Volumetric distribution and reservoir analysis of the Late Ordovician Black Island Member of the Winnipeg Formation, Southeastern Saskatchewan

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Summary

The Late Ordovician (Trentonian) Winnipeg Formation is a siliciclastic unit that occurs in the subsurface of southern Saskatchewan, Manitoba, and North Dakota. The formation unconformably overlies the Middle Cambrian Deadwood Formation and unconformably underlies the carbonates of the Late Ordovician (Edenian) Yeoman Formation. In southeastern Saskatchewan, the Winnipeg Formation consists of two members: lower sandstone-dominated Black Island and upper shale-dominated Icebox members. The Black Island Member is a major oil-producing unit in North Dakota, less productive in Saskatchewan and non-productive in Manitoba. Sedimentologic and diagenetic data from cores drilled in SE Saskatchewan and their wireline logs have been collected and analyzed. This study investigates the reservoir characterization of the Black Island Member. A petrographic study shows that the lower Black Island Member consists of quartz arenite, quartz wacke, siltstone, and shale lithofacies. The textural and structural properties of these lithofacies suggest foreshore (beach) to lower offshore depositional settings.

The reservoir properties of sedimentary rock is defined by the volume of pore spaces and their interconnectivity. The different types of sandstone lithofacies (i.e., the quartz arenites and the wackes) of the Black Island Member are deemed to have fair to excellent reservoir properties. Among the different well cores studied, the combined quartz arenite lithofacies constitute about 47% of the member, whereas the quartz wacke and the mudrock lithofacies constitute 44% and 9%, respectively. The porosity of the quartz arenite lithofacies ranges between ~22% and ~29%, whereas that of the wacke lithofacies varies from ~8% and ~11%. The pore spaces of both sandstone lithofacies are partially filled by subordinate mud matrix and cement, such as clays, quartz overgrowth, and localized carbonate cement. The pore spaces of the various sandstone lithofacies are well to moderately interconnected and expected to provide excellent permeability. The muddy facies (siltstone and shale) have very low porosity. Thus, the sandstone lithofacies (the arenites and the wackes), which form a total thickness of about 91% of the member, are envisaged to constitute fair to excellent reservoirs.

Introduction

The Winnipeg Formation is a Late Ordovician siliciclastic unit that occurs in subsurface SE Saskatchewan. The formation was deposited in the Williston Basin, which covers SW Manitoba and extends farther south into the neighboring states of the USA (Fig.1A). The formation is exposed along the west shore of Lake Winnipeg, but none of these outcrops show a complete stratigraphic section of this formation (Oberg, 1966). The formation represents marine sedimentation during the initial period of northward expansion of Late Ordovician transgression in the Williston Basin (Paterson, 1971; McCabe, 1978; Norford et al., 1994). Middle Cambrian Deadwood Formation occurs disconformably on the Precambrian basement rocks and unconformably under the Winnipeg Fm. (Fig.1B) (LeFever, 1996). Upper Ordovician Yeoman Formation succeeds unconformably the Winnipeg Formation in southeast Saskatchewan. In the study area of SE Saskatchewan, the Winnipeg Formation was deposited in the northeastern edge of the intracratonic Williston Basin and consists of two members: lower sandstone-dominated Black Island Member and upper shale-dominated Icebox member (greenish grey bioturbated shale and mudstone)(Kreis, 2004). The lower member is economically important and produces a fair amount of oil in North Dakota, but much less in Saskatchewan and not in Manitoba.

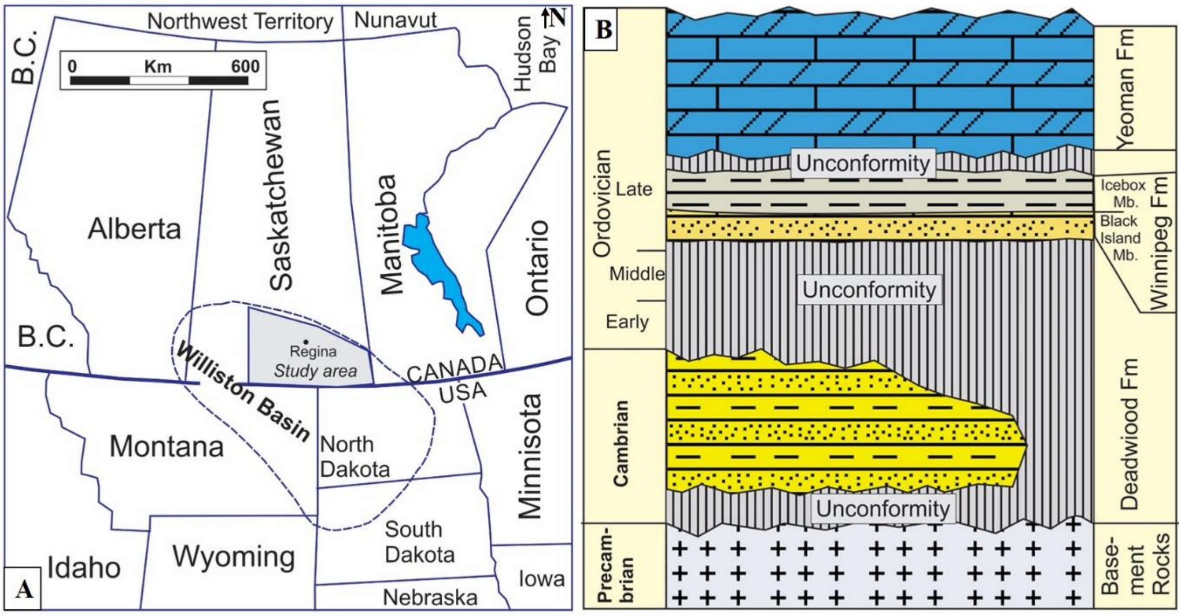

Figure.1. (A) Distribution of Williston basin in the United States and Canada (modified from Nimegeers, 2006), and (B) Precambrian to Ordovician stratigraphy in southeast Saskatchewan province (modified from Dorador et al., 2019).

In this study, a relatively depositionally heterogeneous sandstone interval of Black Island Member of the Late Ordovician strata of Winnipeg Formation in southeastern Saskatchewan is analyzed by using twenty-one well data (cores and wireline logs). Integrated petrographic studies, scanning electron microscope (SEM), energy dispersive spectroscopy (EDS), thin section study, and porosity measurements have been analyzed to diagnose primary depositional facies and diagenetic impacts on the reservoir characteristics of hydrocarbon-producing units of the lower Black Island Member of Winnipeg Formation. This research will help better understand pore types, cement type, diagenetic paragenetic sequence, and diagenetic effects on reservoir quality.

Lithology identification and subsurface distribution

The study of the lithologic properties of the Black Island Member is based on petrographic studies of rock samples from cores and wireline logs of both cored and uncored wells. The core analysis highlights the nature of contact relationships, sedimentary structures, bioturbation index (BI), and vertical lithofacies arrangement. The petrographic analysis demonstrates sedimentary fabric, grain size, sorting, and sedimentary micro-structures (e.g., nature of grain contacts and preferential grain orientation). Integration of the core and petrographic data allowed recognition of ten lithofacies for the Black Island Member (Fig.2). These ten lithofacies are briefly described as F1 - cross-bedded clean quartz arenite, F2 - ferruginous lithic arenite, F3 - slightly bioturbated cross- to planar-laminated quartz arenite, F4 - medium-grained, light grey quartz arenite with vertical bioturbation, F5 - variably bioturbated quartz arenite with floating mudrock pebbles, F6 - moderate to well-bioturbated quartz wacke, F7 - siltstone, F8 - extensively bioturbated feldspathic greywacke, F9 - shale, and F10 - fine-grained, green quartz wacke with discrete patches of light grey bioturbated zones.

Photomicrographs of samples selected from the various lithofacies of Black Island Member (Fig.3). Integration of the core description and petrographic data allowed the construction of the vertical stacking succession of the various lithofacies of the studied sections. The correlation among selected sections is shown in Fig. 2.

Fig.2 shows north to the south correlation of wells in southern Saskatchewan. Black Island Member is more widespread than the Icebox Member. The correlation shows that the Black Island Member is thicker in the central part of the study area and toward the south (Fig.2 at Loc. B-E). In the easternmost section (Fig.2 at Loc. G), the Deadwood Formation is missing, and the Winnipeg Formation sits nonconformably on the Precambrian basement rocks. The Black Island Member is thinner in the east (Fig.2 at Loc. F & Loc. G). In the northeastern section (Fig.2 at Loc. A), the Deadwood is thinner than in the southern localities, and Black Island Member is thinner. By taking the top of the Winnipeg Formation as a datum, it can be inferred that the basin contained higher accommodation space in the south (Paleo-depression). In contrast, the northern and eastern localities represent uplifted shoulders (Paleo-high) of the basin with less accommodation space than in the southern areas. This makes sense since the depocenter of the Williston Basin occurs in North Dakota, south of the study area. However, post-Winnipeg erosion and pre-Winnipeg irregular basin floor configuration may have affected the preserved thickness of the formation, particularly the Black Island Member, which is either missing (due to complete erosion) in some sections or reduced in thickness.

Petrography and modal composition

The various sandstone facies of the Black Island Member are characterized by white to dark brown, very fine to coarse-grained, easily friable to poorly-cemented moderate to well-sorted texture. The facies are variably bioturbated with a bioturbation index (BI) ranging between 0 and 6. Photomicrographs from the various facies of the member are shown in Fig.3. Quartz makes up more than >64 to 96% of the framework grains in the Black Island Member (Fig.3 & Fig.4). EDS analysis shows medium to high concentration of the C, O, and Si elements in sandstone of the Black Island Member. Feldspar was the second most abundant detrital component found in the sandstone, contributing around 1.6 to 30 % of the total framework. The lithic grains comprise around 1.6 % to 10% of the framework grains and are primarily made up of mud clasts, igneous material grains, and debris (Fig.3A-3K). The matrix and cement act as cementing materials among the framework grains. Matrix makes up from the framework grains, and it's largely detrital or diagenetically produced clay minerals. Detrital quartz grains are usually well-rounded and equant, monocrystalline and polycrystalline, and dominate the framework particles in the total rock (Fig.3). Quartz is the most common detrital material detected in the sample under investigation. Polycrystalline quartz is less common than monocrystalline detrital quartz. Detrital and authigenic feldspar minerals, igneous rock fragments, and heavy minerals are present in low concentrations. Pyrite is the most dominant heavy mineral in Black Island Member (Fig.3C &3D). Cement makes up most of the quartz grains; however, quartz overgrowths in some samples tend to unclear them. But few of the facies, the majority being iron and calcite minerals in Black Island Member. These iron-rich zone /oolitic beds (Fig.3C & 3D) mostly occur in the southeastern part of the Saskatchewan province (Iqbal and Hersi, 2021).

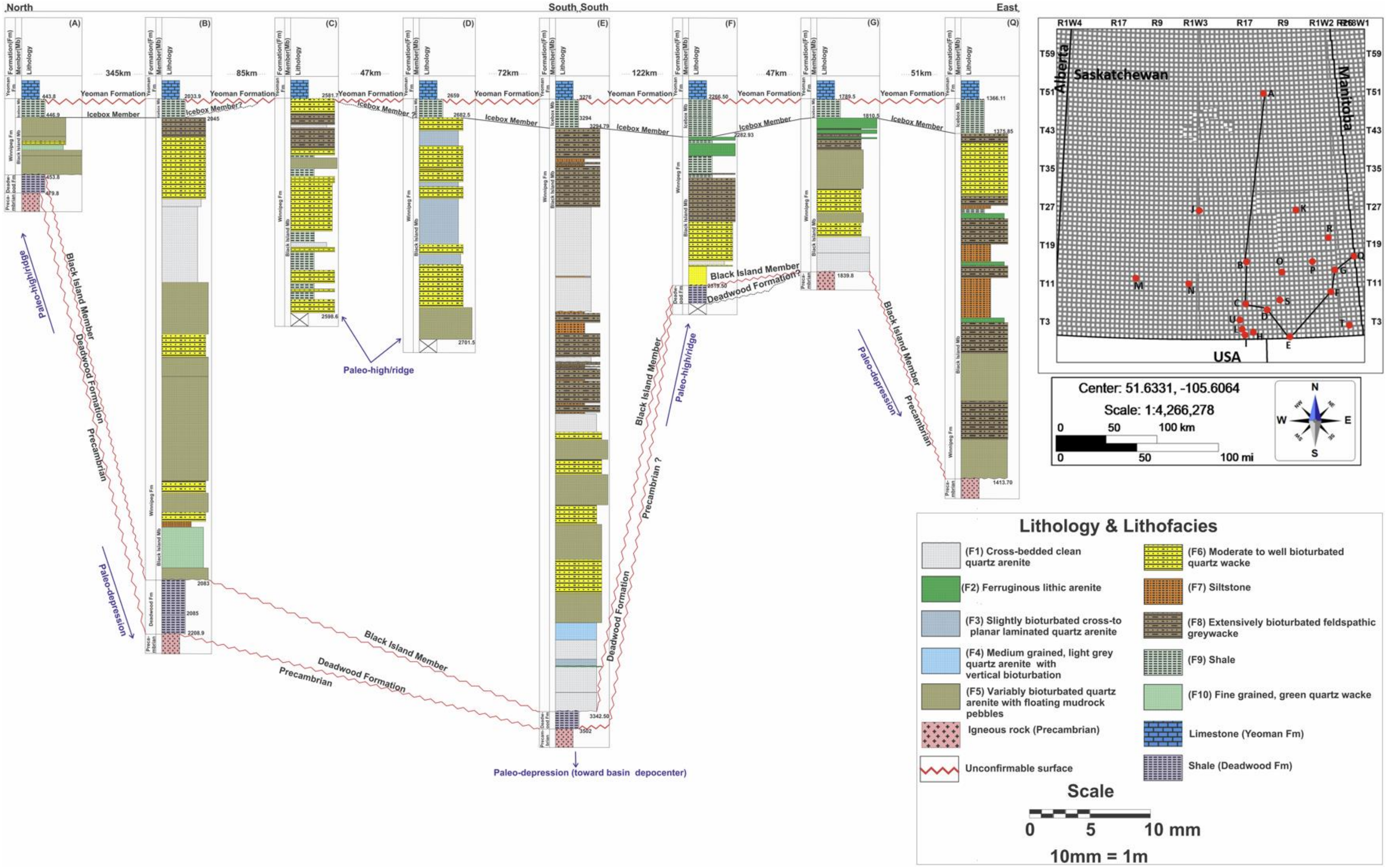

Figure. 2.North-South to South-East correlation of the Winnipeg Fm. Showing thicker sections in the south (i.e., toward the depocenter) and irregular pre-Winnipeg Fm. shelf paleotopography with paleo-highs and paleo-depression. The northward thinning of the formation can be attributed to the elevated Precambrian basement rocks, whereas the intrashelf topographic highs and lows are most likely due to pre-Winnipeg tectonics that affected older rocks (e.g., Deadwood Fm).

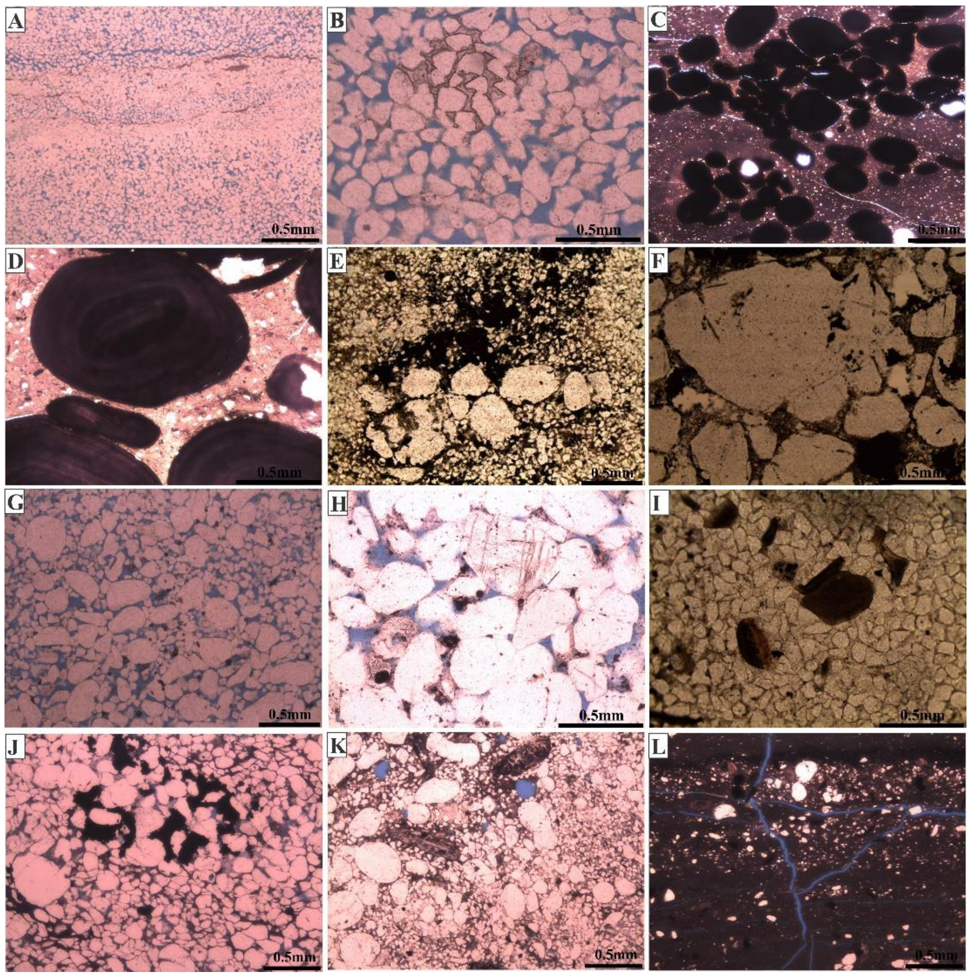

Figure.3. A&B) Photomicrograph showing very fine to fine-grained sandstone at a depth of 2057.7m in 131/03-08-017-19W2/00 well contains; mud drape, blue pore space, quartz overgrowth, and quartz framework grains (F1-Quartz arenite). C) Showing imbricated clasts at a depth of 2283.8m in well 101/05-15-010-02W2/00 well contains coated grain and quartz grains (F2-Lithic arenite). Also, D) shows coated grains like pisolitic/oolitic ferruginous grains with concentric lamination, quartz, and matrix content (F2-Lithic arenite). E) Showing coated grain, iron cement, and moderately sorted quartz grain at 453.2m in 101/12-15-052-14W2/00 well (F5-Quartz arenite). (F) Showing moderately sorted quartz grain, quartz overgrowth, and iron cement at depth 1813m in 111/12-34-014-01W2/00 well (F5-Quartz arenite). G) Petrographic characteristics showing coated grain, iron cement, blue color pore spaces, and moderately sorted (Q)quartz grain are very common at a depth of 2066.5m in 131/03-08-017-19W2/00 well (F5- Quartz arenite). H) medium-grained sandstone at a depth of 2292.9m in well 101/05-15-010-2w2/00 well contains; pore space (blue), moderately sorted framework grains quartz, coated grain, and rock fragments (F6-Quartz wake). I) Showing quartz grain, quartz overgrowth, (Ic)iron cement, and coated grains at a depth of 3019.7m in 101/01-31-001-20W2/00 well (F6-Quartz wacke). J) Showing quartz overgrowth, iron cement, and coated grains are at a depth of 2287.6m in 101/05-15-010-02w2/00 well (F8-Feldspathic greywacke). K) Showing quartz overgrowth, iron cement, and coated grains are at a depth of 3088m in 101/06-13-002-19W2/00 well (F8-Feldspathic greywacke). L) Showing quartz grain, coated grain, and blue color fracture at a depth of 3088.4m in 101/06-13-002-19W2/00 well (F9-Shale/mudstone).

In the study area, cement may have preserved the original loose packing of the grains, and floating grains are widespread. However, the framework grains are well to poorly rounded in a large proportion. Furthermore, the point counting method is used to interpret the composition of the lower Black Island Member of the Winnipeg Formation. The sandstones examined from the Black Island Member is classified as quartz arenite, quartz wacke, and feldspathic greywacke based on the total quartz, feldspar, and lithic fragments (QFL) (Fig.4A) in the ternary diagram (Pettijohn et al. 1987). According to (Pettijohn et al. 1987) (Fig.4), if the total matrix is less than 15% (Fig.4A), the rock is considered quartz arenite (Fig.3A- Fig.3G & Fig.5A & 5B), if the proportion of matrix is between 15% to 75% (Fig.4A), the rock is considered quartz wacke (Fig.3H-Fig.3K & Fig.5C & 5D), and >75% (Fig.4A) matrix is considered mudrock (Fig.3L). QFL plot of Black Island Member on the background ternary diagram showing tectonic province is a continental block (Fiq.4B).

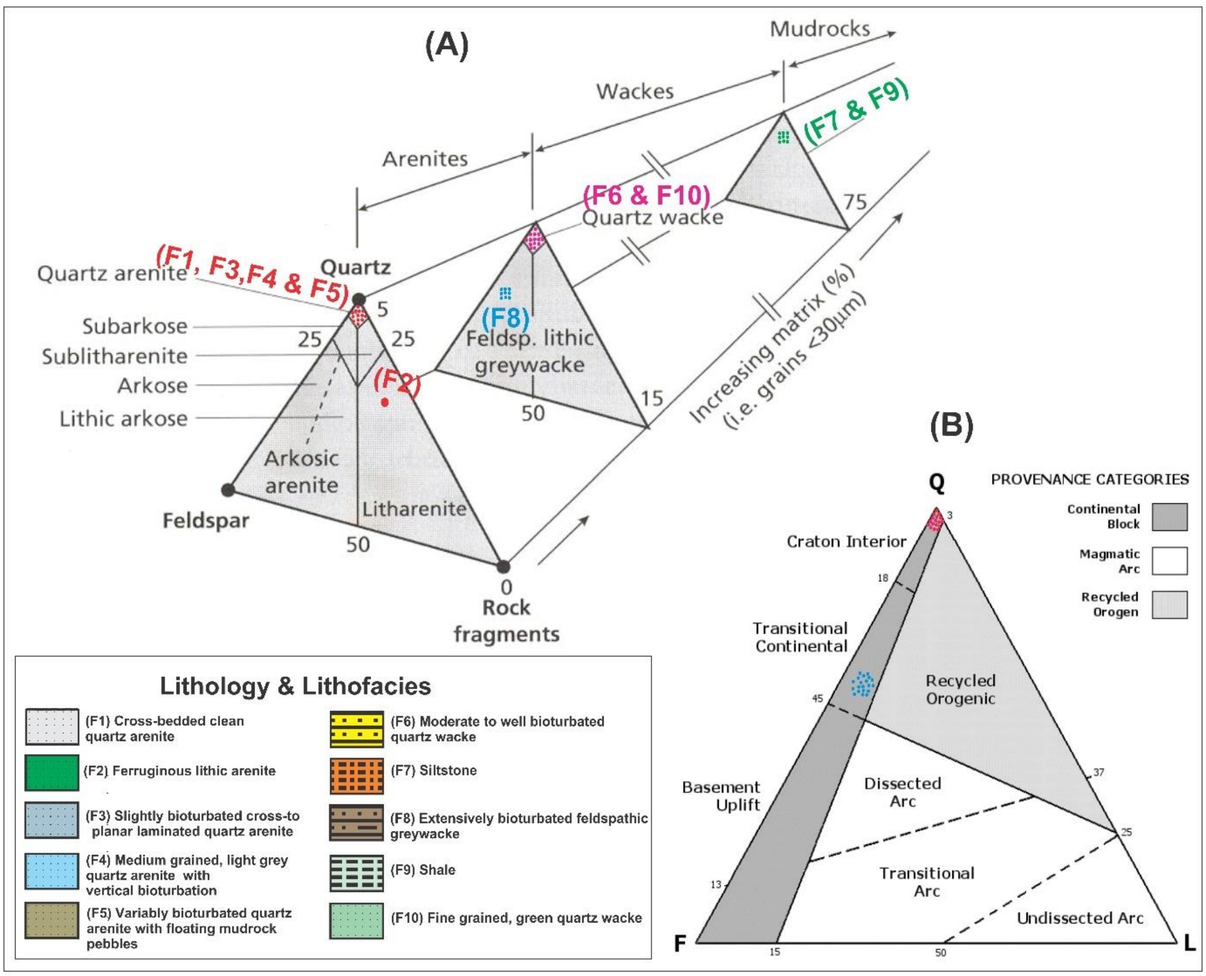

Fig.4. Ternary QFL plots of the analyzed samples (A) and sandstone provenance (B) of the Black Island Member; data is derived from the point-counting method from thin section samples of the Black Island Member. The ternary diagrams are based on the work of Pettijohn (1987) and Dickinson (1985).

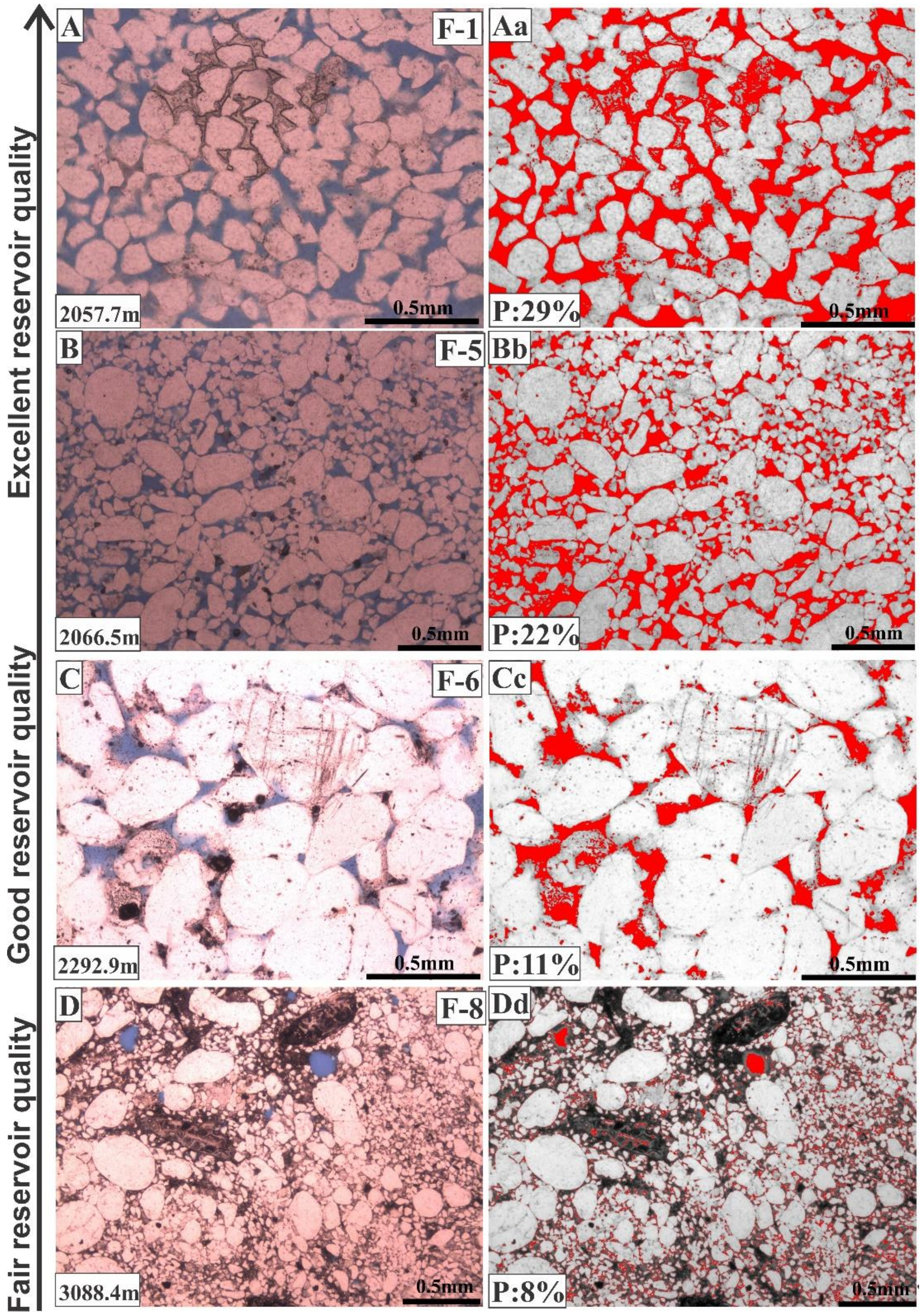

Figure.5. Image segmentation technique is applied to estimate the approximate porosity of the Black Island Member lithofacies (F). Quartz arenite lithofacies indicates excellent reservoir A) (porosity~29% in Aa) (F1) and B) (porosity~22% in Bb) (F5), C) quartz wacke (porosity~11% in Cc) (F6). D) Feldspathic greywacke (F8) is a fair reservoir (porosity~ 8% in Dd).

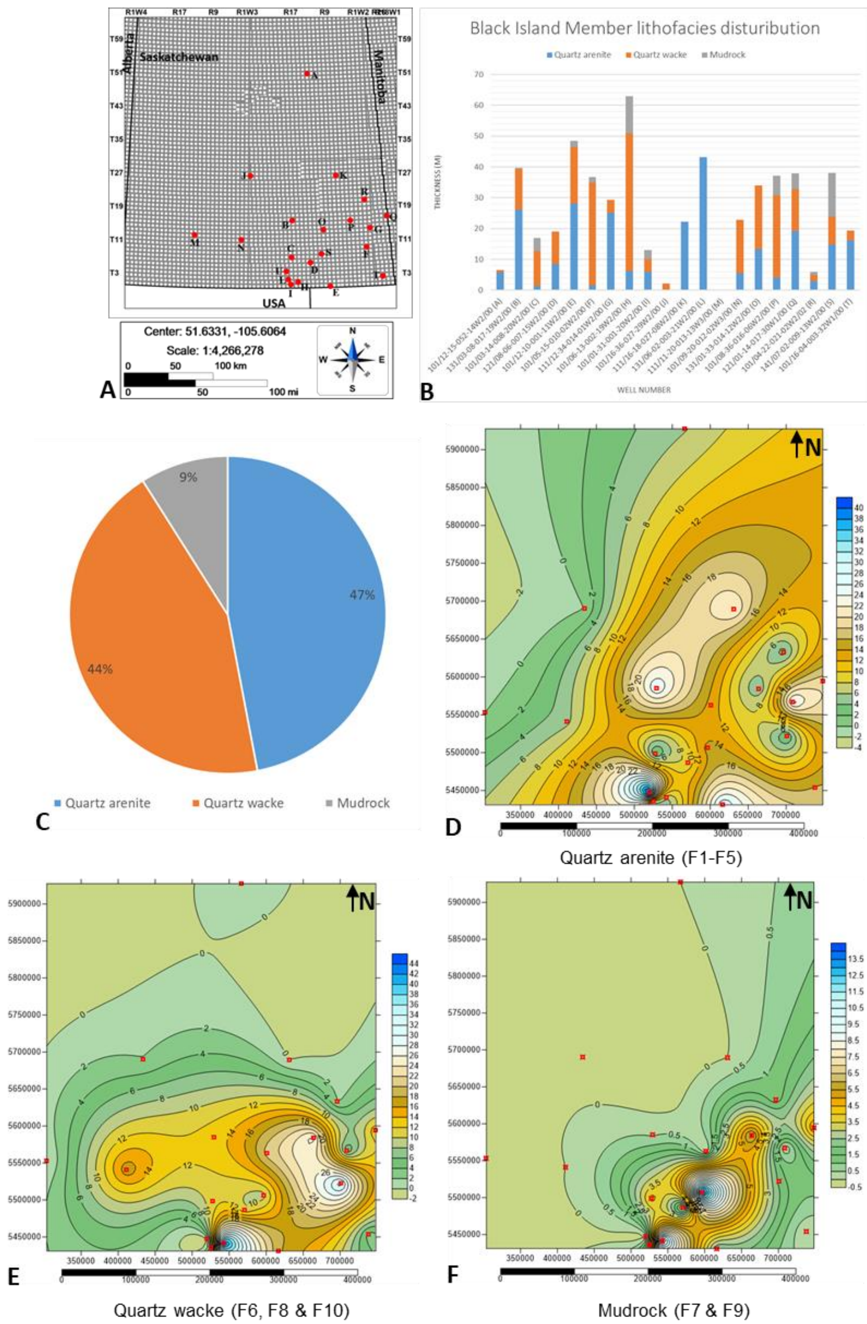

Fig.6. (A) Location map of the 21 (twenty-one) sections studied in this project. (B) Bar graph & (C) pie chart depicting the volumetric distributions of lithofacies in Black Island Member of different well cores in the studied area. D, E & F show isopach maps of each of the three lithofacies groups (arenites, wackes, and mudrocks) in Black Island Member: (D) isopach map of the arenite lithofacies (F1-F5); they are widely distributed towards central and S to SE of the study area, (E) wacke lithofacies (F6, F8 & F10) more common towards the SW to SE, and (F) mudrock lithofacies (F7&F9) more pronounced in SE part of the study area. Overall mud content of the member appears to increase toward the depocenter, most likely due to a gradual decrease in the energy of the depositional environment.

Reservoir properties and flow units

The sandstone examined from the Black Island Member is classified as quartz arenite (F1, F3, F4 & F5) (Fig.3A-Fig.3B & Fig.3E- Fig.3G), lithic arenite (F2) (Fig.3C- Fig.3D), quartz wacke (F6 & F10) (Fig.3H- Fig.3I), feldspathic greywacke(F8) (Fig.3J- Fig.3K), and mudrock (F7 & F9) (Fig.3L), based on the total quartz, feldspar, and lithic fragments (QFL) in the ternary plot interpretation (Pettijohn et al. 1987). The reservoir properties of sedimentary rock is defined by the volume of pore spaces and their interconnectivity. The different types of sandstone lithofacies (i.e., the quartz arenites and the wackes) of the Black Island Member are deemed to have fair to excellent reservoir properties (Fig.3 & Fig.5). The pore spaces of the sandstone facies are partially filled by subordinate mud matrix and cements, such as clays, quartz overgrowth, iron oxide, pyrite, and localized carbonate cement. The diagenetic sequence of main diagenetic processes in Black Island Member are interpreted from the petrographic analysis characterized as an eodiagensis to mesodiagensis. The prominent diagenetic features are quartz overgrowth, cementations, dissolution, replacement, compaction, etc., common in Black Island Member .

Image segmentation technique is applied to estimate the approximate porosity of Black Island Member lithofacies; that indicates quartz arenite lithofacies are an excellent reservoir (porosity~29%) (F1) (Fig.5.A & Fiq.5Aa) and (porosity~22%) (F5) (Fig.5.B & Fiq.5Bb, quartz wacke lithofacies is a good reservoir (porosity ~11%) (F6) (Fig.5.C & Fiq.5Cc). Feldspathic greywacke lithofacies is a fair reservoir (porosity~ 8%) (F8) (Fig.5.D & Fiq.5Dd). The pore spaces of the various sandstone lithofacies are well to moderately interconnected and expected to provide excellent permeability. The muddy facies (siltstone and shale) have very low porosity. Due to high mud concentration influence the reservoir quality in quartz wacke and feldspathic greywacke. Also, reservoir quality is possibly reduced due to bioturbation, which affects the porosity and permeability of the reservoir

Among the different well cores studied (Fig.6A), the combined quartz arenite lithofacies constitute about 47% of the member, whereas the quartz wacke and the mudrock lithofacies constitute 44% and 9%, respectively, as seen in a bar graph and pie chart (Fig.6B & Fig.6C). Thus, the sandstone lithofacies (the arenites and the wackes), which form a total thickness of about 91% of the member, are envisaged to constitute fair to excellent reservoirs. Subsurface isopach maps of Black Island Member lithofacies have been generated and interpreted. The isopach map shows that mapping is applied to investigate thickness variations and subsurface distribution of the Black Island Member's quartz arenite, quartz wacke, and mudrock. Quartz arenite (F1-F5) lithofacies isopach map shows distribution towards south to southeast and maximum thickness in the southeastern part of the province (Fig.6D). Quartz wacke (F6, F8 & F10) lithofacies shows distribution towards the southwest to the southeast, and maximum thickness in the southeastern part of the studied area (Fig.6E). Mudrock (F7 & F9) lithofacies shows distribution towards southeastern and maximum thickness in the southeastern part of the studied area in southeastern Saskatchewan (Fig.6F).

Conclusion:

In southeastern Saskatchewan, the Late Ordovician Winnipeg Formation consists of two members: lower sandstone-dominated Black Island and upper shale-dominated Icebox members. The Winnipeg Formation's Black Island Member in Saskatchewan is a fine to coarse-grained, friable to poorly cemented, bioturbated sandstone that is moderate to highly sorted. The Black

Island Member overwhelmingly constitutes the various lithofacies (quartz arenites, quartz wacke, and mudrock) that was deposited along a shallow marine transect from beach/foreshore through shoreface to lower offshore depositional environments. Correlations from north to south and south to the east indicate Black Island Member is thick toward the south and thin toward the southwest, southeast, and north of the eastern part of southeastern Saskatchewan. Quartz makes up more than >64 to 96% of the framework grains in the Black Island Member. The sandstone examined from the Black Island Member is classified as quartz arenite (F1 & F3-F5), lithic arenite (F2), quartz wacke (F6 & F10), feldspathic greywacke (F8), and mudrock (F7 & F9), based on the total quartz, feldspar, and lithic fragments (QFL) in the ternary plot interpretation. The diagenetic processes in Black Island Member are interpreted from the petrographic analysis characterized as an eodiagensis to mesodiagensis. The prominent diagenetic features are quartz overgrowth, cementations, compaction, etc. Reservoir quality of Black Island Member lithofacies indicates that quartz arenite lithofacies is an excellent reservoir (porosity~29%), quartz wacke lithofacies is a good reservoir (porosity ~11%), and feldspathic greywacke lithofacies is a fair reservoir (porosity~ 8%). However, high mud concentration influences the reservoir quality in quartz wacke and feldspathic greywacke. Also, reservoir quality is possibly reduced due to bioturbation, which affects the porosity and permeability of the reservoir. Isopach maps indicate the distribution of each lithofacies in Black Island Member; quartz arenite (F1-F5) lithofacies is widely distributed towards south to southeast, quartz wacke (F6, F8 & F10) lithofacies is distributed towards the southwest to southeast, and mudrock (F7& F9) lithofacies is dispersed towards southeast part of the studied area in southeastern Saskatchewan.

Acknowledgments

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