GS2018-12

Lithostratigraphy of the Neepawa DDH No. 1 Prov. core at 15-29-14-14W1, southwestern Manitoba (part of NTS 62J3)

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In Brief:

- Examination of nearly 500 m of Paleozoic strata from drillcore Neepawa DDH allowed for positive correlations from the deep subsurface to outcrop belt, and indicates that additional studies may lead to the resolution of the stratigraphic framework of Manitoba
- Refining and resolving Paleozoic stratigraphy of Manitoba has positive implications for petroleum and industrial mineral industries, and carbonate-hosted lead-zinc mineralization exploration

Citation:

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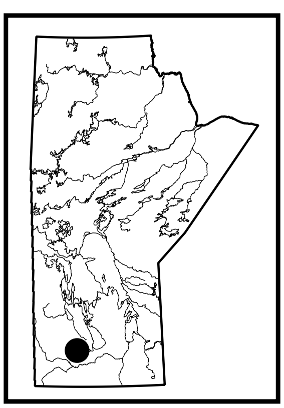

Summary

Drillcore Neepawa DDH No. 1 Prov. 15-29-14-14W1, drilled in the vicinity of the town of Neepawa, provides a rare view of the entire lower Paleozoic section in the subsurface of southwestern Manitoba. Terminating in Precambrian iron formation, this core consists of 491.10 m of continuous core from the Ordovician Winnipeg Formation to the Devonian Souris River Formation. Correlations of established outcrop-based lithostratigraphic units were extrapolated to the subsurface in Manitoba and, where established, mostly Manitoba-derived lithostratigraphic units and nomenclature are used. Several correlation issues were resolved within this core and inconsistencies were identified, which indicates that through additional study of drillcore and outcrop these issues may be resolved Manitoba-wide. Refining the stratigraphic framework of the Williston Basin has positive implications for the petroleum and industrial mineral industries and for Mississippi Valley–type deposit exploration.

Introduction

In 1978, Neepawa Mines Ltd. completed an exploration drillhole at L.S. 15, Sec. 29, Twp. 14, Rge. 14, W 1st Mer. (abbreviated 15-29-14-14W1), near the town of Neepawa, as part of a project investigating base metal potential in Precambrian basement (Figure GS2018-12-1). A total of 937.87 m of core was acquired and the uppermost 763.35 m of core, composed of Paleozoic, Mesozoic and Quaternary strata, was retained by the Manitoba Geological Survey (MGS). This drillcore is officially known as Neepawa DDH No. 1 Prov. 15-29-14-14W1 (oil and gas well licence 2472, Manitoba Growth, Enterprise and Trade, Winnipeg; Assessment File 91210, Manitoba Growth, Enterprise and Trade, Winnipeg) and referred to herein as Neepawa DDH.

Most of the lower Paleozoic stratigraphy in Manitoba has been characterized by outcrop mapping in combination with examination of shallow stratigraphic drillcores. The Neepawa DDH core offers a unique opportunity to observe the entire lower Paleozoic stratigraphy in the subsurface of the Williston Basin in southwestern Manitoba. In addition, downhole wireline geophysical spontaneous potential and resistivity logs are available and provide a critical correlation tool to link lithostratigraphy and geophysical log signatures in the subsurface.

The lower Paleozoic stratigraphic framework of southwestern Manitoba contains many inconsistencies (Lammers, 1988; Bezys and Conley, 1998; Nicolas and Barchyn, 2008; Lapenskie and Nicolas, 2017). Lateral variations in lithology, facies changes and stratigraphic boundaries, coupled with few core available in this transitional area, have made correlating units across the basin challenging. In particular, parts of the Ordovician Red River Formation, the Silurian Interlake Group, and parts of the Devonian Dawson Bay and Souris River formations are not consistently correlated between outcrop and the subsurface. Neepawa DDH provides an opportunity to address these issues by identifying which units can be correlated and which require more work to refine the correlations.

Regional geology

Southwestern Manitoba is covered by a thick succession of gently southwest-dipping sedimentary rocks deposited on the northeastern edge of the Williston Basin during the Phanerozoic (Figure GS2018-12-1). Deposition spanned the Cambrian to Mississippian, Triassic to Cretaceous, early Paleogene and Quaternary periods. Significant periods of

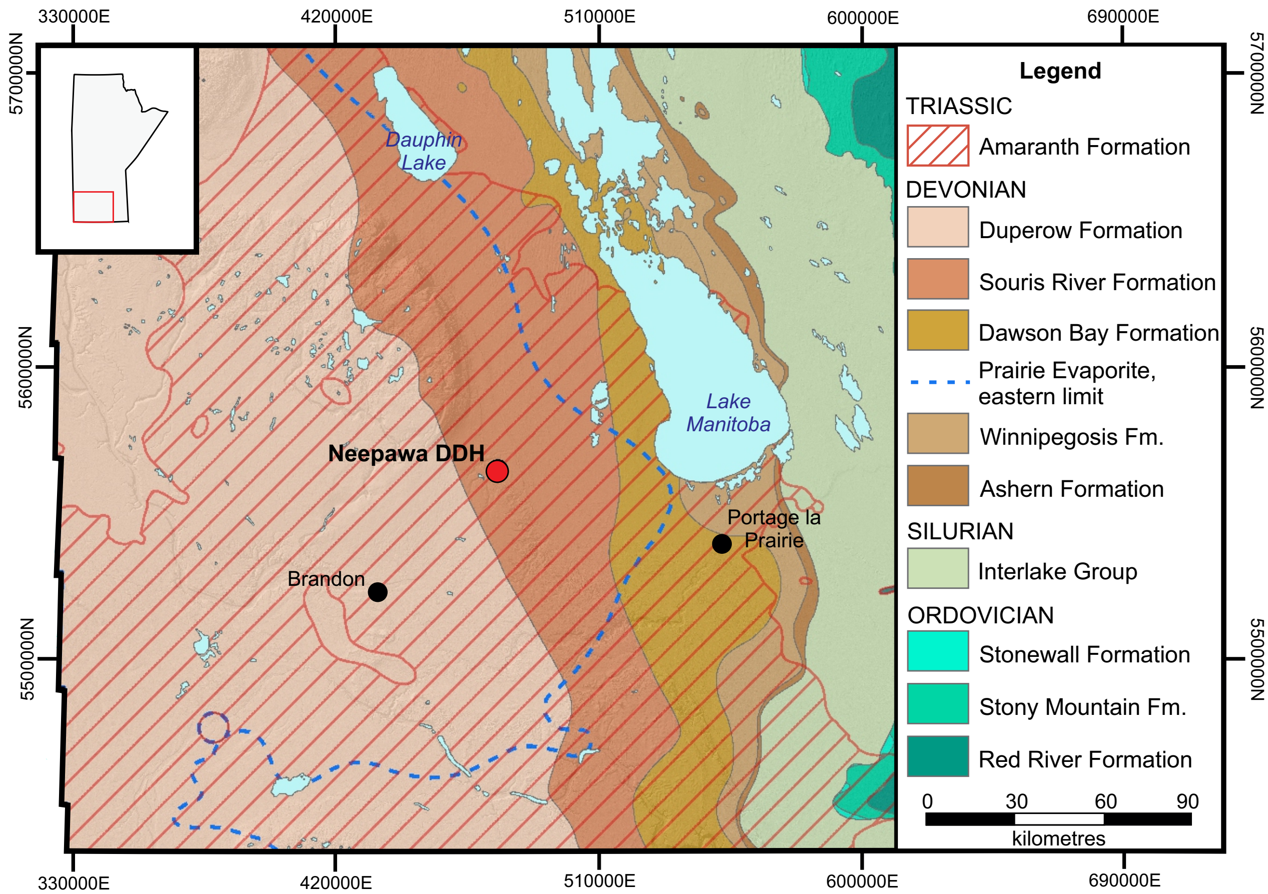

***Figure GS2018-12-1:** Regional bedrock geology of southwestern Manitoba (after Nicolas et al., 2010); formations younger than the Duperow Formation (excluding the Triassic Amaranth Formation) are not shown. The area is underlain by Precambrian igneous and metamorphic rocks (not exposed in map area). Location of drillhole Neepawa DDH No. 1 Prov. 15-29-14-14W1 (Neepawa DDH) is shown.*

nondeposition and/or erosion occurred at the boundary between the Cambrian and Ordovician, at the boundary between the Silurian and Devonian, within most of the Paleogene, and during lesser hiatus periods within the Jurassic and Cretaceous. The Paleozoic rocks of the Williston Basin are predominantly composed of marine platform carbonate rocks, interbedded with minor successions of siliciclastic rocks and evaporites, and overlie basement Precambrian igneous and metamorphic rocks.

Stratigraphy

Neepawa DDH provides a nearly complete core of the lower Paleozoic from the basal Ordovician Winnipeg Formation to the middle Devonian Souris River Formation (Figure GS2018-12-2). The section is mostly composed of dolostone and limestone, with subordinate sandstone, shale and evaporitic units. A detailed description of the lithostratigraphy of Neepawa DDH is provided in Table GS2018-12-1 and a core log with the lithostratigraphy and geophysical signatures is provided in Figure GS2018-12-3. Neepawa DDH was drilled to a true vertical depth of 937.87 m, with the upper 763.35 m composed of Paleozoic, Mesozoic and Quaternary strata and the lower 174.52 m composed of Precambrian rocks. Assessment File 91210 provides a brief description of the Precambrian section. Mesozoic and Quaternary strata were not examined for this study.

Ordovician

The Ordovician section of Neepawa DDH is composed of the siliciclastic Winnipeg Formation, and a thick succession of lime mudstone, lime wackestone, dolomudstone, dolowackestone and dolobindstone of the Red River, Stony Mountain and Stonewall formations. The Cambrian Deadwood Formation is absent in this core. The upper Stonewall Formation is Silurian in age, with the Ordovician–Silurian boundary present in the vicinity of the t-marker bed (Norford et al., 1998; Kleffner et al., 2005; Desrochers et al., 2010; Demski et al., 2010a, b, 2011a, b).

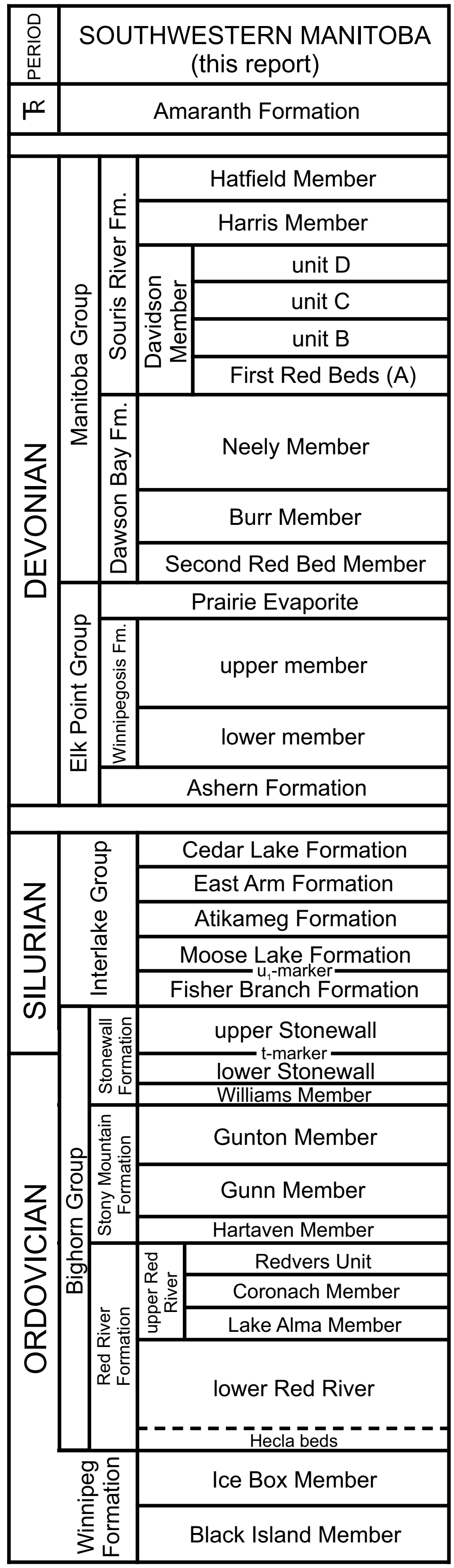

Figure GS2018-12-2: *Stratigraphic column of Neepawa DDH No. 1 Prov. 5-29-14-14W1 core. Abbreviations: Fm., Formation; TR, Triassic.*

Table GS2018-12-1: Lithostratigraphy and generalized lithology of drillcore Neepawa DDH No. 1 Prov. 15-29-14-14W1; refer to Assessment File 91210 (Manitoba Growth, Enterprise and Trade, Winnipeg) for a description of the Precambrian section. Asterisks indicate estimated depths (core boxes were missing at these depths).

Total vertical depth (m)	Thickness (m)	Description
n/a–272.25	n/a	**Amaranth Formation**
		Lower Amaranth Member
		Pinkish-red feldspathic to lithic wacke
272.25–388.60	116.35	**Manitoba Group**
272.25–323.15	50.90	**Souris River Formation**
272.25–273.88	1.63	**Hatfield Member**
		Pinkish-buff dolomudstone; laminated to bedded; argillaceous; evaporitic, gypsum-anhydrite nodules and beds; pyritic; intercrystalline porosity, 10%; upper contact sharp
273.88–301.85	27.97	**Harris Member**
		Reddish-, greyish- to bluish-buff cyclical dolomudstone to gypsum-anhydrite; laminated to bedded; dolomudstone sequences laminated to bedded, argillaceous, stromatolitic, uncommonly brecciated, bituminous, intercrystalline porosity, 15%, passing sharply upward to evaporite; gypsum-anhydrite sequences laminated to massively bedded, nodular, impermeable, passing sharply to carbonate rocks; upper contact sharp
301.85–323.15	21.30	**Davidson Member**
301.85–305.80	3.95	**unit D**
		Blue-grey to purplish-buff interbedded dolomudstone and gypsum-anhydrite; laminated to massively bedded, nodular; argillaceous; intercrystalline porosity, 2%; pyritic; upper contact sharp
305.80–309.30	3.50	**unit C**
		Pinkish- to bluish-buff interbedded shale, dolomudstone and gypsum-anhydrite; laminated to massively bedded, nodular; intercrystalline porosity, 5%; upper contact sharp
309.30–321.50	12.20	**unit B**
		Pinkish-yellowish–buff calcareous dolomudstone; laminated to bedded to massive, porcelaneous, wispy argillaceous laminations, stylolitic, mottled; biostromal; evaporitic, gypsum-anhydrite nodules; intercrystalline to vuggy porosity, 10%; upper contact sharp
321.50–323.15	1.65	**First Red Beds (unit A)**
		Purple to red-brown interbedded dolomudstone, shale and gypsum-anhydrite; laminated to bedded, burrowed, nodular; intercrystalline porosity, 10%; upper contact sharp
323.15–388.60*	65.45	**Dawson Bay Formation**
323.15–351.90	28.75	**Neely Member**
		Tan-buff (pinkish-yellowish) lime mudstone-wackestone to calcareous dolomudstone-wackestone; coarsely crystalline; laminated to massively bedded, wispy argillaceous laminations, bituminous beds, brecciated beds, probably crossbeds, burrowing; argillaceous to shaly; evaporitic, gypsum-anhydrite nodules, laminations and beds; fossiliferous, tabulate corals, rugose corals, stromatoporoids; becomes increasingly evaporitic upward; upper contact gradational
351.90–382.55	30.65	**Burr Member**
		Tan-buff (purplish-yellowish) lime mudstone to lime wackestone; laminated to massively bedded to massive, mottled; argillaceous; fossiliferous (brachiopods, crinoids); evaporitic, gypsum-anhydrite infilling horizontal and vertical fractures; intercrystalline porosity, 10%; upper contact sharp? core is very rubbly, lithology changes significantly
382.55–388.60*	6.05	**Second Red Bed Member**
		Red-brown to mottled grey dolomudstone to shale; massive; very argillaceous; uncommon gypsum laminations; pyritic; intercrystalline porosity, 10%; upper contact sharp
388.60*–448.37	59.77	**Elk Point Group**
388.60*–403.90*	15.30	**Prairie Evaporite**
		Pink, grey, buff and red-brown shale to dolomudstone interbedded with blue-grey gypsum-anhydrite; laminated to bedded; argillaceous; upper contact not observed

Table GS2018-12-1 (continued): Lithostratigraphy and generalized lithology of drillcore Neepawa DDH No. 1 Prov. 15-29-14-14W1; refer to Assessment File 91210 (Manitoba Growth, Enterprise and Trade, Winnipeg) for a description of the Precambrian section. Asterisks indicate estimated depths (core boxes were missing at these depths).

Total vertical depth (m)	Thickness (m)	Description
403.90*–437.30	33.40	**Winnipegosis Formation**
403.90*–406.20	2.30	**upper member**
		Light tan-buff, calcareous dolofloatstone to doloboundstone; reefal facies; massively bedded; fossiliferous, stromatoporoidal; evaporitic, gypsum-anhydrite nodules and infilling vugs; vuggy and intercrystalline porosity, 10%; upper contact not observed
406.20–437.30	31.10	**lower member**
		Tan-buff (yellowish-pinkish to brownish) dolomitic lime wackestone to calcareous dolowackestone; massively bedded, mottled; coarsely crystalline; fossiliferous; evaporitic, gypsum-anhydrite infilling porosity; pyritic; vuggy, mouldic, intercrystalline and fracture porosity, 15%; upper contact sharp, associated with a very argillaceous interval with bituminous laminations
437.30–448.37	11.07	**Ashern Formation**
		Reddish-brown to reddish- or purplish-grey dolomudstone; mottled; very argillaceous; evaporitic, gypsum-anhydrite nodules and laminations; pyritic; intercrystalline porosity, 5%; upper contact sharp
448.37–529.75	81.38	**Interlake Group**
448.37–476.90	28.53	**Cedar Lake Formation**
		Tan-buff (greyish, greenish to reddish) interbedded dolomudstone, dolowackestone, dolobindstone-doloboundstone; laminated to massively bedded, mottled, intraclastic beds, porcelaneous beds; 'raindrop' texture; fossiliferous, stromatoporoids, crinoids; argillaceous, reddish- and greenish-grey clay; intercrystalline, vuggy and fracture porosity, 15%; upper contact sharp, disconformable
476.90–504.15	27.25	**East Arm Formation**
		Tan-buff (greenish, pinkish and reddish) interbedded dolomudstone, dolowackestone-dolofloatstone and dolobindstone-doloboundstone; laminated to massively bedded, porcelaneous beds, intraformational clasts, stromatolitic, stromatoporoidal; variably fossiliferous; argillaceous, greenish-grey clay; intercrystalline and vuggy porosity, 10%; upper contact gradational
504.15–508.25	4.10	**Atikameg Formation**
		Tan-buff dolomudstone; laminated to bedded, compact interbeds, stromatolitic; mouldic and vuggy porosity, 20%; upper contact gradational
508.25–511.25	3.00	**Moose Lake Formation**
		Tan-buff dolomudstone to dolowackestone to dolobindstone; laminated, stromatolitic; fossiliferous; intercrystalline, mouldic and vuggy porosity, 15%; upper contact gradational
511.05–511.25	0.20	**u_1-marker bed**
		Pinkish–tan-buff dolomudstone; burrowed; argillaceous; upper contact gradational
511.25–529.75	18.50	**Fisher Branch Formation**
		Pinkish–tan-buff dolomudstone interbedded with yellowish tan-buff dolowackestone to dolofloatstone; laminated to massively bedded, burrowed, mottled, upper beds porcelaneous; basal marker bed reddish-pink argillaceous dolomudstone; fossiliferous, brachiopods (i.e., *Virgiana decussata*), solitary rugose corals (i.e., *Rhegmaphyllum*), tabulate corals (i.e., favositids), stromatoporoids; mouldic, vuggy, fracture porosity, 10%; evaporitic, gypsum-anhydrite infilling vugs, fractures; pyritic; upper contact gradational
529.75–725.00	195.25	**Bighorn Group**
529.75–544.20	14.45	**Stonewall Formation**
529.75–531.85	2.10	**upper Stonewall**
		Pinkish– to greyish–tan-buff dolomudstone; laminated to massively bedded; intercrystalline and fracture porosity, 2%; upper contact sharp
531.85–533.55	1.70	**t-marker bed**
		Tan to red to grey quartz wacke to dolomudstone; laminated to bedded, burrowed; argillaceous and arenaceous, coarse- to medium-grained quartz sand, frosted, intraformational clasts; intercrystalline and vuggy porosity, 2%; upper contact sharp

Table GS2018-12-1 (continued): Lithostratigraphy and generalized lithology of drillcore Neepawa DDH No. 1 Prov. 15-29-14-14W1; refer to Assessment File 91210 (Manitoba Growth, Enterprise and Trade, Winnipeg) for a description of the Precambrian section. Asterisks indicate estimated depths (core boxes were missing at these depths).

Total vertical depth (m)	Thickness (m)	Description
533.55–537.50	3.95	**lower Stonewall**
		Tan-buff dolomudstone to dolobindstone; laminated, biostromal; argillaceous to arenaceous; intercrystalline, vuggy and fracture porosity, 5%; upper contact gradational
537.50–544.20	6.70	**Williams Member**
		Reddish-brown to pinkish–tan-buff dolomudstone; laminated to bedded, mottled, burrowed; argillaceous and arenaceous, medium-grained quartz sand, frosted, well rounded; vuggy porosity, 10%; upper contact sharp
544.20–586.40	42.20	**Stony Mountain Formation**
544.20–563.45	19.25	**Gunton Member**
		Light tan-buff (yellowish to reddish) dolomudstone; laminated to bedded to massive, wispy argillaceous laminations, mottled; argillaceous; rarely fossiliferous; pyritic; intercrystalline to fracture porosity, 5%; upper contact sharp
563.45–571.50	8.05	**Gunn Member**
		Light to medium grey slightly calcareous dolomudstone; laminated to massively bedded, burrowed; argillaceous, uncommon beds of shale; intercrystalline porosity, 5%; upper contact gradational
571.50–586.40	14.90	**Hartaven Member**
		Medium grey variably dolomitic lime wackestone interbedded with minor shale beds; laminated to bedded, mottled, burrowed; very fossiliferous, brachiopods, solitary corals, skeletal fragments; argillaceous; pyritic; intercrystalline and vuggy porosity, 10%; upper contact gradational
586.40–725.00	138.60	**Red River Formation**
586.40–615.95	29.55	**upper Red River**
586.40–592.75	6.35	**Redvers Unit**
		Tan- to grey-buff dolomudstone and lime mudstone; laminated to bedded, wispy argillaceous laminations, some mottled and burrowed beds; some chert nodules; uncommon anhydrite nodules; pyritic; intercrystalline porosity, 10%; upper contact sharp
592.75–601.50	8.75	**Coronach Unit**
		Tan-buff to blue-grey dolomudstone; arenaceous bed above contact, coarse-grained quartz sand, frosted, well rounded; laminated to bedded, mottled, brecciated beds; wispy argillaceous laminations; argillaceous; some gypsum-anhydrite nodules; pyritic; intercrystalline porosity, 5%; upper contact sharp and irregular
601.50–615.95	14.45	**Lake Alma Member**
		Tan-buff to blue-grey dolomudstone; laminated to bedded to massive, mottled and burrowed, wispy argillaceous laminations; gypsum-anhydrite common; intercrystalline and vuggy porosity, 5%; upper contact sharp
615.95–724.70	108.75	**lower Red River**
		Grey-buff lime mudstone to lime wackestone interbedded with dolomudstone to dolowackestone; massive to massively bedded, wispy argillaceous laminations, mottled and burrowed; fossiliferous; rare nodular gypsum-anhydrite, rare chert nodules; intercrystalline and vuggy porosity, 5%; rare irregular fractures; upper contact gradational
724.70–725.00	0.30	**Hecla beds**
		Dark grey lime wackestone; argillaceous and arenaceous, abundant frosted quartz grains; upper contact sharp
725.00–763.35	38.35	**Winnipeg Formation**
725.00–757.05	32.05	**Ice Box Member**
		Medium to dark olive-grey shale; laminated, fissile, burrowed intervals, slickenslides; fossiliferous; intercrystalline porosity, 5%; hematitic; pyritic; tertiary gypsum; upper contact sharp
757.05–763.35	6.30	**Black Island Member**
		Reddish–dark grey slightly calcareous quartz wacke; bedded, flaser bedding in places; burrowed; hematitic; pyritic; intercrystalline porosity, 5%; upper contact gradational
763.35–937.87	n/a	**Precambrian**
		Iron formation; iron oxide, mostly magnetite, but also includes maghemite and hematite; iron formation is fine grained and finely laminated, interbedded with green siltstone and greywacke

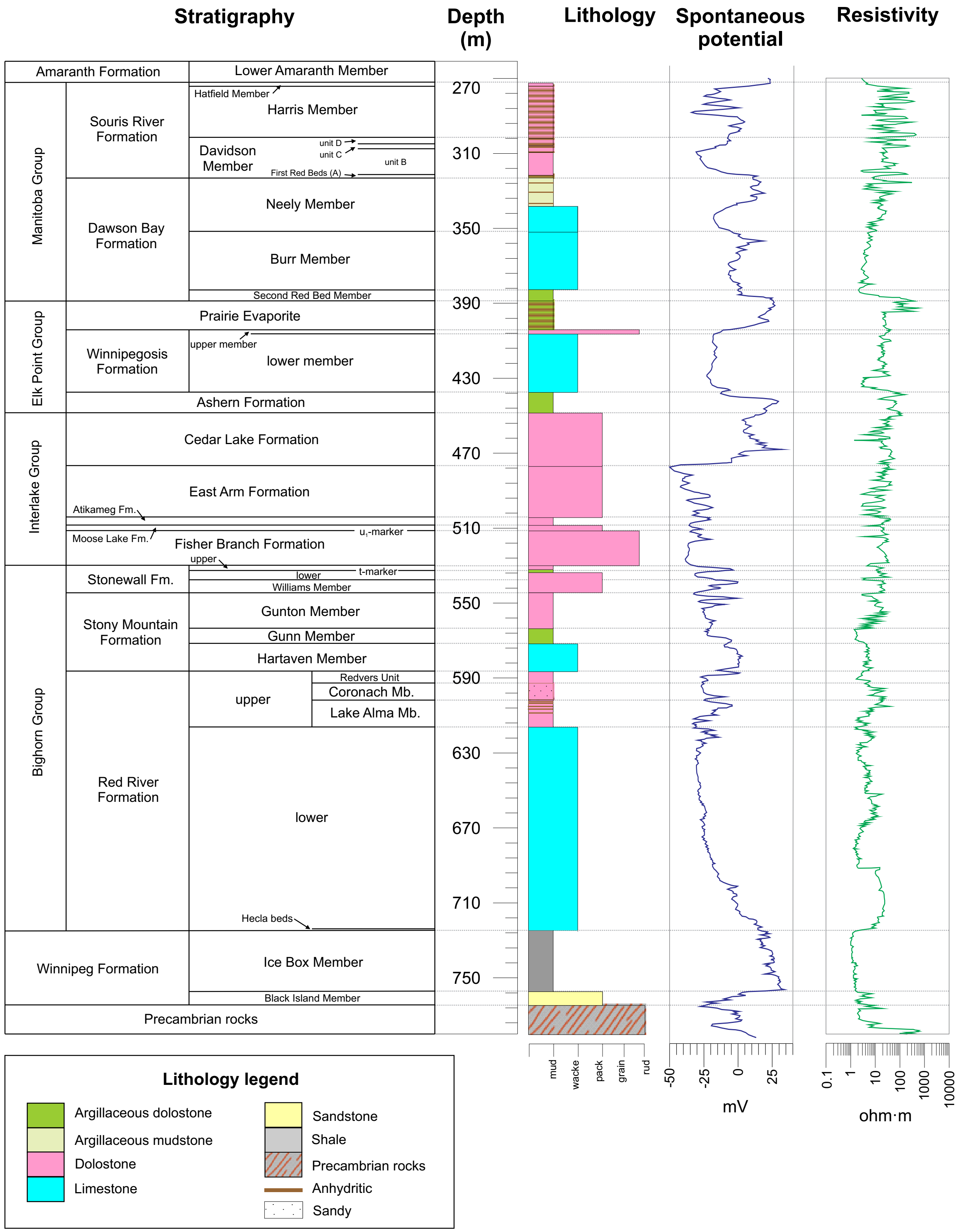

Figure GS2018-12-3: *Core log for the Neepawa DDH No. 1 Prov. 5-2914-14W1 core, showing tracks for lithology and geophysical logs. Geophysical logs have been depth corrected relative to the lithology log. Abbreviations: Fm., Formation; grain, grainstone; Mb., Member; mud, mudstone; mV, millivolt; pack, packstone; rud, rudstone; wacke, wackestone.*

Winnipeg Formation

The Winnipeg Formation disconformably overlies Precambrian iron formation. The formation is 38.35 m thick, with the basal Black Island Member composing 6.30 m of the formation and the remainder of the section composed of the Ice Box Member. The Black Island Member is a fairly well consolidated quartz wacke. Compared to the outcrop belt of southern Manitoba, this sandstone is less well sorted and much more friable (Lapenskie, 2016). The Black Island Member gradationally transitions into arenaceous shale of the overlying Ice Box Member. The Winnipeg Formation is disconformably overlain by the Red River Formation.

Red River Formation

The Red River Formation is composed of variably argillaceous carbonate rocks, with a basal 0.30 m thick argillaceous and arenaceous lime wackestone transitional unit referred to as the Hecla beds. The remainder of the lower Red River Formation is composed of argillaceous carbonate rocks. The lower Red River Formation is not completely dolomitized, and consists of interbedded calcareous and dolomitic mudstone and wackestone. The boundary between the upper and lower Red River Formation is conformable.

The upper Red River Formation in the subsurface in Saskatchewan is subdivided into the Lake Alma Member, Coronach Member and Redvers Unit. Nicolas and Barchyn (2008) noted that these units could be successfully correlated eastward into Manitoba using geophysical logs, and that formal adoption should be considered. The Lake Alma Member, Coronach Member and Redvers Unit were identified in Neepawa DDH, demonstrating that these units can be successfully correlated eastward into Manitoba. However, previous attempts at picking these units have been inconsistent, and detailed stratigraphic work is needed to fully address this issue.

The Lake Alma Member conformably overlies the lower Red River Formation, and is composed of argillaceous and evaporitic dolomudstone; the Lake Alma anhydrite is absent from this core, as it is limited to the extreme southwestern corner of Manitoba and eastern Saskatchewan. The Coronach Member disconformably overlies the Lake Alma Member and is composed of, in ascending order, a basal arenaceous dolomudstone, laminated to bedded dolomudstone and evaporitic dolomudstone. The Coronach Member is reported as being composed of a cyclical sequence of four units in Saskatchewan: a basal arenaceous dolomudstone, fossiliferous wackestone, laminated microdolomite and upper evaporite (Glass, 1990; Natural Resources Canada, 2018). Three of these four units are present in Neepawa DDH: the basal arenaceous dolomudstone, laminated dolomudstone and evaporitic dolomudstone. The Redvers Unit disconformably overlies the Coronach Member and is composed of bedded to laminated dolomudstone and lime mudstone. The Stony Mountain Formation disconformably overlies the Red River Formation.

Stony Mountain Formation

The Stony Mountain Formation is composed of a variable sequence of lime wackestone and dolomudstone interbedded with subordinate amounts of shale. The formation is subdivided into the Hartaven, Gunn and Gunton members; the Penitentiary Member is not recognized in southwestern Manitoba (Nicolas and Barchyn, 2008). The Hartaven Member is composed of shaly, fossiliferous lime wackestone. The Gunn Member is composed of a burrowed, argillaceous dolomudstone that gradationally transitions into the rarely fossiliferous, argillaceous dolomudstone of the Gunton Member. The upper contact of the Stony Mountain Formation is disconformable and occurs in the vicinity of two significant argillaceous beds. The higher of the two argillaceous beds contains quartz sand grains, which is indicative of the arenaceous Williams Member of the Stonewall Formation, therefore, the base of the upper marker bed was selected as the contact between the Stony Mountain and Stonewall formations.

Stonewall Formation

The Stonewall Formation is composed of a succession of dolostone beds, and is subdivided by the arenaceous t-marker bed. The basal Williams Member is composed of an argillaceous and arenaceous dolomudstone. The lower Stonewall Formation is composed of dolomudstone to dolobindstone and is biostromal in places.

The t-marker bed occurs as a distinctive quartz wacke to arenaceous dolomudstone in the upper portion of the Stonewall Formation. Historically, this marker bed, used in conjunction with the *Aphelognathus–Ozarkodina* conodont turnover boundary, was used to demarcate the Ordovician–Silurian boundary (Norford et al., 1998). Recent chemostratigraphic studies have demonstrated that the Ordovician–Silurian boundary occurs at a positive $\delta^{13}C$ excursion, termed the Hirnantian isotopic carbon excursion (HICE; Kleffner et al., 2005; Desrochers et al., 2010), and that this excursion generally occurs in the vicinity of the t-marker bed and conodont turnover (Demski et al., 2010a, b, 2011a, b; Lapenskie, 2012). Further study of Neepawa DDH is required to confirm the presence of the *Aphelognathus–Ozarkodina* conodont turnover and HICE to accurately identify the Ordovician–Silurian boundary.

The upper Stonewall Formation is composed of dolomudstone, but is lacking fossils and biostromal development. The upper contact is disconformable.

Silurian

The majority of the Silurian stratigraphy of Neepawa DDH consists of the Interlake Group. In the subsurface of Manitoba, the Interlake Group has been informally subdivided into lower and upper units, divided by a v-marker bed (Bezys and Conley, 1998). In the outcrop belt of Manitoba, the Interlake Group is formally subdivided, in ascending order, into the Fisher Branch, Moose Lake, Atikameg, East Arm and Cedar Lake formations (Stearn, 1956; Glass, 1990; Natural Resources Canada, 2018). Historically, the Inwood Formation was formally recognized between the Fisher Branch and Moose Lake formations but the name has been discarded as further study of northern and southern outcrops in Manitoba's Interlake region demonstrated that the Inwood Formation was being picked inconsistently in relation to the Fisher Branch, Moose Lake and Atikameg formations (Lammers, 1988; Bezys and Conley, 1998). For this study, the Inwood Formation is not formally recognized and Inwood Formation–type lithology is considered to be uppermost Fisher Branch Formation.

A lack of sufficient core of the Interlake Group in southwestern Manitoba and the challenges of using geophysical logs that have never been adequately compared to core lithology, has made correlation efforts of the Interlake Group formations into the deeper subsurface difficult (Bezys and Conley, 1998). This has resulted in numerous correlation inconsistencies between the subsurface and outcrop belt, which is compounded by the subtle and frequent lithological variations that occur throughout the Interlake Group.

Fisher Branch Formation

The lowermost Fisher Branch Formation is composed of interbedded dolomudstone and fossiliferous dolowackestone to dolofloatstone. The early Silurian index fossil *Virgiana decussata* (Norford, 1971), a pentamerid brachiopod, occurs within this unit, as well as diverse and abundant coral and stromatoporoid fauna. The uppermost Fisher Branch Formation is porcelaneous, similar to an Inwood Formation–type lithology. The upper contact of the Fisher Branch Formation is gradational and marked by the u_1-marker bed.

Moose Lake Formation

The basal Moose Lake Formation is defined by the u_1-marker bed, a burrowed and argillaceous dolomudstone. The remainder of the formation is characterized as dolomudstone to dolowackestone to dolobindstone, and is stromatolitic and fossiliferous. The upper contact of the Moose Lake Formation is gradational and was demarcated where porosity became more pervasive.

Atikameg Formation

The Atikameg Formation is composed of dolomudstone interbedded with compact stromatolitic beds. It is less stromatolitic than the Moose Lake Formation and lacks macrofossils. The u_2-marker bed is absent, however, the core is missing and mixed where the u_2-marker bed was expected to occur, between 501.40 and 504.40 m. The upper contact of the Atikameg Formation is gradational.

East Arm Formation

Highly variable interbeds of dolostone comprise the East Arm Formation. The v-marker bed, commonly found within the middle of this formation, is absent in Neepawa DDH. The lithology of the formation varies from dolomitic mudstone, wackestone, floatstone, bindstone to boundstone. Porcelaneous, intraformational clastic, brecciated, and stromatolitic and stromatoporoidal beds are common throughout. The East Arm Formation and Cedar Lake formations are both argillaceous, containing variable amounts of reddish-pink and greenish-grey clay associated with brecciated beds and increased porosity.

Two zones of diagenetic alteration were observed from 496.53 to 496.65 m and 478.80 to 478.82 m (Figure GS2018-12-4). These zones are characterized by greatly increased vuggy porosity and the majority of the original lithology has been replaced by fine- to coarse-crystalline, brown to blue-grey dolomite. These zones superficially resemble hydrothermal dolomite identified in drillcore M-01-07 in southwestern Manitoba (NTS 63C/1; Bamburak, 2007; Rawluk, 2010); thin section and carbon and oxygen isotope work is required to determine the nature of this alteration.

The upper contact of the East Arm Formation was difficult to pick and is uncertain since the contact is best defined when the Cross Lake Member of the overlying Cedar Lake Formation is present and its presence was questionable in Neepawa DDH. In this core the occurrence of the Chemahawin Member of the overlying Cedar Lake Formation was also questionable. However, prominent crinoid-rich and stromatoporoidal beds, similar to the Cross Lake and Chemahawin members, occur a)

b)

Figure GS2018-12-4: Diagenetic alteration of the East Arm Formation in drillcore from Neepawa DDH No. 1 Prov. 15-29-14-14W1: ***a)*** *photograph of dolostone from 495.30 to 498.40 m, zone of alteration outlined in green dashes;* ***b)*** *photograph of diagenetic alteration from 496.53 to 496.65 m, scale bar in centimetres. Arrow indicates up direction in core.*

above the designated contact between the East Arm and Cedar Lake formations in Neepawa DDH. This may indicate that the contact between the formations is significantly higher than placed, as discussed below. The upper contact was designated as gradational.

Cedar Lake Formation

The Cedar Lake Formation is similar to the East Arm Formation in that it also consists of a highly varied sequence of dolostone. In outcrop, the base of this formation is marked by the Chemahawin and Cross Lake members, but their presence in this core is uncertain, since no previous attempts have been made to extrapolate these members this far to the west (Glass, 1990; Natural Resources Canada, 2018). Interestingly, approximately 17.00 m above the lower contact there are two thin, red, argillaceous, crinoid-rich beds between 459.20 and 459.90 m, with the uppermost bed overlain by a stromatoporoidal bed from 458.65 to 459.20 m (Figure GS2018-12-5). These beds are similar to the crinoidal Cross Lake Member and reefal to stromatoporoidal Chemahawin Member. Further work is needed to confirm if these beds are the Cross Lake and Chemahawin members, and confirm if these beds can be correlated from the outcrop to the subsurface.

The remainder of the Cedar Lake Formation is composed of beds of dolomudstone, dolowackestone, and dolobindstone to doloboundstone. Beds are variably porcelaneous, fossiliferous and intraclastic. The distinctive 'raindrop' texture of the Silurian strata of Manitoba occurs within this formation. The upper contact of the Cedar Lake Formation is an angular unconformity and represents a significant period of nondeposition and erosion.

Devonian

The Devonian section of Neepawa DDH consists of interbedded shale, dolostone, limestone and evaporite, which comprise three complete shale-carbonate-evaporite cycles (Ashern Formation–Winnipegosis Formation–Prairie Evaporite; Dawson Bay Formation; and Davidson Member of the Souris River Formation) and the beginning of a fourth incomplete cycle (Harris and Hatfield members of the Souris River Formation; Fedikow et al., 2004).

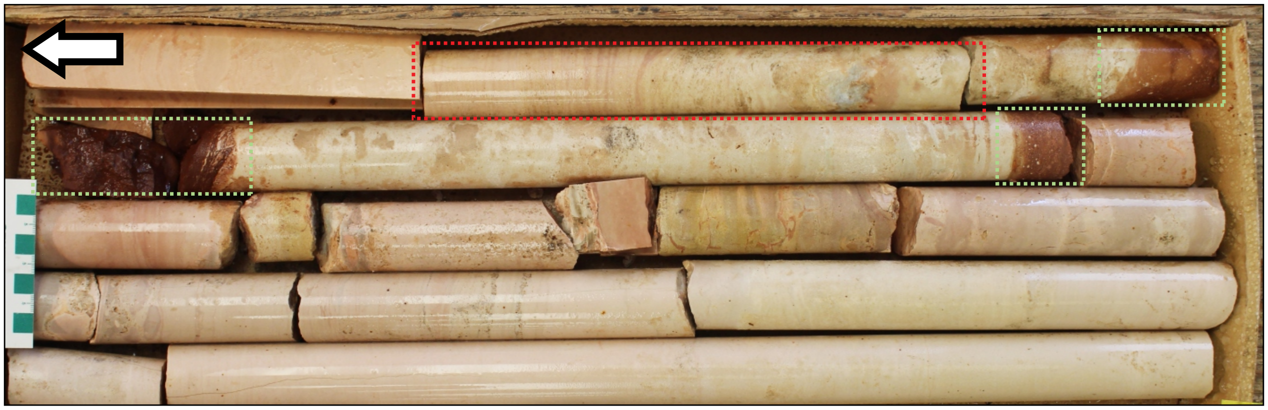

Figure GS2018-12-5: Photograph of core from drillhole Neepawa DDH No. 1 Prov. 15-29-14-14W1 from 458.70 to 461.80 m. Two red, argillaceous, crinoid-rich beds are outlined in green dashes, and the single stromatoporoidal bed is outlined in red. Arrow indicates up direction in core. Scale bar in centimetres.

Ashern Formation

The Ashern Formation is composed of reddish- or purplish-grey dolomudstone. The formation is very argillaceous, but not shaly. In places the Ashern Formation is evaporitic, with gypsum-anhydrite nodules and laminations. The upper contact is sharp.

Winnipegosis Formation

The Winnipegosis Formation is informally subdivided into lower and upper members. The lower member is composed of lime wackestone to dolowackestone. The upper contact of the lower member is sharp and occurs at a prominent bituminous marker bed that has been noted elsewhere in Saskatchewan and Manitoba (Jones, 1964, 1965; Norris et al., 1982). This bituminous bed is a local marker bed and cannot be used for basin-wide correlations. This contact occurs within a very argillaceous zone and is characterized by a gradual decrease in argillaceous content up-section into the upper member.

The upper member of the Winnipegosis Formation is composed of reefal facies dolofloatstone to doloboundstone. The member is fossiliferous, with stromatoporoids comprising the main faunal component. The upper contact of the Winnipegosis Formation was not observed, as core was missing from 397.80 to 403.90 m; it is inferred to be sharp.

Prairie Evaporite

The Prairie Evaporite is composed of interbedded shale, evaporitic dolomudstone and gypsum-anhydrite. The basal transition beds are absent, and no salt beds were encountered because the Neepawa DDH was drilled east of the salt dissolution edge of the Prairie Evaporite. The upper contact of the Prairie Evaporite was inferred to be sharp, as the strata immediately above this contact is disturbed. The Prairie Evaporite caps the first shale-carbonate-evaporite sequence in the Devonian strata.

Dawson Bay Formation

The Dawson Bay Formation encompasses the second shale-carbonate-evaporite cycle in the Neepawa DDH. The Second Red Bed, Burr and Neely members comprise the Dawson Bay Formation in the subsurface of Manitoba. The basal Second Red Bed Member is composed of dolomudstone to shale. It is disconformably overlain by lime mudstone to lime wackestone of the Burr Member. This member is fossiliferous, with brachiopods and crinoids as the primary faunal component. The upper contact is inferred as sharp, as the core was in poor condition at this interval.

The uppermost Neely Member is composed of calcareous and dolomitic mudstone and wackestone interbedded with shale and evaporite. The member becomes increasingly evaporitic upward, with gypsum-anhydrite occurring as nodules, laminations and beds. The Hubbard Evaporite is absent in Neepawa DDH. When the Hubbard Evaporite is absent, the contact between the Neely Member and the overlying Souris River Formation is gradational (Glass, 1990; Natural Resources Canada, 2018), therefore picking this boundary in the Neepawa DDH was difficult. The gradational contact was placed where non-evaporitic beds became red, argillaceous dolomudstone to shale.

Souris River Formation

The third and fourth shale-carbonate-evaporite cycles comprise the Souris River Formation. The Davidson Member encompasses the third cycle. The member is subdivided into four units: the First Red Beds (unit A), unit B, unit C and unit D (Figure GS2018-12-2; Lane, 1964;

Glass, 1990; Natural Resources Canada, 2018). The First Red Beds is composed of purple to red-brown evaporitic dolomudstone to shale and is formally recognized in the subsurface and outcrop belt of Manitoba. It is disconformably overlain by unit B, which consists of biostromal to porcelaneous calcareous dolomudstone. Unit B is disconformably overlain by unit C, an interbedded shale, dolomudstone and evaporite. Unit C is disconformably overlain by unit D, which is composed of evaporitic dolomudstone and gypsum-anhydrite. Unit D marks the end of the third complete shale-carbonate-evaporite sequence in Neepawa DDH. The Davidson Member is disconformably overlain by the Harris Member.

The one formal and three informal units of the Davidson Member may be correlative with the four units of the Point Wilkins Member (Norris et al., 1982) of the outcrop belt of Manitoba. Examination of additional drillcore across the Manitoba section of the Williston Basin is required to determine if these members can be correlated.

The Harris Member marks the beginning of the incomplete fourth shale-carbonate-evaporite cycle. The member is composed of at least 14 discrete shale-carbonate-evaporite cycles and a 15th incomplete cycle at the top of the member. Some of the cycles did not have a middle carbonate bed. In the west, the Harris Member is reported as being composed of eight cycles, with two prominent halite zones, informally referred to as the lower and upper Harris halite (Lane, 1964; Glass, 1990; Natural Resources Canada, 2018). The halite zones do not extend to Manitoba, and are therefore absent in this core. The Harris Member is disconformably overlain by the Hatfield Member.

The Hatfield Member is composed of an argillaceous and evaporitic dolomudstone. It is disconformably overlain by feldspathic to lithic wacke of the Triassic Lower Amaranth Member, Amaranth Formation. This contact marks the uppermost limit of the Paleozoic section of Neepawa DDH.

Results

Examination of Neepawa DDH resulted in the resolution of several stratigraphic issues. The lower Paleozoic stratigraphic framework in Manitoba contains correlation inconsistencies from the outcrop belt to deeper subsurface in the southwestern part of the province. In the subsurface of Manitoba, some formations and members are not formally recognized, whereas these intervals have formally recognized units in the outcrop belt of Manitoba and eastern Saskatchewan. Where possible, nomenclature from the outcrop belt, and to a lesser degree from eastern Saskatchewan, were applied to Neepawa DDH. Below is a summary of the correlation issues that were successfully resolved:

- the Lake Alma Member, Coronach Member and Redvers Unit, where defined in the upper Red River Formation; these units are formally recognized in eastern Saskatchewan; and
- the Fisher Branch, Moose Lake, Atikameg, East Arm and Cedar Lake formations, where defined in the Interlake Group; these units are formally recognized in the outcrop belt of Manitoba.

Some correlation issues still remain to be resolved and additional work is required to address these issues:

- investigating the occurrence and reliability of the u_2- and v-marker beds in the Interlake Group;
- formalizing and correlating the informal units of the subsurface Davidson Member to the informal beds of the outcrop-based Point Wilkins Member; and
- resolving the number of discrete shale-carbonate-evaporite cycles present in the Harris Member, Souris River Formation in the subsurface of Manitoba.

Investigations of additional drillcore from the subsurface are essential in resolving the above stratigraphic inconsistencies. Additional core logging will also confirm if the upper Red River Formation and Interlake Group can be successfully subdivided in other parts of the subsurface of Manitoba.

Future work

Future work on this core may include $\delta^{13}C$ and $\delta^{18}O$ stable isotope profiling of the entire core to assist in stratigraphic correlations and resolving stratigraphic inconsistencies. As mentioned, this would be useful for identifying the Ordovician–Silurian boundary, in conjunction with conodont analysis of the core. The diagenetically altered zones from 496.53 to 496.65 m and 478.80 to 478.82 m in the East Arm Formation require thin section work and $\delta^{13}C$ and $\delta^{18}O$ isotopic analysis to determine the nature of diagenesis and whether these zones may be hydrothermal dolomite.

Economic considerations

The Neepawa DDH core provided an important first step to successfully correlating outcrop with the subsurface in Manitoba, but further work is required to resolve issues and formalize stratigraphic relationships. An accurate and well-defined stratigraphic framework in Manitoba's Williston Basin will be beneficial for petroleum exploration, understanding of brines and groundwater, industrial mineral deposit exploration, and Mississippi Valley-type Pb-Zn deposit exploration.

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