

Introduction

The distribution and thickness of seven Lower Paleozoic evaporite beds were mapped in southeastern Saskatchewan (Townships 1 to 17, Ranges 1W2 to 24W2) and the northern region of North Dakota and Montana during the development of the geoscience framework for the IEA Weyburn CO₂ Monitoring and Storage Project.

Subsequently, Saskatchewan Industry and Resources updated the isopach maps for these evaporite beds in the Saskatchewan portion of the Weyburn study area. Included in Appendix B are [stratigraphic data \(in Excel format\)](#) used to generate the evaporite maps and [a paper \(PDF format\) by Nimegeers and Haidl](#), originally published in the 2004 Saskatchewan Industry and Resources Summary of Investigations (Volume 1). The paper includes isopach maps and descriptions of the evaporite beds, with a preliminary interpretation of factors affecting their distribution.

Geophysical density and/or neutron logs from a total of 232 wells were used to identify and correlate anhydrite beds in the study area. Only wells with density logs were used for mapping because they provide the best definition of thin anhydrite units. Data interpreted from density logs of all wells that penetrate the Red River Formation and deeper strata and that were off confidential as of July 31, 2003, were used to construct isopach maps with Surfer Version 8 software and a kriging algorithm that gridded the data. Editing of the contours was restricted to minor changes associated, for the most part, with the anhydrite zero edges.

[<link> Evaporite stratigraphic data \(Excel format\)](#)

[<link> Nimegeers and Haidl \(2004\) – Evaporite maps and interpretations](#)

Appendix C – Additional References

Stratigraphy and Sedimentology of Lower Paleozoic Strata

The following papers on the sedimentology and stratigraphy of Saskatchewan's Lower Paleozoic strata were published in Summary of Investigations Volumes from 1987 to 2004. They can be accessed by linking to www.ir.gov.sk.ca/SOI and choosing the volume for the year in which each paper was published.

Greggs, D.H. and Hein, F.J. (2000): The sedimentology and structure of the Lower Paleozoic Deadwood Formation of Saskatchewan; *in* Summary of Investigations 2000, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2000-4.1, p7-13.

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Appendix C – Additional References (cont'd)

IEA GHG Weyburn CO₂ Monitoring and Storage Project

The IEA GHG Weyburn CO₂ Monitoring and Storage Project was initiated to study the potential for geological storage of CO₂ in the Weyburn oil field in southeastern Saskatchewan. General information on this project is available on the website of the Petroleum Technology Research Centre (Regina), the project manager:
<http://www.ptrc.ca/access/DesktopDefault.aspx?tabindex=8&tabid=81>

Many papers have been published on more detailed aspects of the project, including those in the Saskatchewan Industry and Resources (SIR) Summary of Investigations Volumes from 2001 to 2004, and those published in conjunction with the 7th International Conference on Greenhouse Gas Control Technologies (GHGT 7) held in Vancouver in September 2004. Links to some papers of interest are given below. Data and mapping products from the Geoscience Framework aspect of the project are available at:
<http://www.ir.gov.sk.ca/files/co2monitoring/index.html>

The following papers were published in Summary of Investigations Volumes from 2001 to 2004. They can be accessed by linking to www.ir.gov.sk.ca/SOI and choosing the volume for the year in which each paper was published.

Burrowes, G. (2001): Investigating CO₂ storage potential of carbonate rocks during tertiary recovery from a billion barrel oil field, Weyburn, Saskatchewan: Part 2 – reservoir geology (IEA Weyburn CO₂ Monitoring and Storage Project); *in* Summary of Investigations 2001, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2001-4.1, p64-71.

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Appendix C – Additional References (cont'd)

General Interest

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