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Sedimentologic properties and depositional setting of the Black Island Member of the Late Ordovician Winnipeg Formation, Southeastern Saskatchewan

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Summary

The Winnipeg Formation is a Late Ordovician siliciclastic unit that occurs in the southeast subsurface of Saskatchewan. Deposition of the formation took place in the northeastern shelf of the sub-circular intracratonic Williston Basin. In the study area, the formation consists of two members: a lower sandstone-dominated Black Island and an upper shale-dominated Icebox members. The lower member constitutes a good hydrocarbon reservoir in Saskatchewan and the neighboring state of South Dakota. This study addresses the sedimentologic properties of the Winnipeg Formation, emphasizing the lower reservoir-forming Black Island Member of the formation. Sedimentologic properties from cores collected from wells drilled in SE Saskatchewan, their wireline logs and petrographic analysis were analyzed, integrated, and interpreted. This study reveals that the Black Island Member consists of ten lithofacies units. These lithofacies are discriminated based on their textural and structural properties, e.g., grain size, level of bioturbation index (BI), hydrodynamic sedimentary structures, and matrix content. Facies-1: cross-bedded clean quartz arenite with zero bioturbation index, Facies-2: ferruginous lithic arenite, Facies-3: slightly bioturbated cross- to planar-laminated quartz arenite, Facies-4: medium-grained, light grey quartz arenite with vertical bioturbation, Facies-5: variably bioturbated quartz arenite with floating mudrock pebbles, Facies-6: moderate to well-bioturbated quartz wacke, Facies-7: siltstone, Facies-8: extensively bioturbated feldspathic greywacke, Facies-9: shale, and Facies-10: fine-grained, green quartz wacke with discrete patches of light grey bioturbated zones. These lithofacies are interpreted to have been accumulated in a beach/foreshore to lower offshore setting (high to low energy). The Icebox Member is almost exclusively formed by shale lithology accumulated in the lower offshore to outer shelf environment. Thus, the two members of the formation define a deepening-upward succession that resulted from the eustatically-recorded Late Ordovician (Caradocian) sea-level rise. An unconformity at the top of the formation has been attributed to differential erosion that has affected the thickness of the formation in different locations of the study area.

Introduction

The Winnipeg Formation is a Late Ordovician siliciclastic unit that occurs 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 the northward expansion of the 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 is unconformably overlain by the Winnipeg Fm (Fig.1B) (LeFever, 1996). Upper Ordovician Yeoman Formation succeeds unconformably the Winnipeg Formation in southeast Saskatchewan. In 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 less in Saskatchewan and not in Manitoba. Therefore, Sedimentologic and stratigraphic properties of the lower sandstone-dominated member of the formation is deemed to be essential for improving our understanding of the subsurface distribution and hydrocarbon potential of the Black Island reservoir unit in SE Saskatchewan. This short paper aims to address the sedimentologic aspect of the Black Island Member and its depositional environment. Well core data from twenty-one wells allowed identification of the lithologic attributes and lithostratigraphic architecture of the various lithofacies that constitute the member in southeastern Saskatchewan.

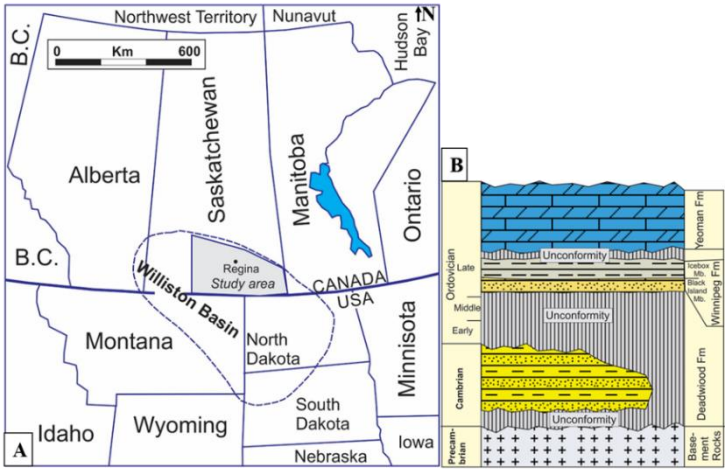

Figure.1. (A) Distribution of Williston basin in the United States and Canada (modified from Nimegeers, 2006), and (B) Precambrian to Ordovician stratigraphy in southeast Saskatchewan province (modified from Dorador et al., 2019).

The methodology of achieving the purpose of this study includes collection, analysis, and integration of sedimentologic properties collected from available data: (1) core logging and cutting analysis, (2) wireline log analysis, (3) well summary sheets/published papers, and (4) petrographic study of collected samples.

Lithofacies interpretation

Cores from twenty-one wells were measured described based on their lithofacies properties, nature of facies contacts, facies association, sedimentary structures and textures, bioturbation index (BI), thickness, and relationship with the subjacent and superjacent rock units. Deep Earth Energy Production Corp well 101/12-10-001-11w2/00, 131/03-08-017-19w2/00, and 101/05-15-010- 02w2/00 are also proposed as reference sections of the formation for the southern, central, and eastern part of the province, respectively. In the study area, the two members of the Winnipeg Formation are lithologically distinct. They consist of lower sandstone-dominated Black Island Member and upper shale-dominated Icebox Member (Kreis, 2004). Then lithofacies units are recognized and their attributes are summarized in Table.1.

Table.1 Black Island Member lithofacies description from well core data

Facies	Lithofacies	Brief description	Bioturbation Index (BI)	Depositional setting
1	Cross-bedded clean quartz arenite	Milky white to light grey very fine to fine grain. Steep cross-bedding, low angle cross-bedding, horizontal laminations, and mud drapes.	0	High to moderate energy setting (Beach/ foreshore to Upper Shoreface).
2	Ferruginous lithic arenite	Medium to coarse-grained, greenish with reddish spots, highly ferruginous well-rounded, pisolitic and oolitic texture.	0-1	High energy setting (shallow marine and oxygenated environment
3	Slightly bioturbated, cross- to planar-laminated quartz arenite	Fine-grained quartz arenite with horizontal lamination. Mud drapes are common, may also indicate flaser bedding that has been deformed by the compaction.	0-1	Low to moderate energy setting (Upper to middle shoreface).
4	Medium grained, light grey quartz arenite with no to rare vertical bioturbation	Light to dark grey, medium grained quartz arenite.	0-2	Moderate energy setting (upper to middle shoreface).
5	Variably bioturbated quartz arenite with floating mudrock pebbles	Light to medium grey, coarse grained quartz arenite with iron nodules and mud rock pebbles.	1-3	High to moderate energy setting (upper to middle shoreface).
6	Moderate to well bioturbated quartz wacke	Light grey, medium to fine grained quartz wacke, and laterally discontinuous dark shale laminae.	3-4	Low energy settings (lower shoreface to upper offshore).
7	Siltstone	Dark color, silt size grained, and bioturbated.	0- 3	Low energy setting (upper offshore -L offshore).
8	Extensively bioturbated feldspathic greywacke	Light to medium grey, medium to fine grained muddy feldspathic greywacke, with mudstone interlaminae, and wispy shale.	5-6	Low energy setting (lower offshore).
9	Shale	Light to dark grey mudstone/shale.		Low energy setting (lower offshore).
10	Fine grained, green quartz wacke with discrete patches of light grey bioturbated zone.	Fine to medium grain quartz wacke	2-3	Low to moderate energy (middle to lower shoreface).

Depositional environment of the Black Island Member

In the studied area, the overall depositional setting of Black Island Member is interpreted based on the lithologic and structural characteristics of the ten facies recognized to constitute the formation. The depositional environment proposed for the Black Island Member extends from the beach to lower offshore settings (Fig.2). It is characterized by gradual energy reduction from the foreshore to offshore, thus producing a "sieved" facies change from coarser sediments in the shallower zones to finer in the distal shelf area. The Black Island Member overwhelmingly constitutes the various sandstone (quartz arenites and quartz wackes) lithofacies and mudstone deposited along a shallow marine transect from beach/foreshore through shoreface to lower offshore environments. The shale-dominated Icebox Member was deposited farther offshore.

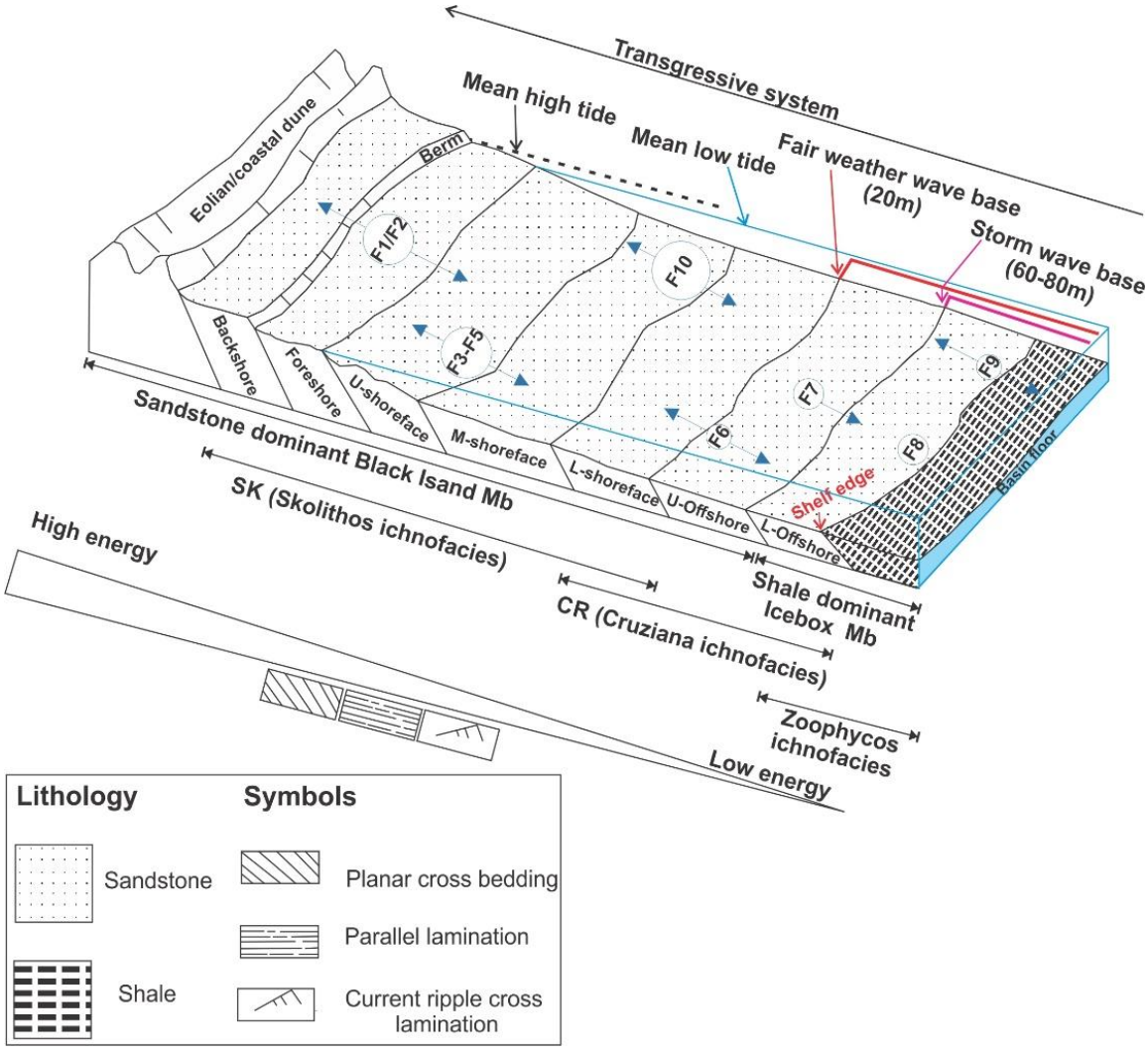

Figure 2. The depositional setting for Winnipeg Formation in southeastern Saskatchewan. This setting is based on the inferred depositional properties of the various lithofacies that form the formation. The formation accumulated from shallow marine foreshore (Facies 1 & 2) through shoreface (Facies 3 to 6 & 10) to offshore (Facies 7 to 9) environments.

Conclusions

In southeastern Saskatchewan, the Late Ordovician Winnipeg Formation consists of lower sandstone-dominated Black Island Member and upper shale-dominated Icebox Member. Sedimentological investigation from twenty-one cores allowed identification of ten lithofacies units that constitute the Winnipeg Formation of southeastern Saskatchewan, the depositional setting of the formation, an overall stratigraphic pattern of the different members of the formation, and paleotopographic setting of the basin and effect of sea-level changes on the basin-fill architecture. The ten lithofacies are (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. These lithofacies suggest a depositional environment characterized by gradual energy reduction from the foreshore to offshore. The Black Island Member overwhelmingly constitutes the various lithofacies (arenites, wackes, and mudrock) deposited along a shallow marine transect from in beach /foreshore through shoreface to lower offshore depositional environments. The shale-dominated Icebox Member was deposited farther offshore setting. The overall stratigraphic arrangement of the two members suggests a deepening-upward succession which resulted from a net depth increase of the marine depositional site. This depth increase of the basin reflects a globally-documented sea level rise in the early Late Ordovician (Caradocian) time.

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