Ferruginous sandstone in Late Ordovician Winnipeg Formation, SE Saskatchewan: sedimentary properties and their genetic implications

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Summary

The Late Ordovician Winnipeg Formation is a siliciclastic stratigraphic unit which occurs in the subsurface of the Province of Saskatchewan, nearby Manitoba and North Dakota. In southeastern Saskatchewan, the formation accumulated in the northeastern edge of the intracratonic Williston Basin and consists of two members: lower sandstone-dominated Black Island and upper shale-dominated Icebox members. The lower member of the formation consists of well- to moderately-sorted, fine- to coarse-grained, bioturbated, locally cross bedded quartz arenite with subordinate shale laminae and subordinate layers of ferruginous, pisoilitic and oolitic sandstone. The ferruginous sandstone is only observed in few of the wells in the study area of SE Saskatchewan Province. The ferruginous layers are characterized by red to green, medium to coarse-grained, slightly bioturbated sandstone. Petrographic properties show that the ferruginous rocks contain well-rounded to oval-shaped concentric (pisolitic/oolitic) laminations and non-laminated cortexes that are locally imbricated. Interstitial spaces of these pisolitic grains are filled by pyrite cement. The facies also contains well to moderately sorted grains with either quartz nuclei or without apparent nuclei. The pisolitic/oolitic grains are associated with clay and fine sand/silt matrix. The ferruginous sandstone has either gradual contact or sharp or scoured contact with the underlying lithofacies, which is commonly bioturbated quartz arenite. The composition of these ironstones are limonite and pyrite. The origin of the ferruginous layers can has been previously attributed to be diagenetic. However, the sedimentary features of these ferruginous sandstones indicate mixed depositional and diagenetic origin. On one hand, the scoured surfaces, imbricated clasts and mixing of pisolitic/ooilitic grains with a matrix of sand- to silt-size quartz grains indicate hydrodynamically-agitated depositional conditions. The limonitic content indicates underscores formation under oxygenated environment. On the other hand, pyritic cement and grain cortexes suggests precipitation under euxinic conditions. Thus, we envisage that these ferruginous sandstones accumulated as primary depositional grains in an oxygenated environment. Subsequent burial conditions with the presence of sulfate ions in a reduced diagenetic realm have later favored alteration of the original iron oxides to pyrite.

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 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 (LeFever 1996). Upper Ordovician Yeoman Formation succeeds unconformably the Winnipeg Formation in southeast Saskatchewan (Fig.1B & 1C). In SE Saskatchewan, the Winnipeg Formation was deposited in the northeastern edge of the intracratonic Williston Basin and consists of two members (Fig.1C): lower sandstone-dominated Black Island Member (bioturbated quartz arenite) 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. Sedimentologic, stratigraphic, diagenetic, subsurface distribution and reservoir quality of the lower sandstone-dominated member of the formation is deemed to be essential for better understanding of the hydrocarbon potential of this unit.

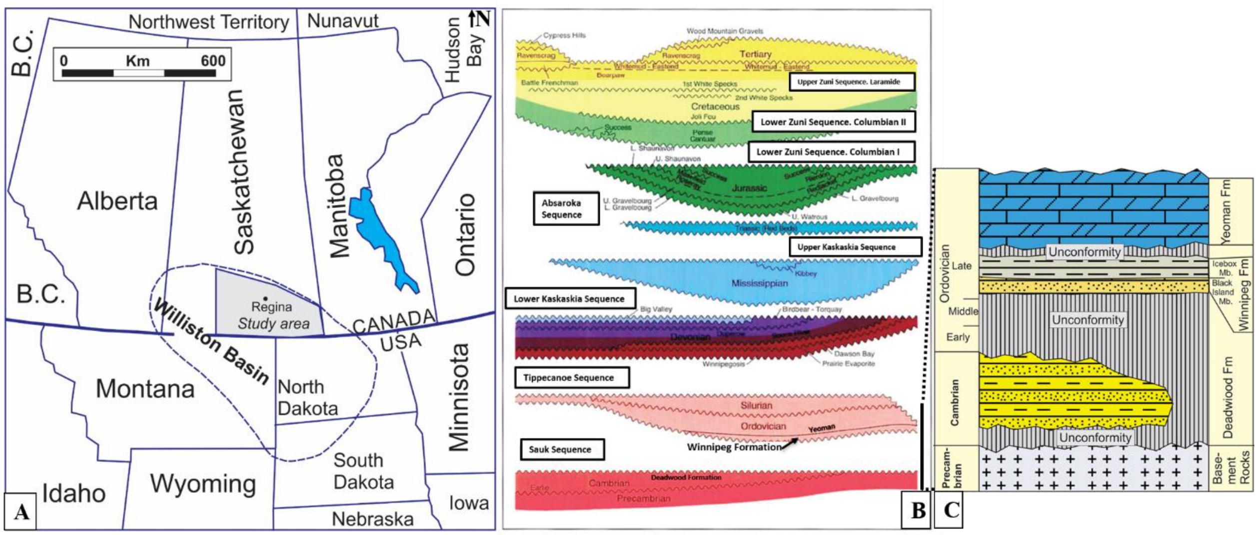

Figure.1. (A) Location map showing the study area in southeastern Saskatchewan and the delimitation of an estimated outline of the Williston Basin. The study area (shaded) occurs in the north-central shelf of the basin (modified from Nimegeers, 2006). (B) Phanerozoic stratigraphic fill and intervening unconformities among the different Sloss' (1963) supersequences of the Williston Basin (modified from Osadetz et al., 2018). The arrow shows the stratigraphic position of the Winnipeg Formation. (C) Precambrian to Ordovician stratigraphy in southeast Saskatchewan Province. The stratigraphic position of the Winnipeg Formation and its two members are also shown. The formation is bounded by two unconformities (modified from Dorador et al., 2014).

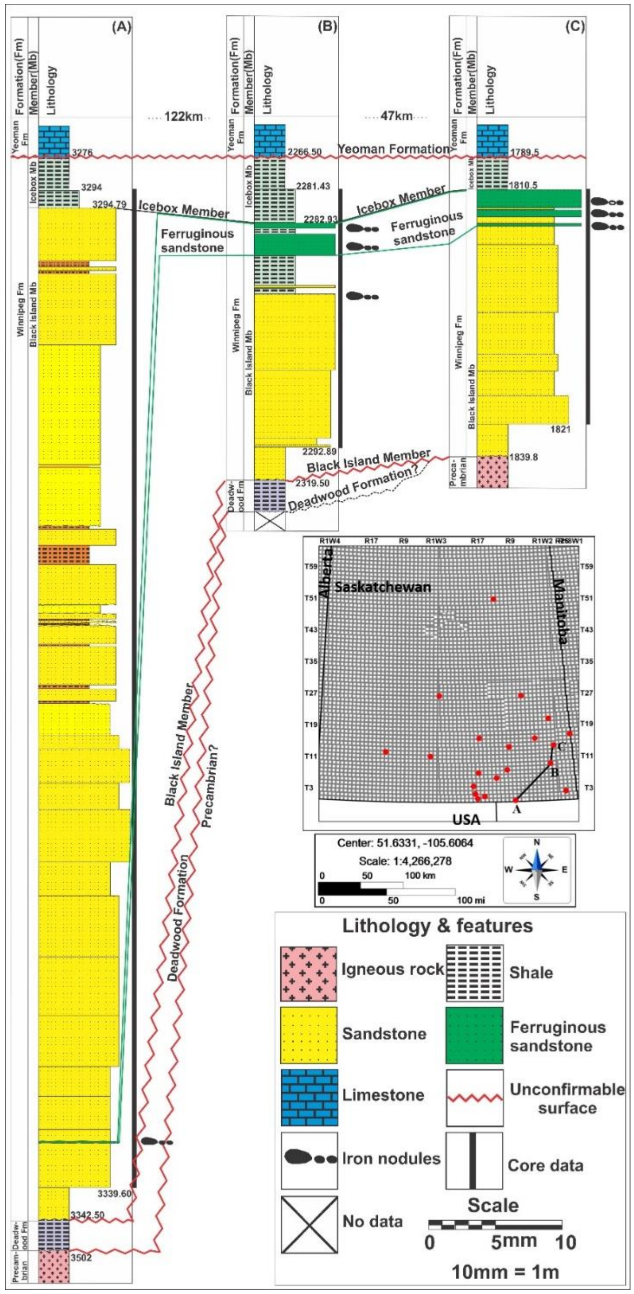

Figure.2. Showing core logging of the Winnipeg Formation and its contact above with Yeoman Formation, below with Deadwood Formation and Precambrian basement rock. Wireline logs and well summary sheet are also used for logging, where core data is missing. The datum is the base of the Yeoman Formation that is unconformable surface. Correlation indicates the formation is thickening toward south and thinning eastward. It also shows ferruginous sandstone lithofacies deposition in lower portion of Black Island Member is thinning southward in well (A)101/12-10-001-11W2/00 and it is thickening eastward in the upper portion of the Black Island Member in well (B)101/05-15-010-02w2/00, and (C)111/12-34-014-01W2/00 of the Winnipeg Formation.

We present here preliminary results of an on-going research work. The lithofacies properties of the ferruginous sandstone layers include reddish sandstone and green sandstone. Associated lithofacies (i.e., above and below the iron-rich layers) are shale and bioturbated sandstone (Fig.2). The contact between the two members is marked by a ferruginous zone in well (Fig.2B & 2C). Lithologically comparable ferruginous layers have been reported in the lower sandstone member of the formation in other parts of the province, as well as in Manitoba Paterson, D.F. (1971). Pyrite is very common in both sand and shale and occurred as the dispersed crystals. The sedimentary features and limonite mineralogy suggest that the ferruginous sandstone accumulated in a shallow marine high energy, oxygenated environment (Paterson, D.F.,1971). However, based on the pyrite contents by Baillie (1952), Genik (1954) and Macauley (1955), previous work suggests diagenetic origin in a reducing environment.

The methodology to study the lithologic properties of the formation includes collection, analysis and integration of data: (1) core logging and cutting analysis, (2) petrographic study (thin sections), (3) well summary sheets/published papers, and (4) wireline log analysis. Core stratigraphic log, correlation, sedimentary features and petrographic interpretation are used to understand the formation, depositional style, depositional environment and occurrence of thin ferruginous interval in Back Island Member of the Winnipeg Formation within the Saskatchewan province. The objective of this short paper is to understand the sedimentological attributes and subsurface distribution of the ferruginous sandstone in lower Black Island Member of the formation.

Result and observations

The descriptions of the ferruginous sandstone lithofacies based on data from three well (101/12-10-001-11W2/00 (Fig.2A), 101/05-15-010-02w2/00 (Fig.2B), and 111/12-34-014- 01W2/00 (Fig.2C)) is given in this short paper. The lithofacies properties of the ferruginous sandstone includes reddish sandstone and green sandstone (Fig.3A & 3B). Associated lithofacies (i.e., above and below the iron-rich layers) are gray shale and bioturbated sandstone. This is medium to coarse grained sandstone, greenish with reddish spots, highly ferruginous well-rounded, pisolitic and oolitic texture (Fig.3B & 3C). This lithofacies shows some sedimentary features such as imbricated clasts and scour surfaces in different wells (Fig.3D & 3E)).

Green sandstone lithofacies occurs at lower part of Black Island Member of the Winnipeg Formation in well 101/12-10-001-11W2/00 (Fig.2A). This lithofacies is about 0.4m thick, greenish with reddish spots, highly ferruginous (limonite), pisolitic, medium to coarse-grained sandstone. The iron content decreases downward and merge into light grey and very fine-grained quartz arenite, while iron content neither decreases upward and merge into light grey, slightly bioturbated quartz arenite (Fig.2A). This lithofacies also shows some sedimentary features like imbricated clasts and scour surfaces that indicates the possibility of sea level changes (Fig.3E).

Reddish sandstone lithofacies is about 0.72m thick occurs at upper part of Black Island Member of the Winnipeg Formation in well 101/05-15-010-02w2/00 (Fig.2B). It consists of iron-bearing (ferruginous), medium grained, slightly bioturbated sandstone (Fig.3A). The iron content decreases downward and merges to dark grey, heavily bioturbated, and fine-grained sandstone. In the lower part of this lithofacies, the ferruginous material fills in fractures but in the upper part it forms spheroidal texture with quartz core in some cases (Fig.2B & Fig.3A). The reddish sandstone lithofacies accumulated in shallow marine environment.

Green sandstone lithofacies is about 1.5 m thick occurs at upper part of Black Island Member of the Winnipeg Formation in well 101/05-15-010-02w2/00 (Fig.2B). It consists of greenish with reddish spots, highly ferruginous (limonite), pisolitic, and medium to coarse-grained sandstone. It grades upward to light brownish yellow (buff), fine sandstone with irregular pyrite-filled zones, as well as well-rounded, limonitic pisoids (Fig.3B & 3C). The lithofacies is overlain by gray shale that is typical for the Icebox Member (Fig.2B). The green sandstone lithofacies accumulated in high energy environment which becomes quieter upward as indicated by the shale in its upper part.

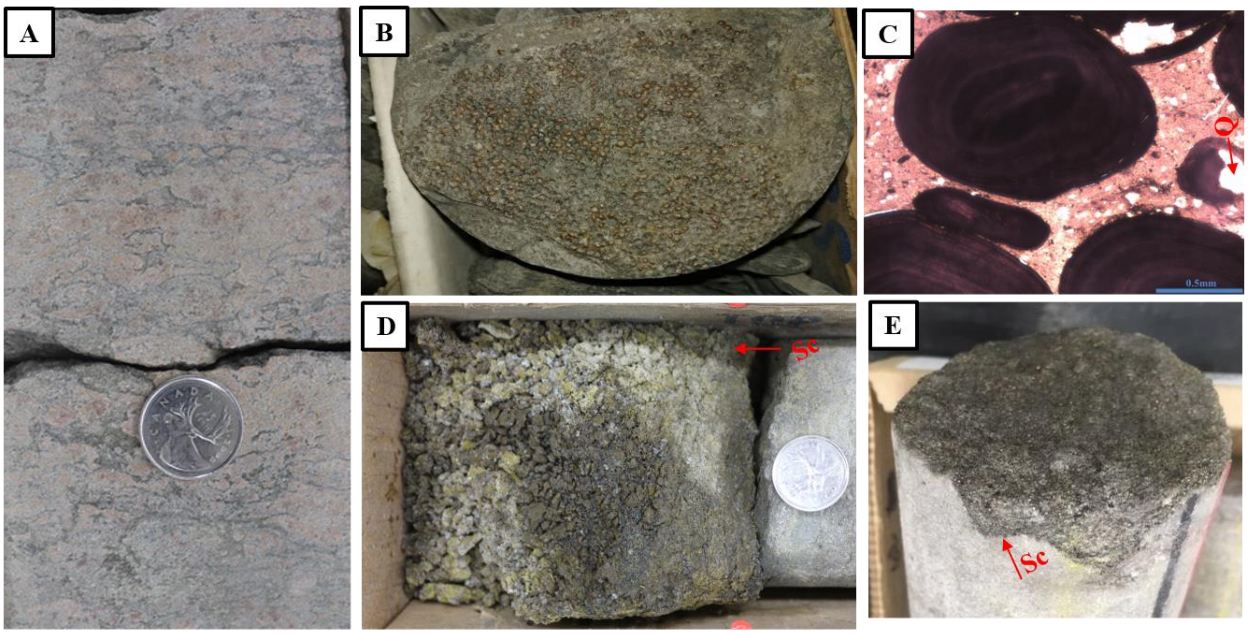

Figure.3. Ferruginous sandstone is coarse to very coarse grained, subrounded to well-rounded and moderate to very poorly sorted. (A) Reddish sandstone lithofacies from well 101/05-15-010-02w2/00 at depth of 2286.59m with 0.72m thick in core sample contains iron cement. It shows infiltration of iron minerals in discrete, irregular zones within the bioturbated sandstone. (B) Green sandstone lithofacies is about 1.5m thick with reddish spots, pisolitic/oolitic texture highly ferruginous sandstone at depth of 2283.37m in well101/05-15-010-02w2/00. (C) Photomicrograph of well 101/05-15-010-02w2/00 at depth of 2283.8m showing of green sandstone comprises of pisolitic and oolitic grains with concentric lamination, Q(quartz) grains, and Iron cement. (Sc) Scour surfaces are also prominent in well 111/12-34-014-01W2/00 (D) and also in (E) 101/12-10-001-11W2/00 well.

Green sandstone lithofacies is about 1.5 m thick occurs at upper part of Black Island Member of the Winnipeg Formation in well 111/12-34-014- 01W2/00 (Fig.2C). It consists of greenish sandstone, highly ferruginous (limonite), pisolitic, interbedded with yellow color sulphur content, and medium to coarse-grained sandstone (Fig.3D). The iron content decreases downward and merges to dark grey, heavily bioturbated, and fine-grained sandstone. The lithofacies is overlain by upper Icebox Member (shale) (Fig.2C). The green sandstone lithofacies is also accumulated in high energy settings.

Previous studied indicates they mineralogical contained pyrite and limonite. This lithology is thinly bioturbated (BI of 0-1). This facies represent high energy conditions. In ferruginous sandstone lithofacies two type of sedimentary features are observed.

(A). Features that suggest depositional origin:

1. Imbricated clasts: Imbricated clasts (Fig. 4A & 4B) indicates a primary depositional fabric consisting of a preferred orientation of clasts such that they overlap one another in a consistent fashion. This occur when granule-grade plus clast is aligned and overlay in a preferred orientation in the direction of flow. Imbricated sediments are deposited in relatively high energy, unidirectional flow.

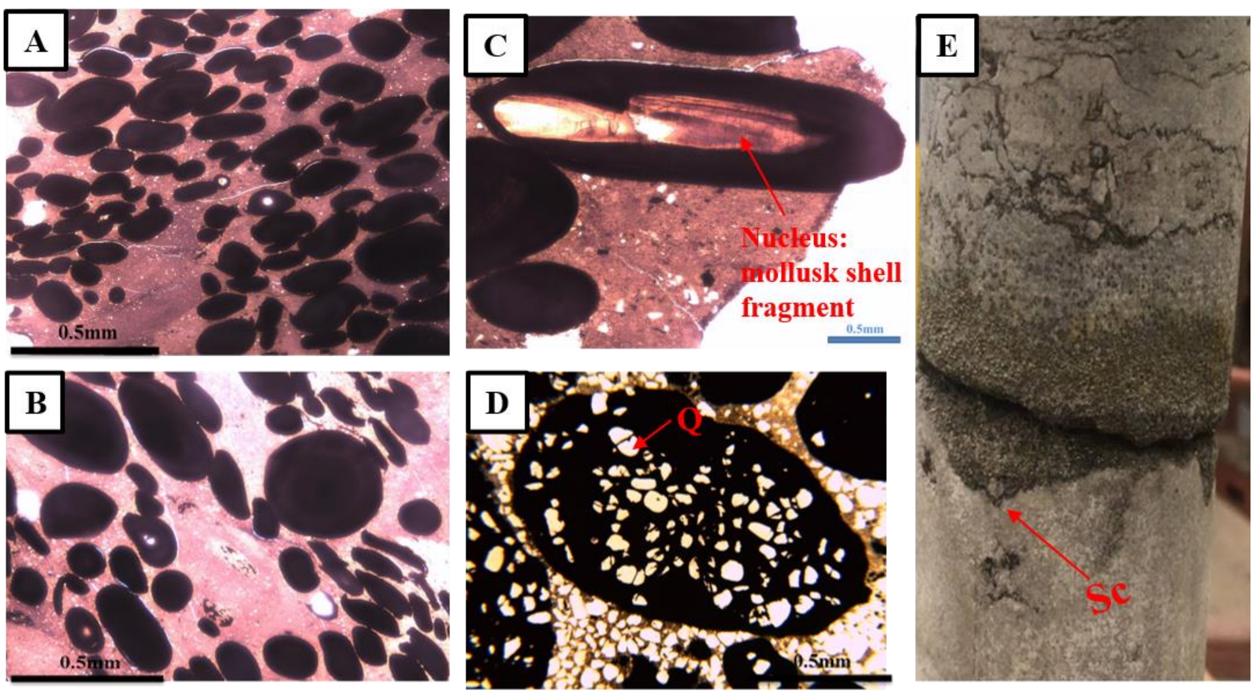

Figure.4. In ferruginous sandstone, (Q) quartz grains are commonly sub-rounded to subangular in shape. (A) Showing imbricated clasts at depth of 2283.8m in well 101/05-15-010-02W2/00 contains coated grain and quartz grains. (B) Showing imbricated clasts in thin section of well 101/05-15-010-02W2/00 at depth of 2283.8m that contains coated grains, quartz grains and iron cement. (C) Coated grains with concentric laminations at depth of 2283.8m in well 101/05-15-010-02W2/00 that contain mollusk shell fragment and iron cements as well. (D) Showing coated grain with concentric laminations in well 111/12-34-014-01W2/00 at depth of 1813 m. (E) Showing Sc (scour) surfaces in well 101/12-10-001-11W2/00 that are filled by the ferruginous sandstone at depth of 3337.55m.

2. Coated grains: Ooids are small (generally ≤2 mm in diameter), spheroidal, "coated" (layered) sedimentary grains, usually composed of calcium carbonate, but sometimes made up of iron- or phosphate-based minerals. Ooids usually form on the sea floor, most commonly in shallow tropical seas. An ooid forms as a series of concentric layers around a mollusk shell fragment nucleus (Fig.4C & 4D). The layers contain crystals arranged radially, tangentially or randomly. The concentric laminated nature of most coated grains implies episodic deposition and precipitation. Fig.4D shows that these clasts were deposited earlier or during deposition of the quartz.

3. Scour surfaces: These features are produced as a result of erosion of a sediment surface by the current flowing over it (Reineck and Singh, 1980). These are formed through the impingement of usually sediment-laden eddies on beds (Dzulynsky and Saunders, 1962). These scour surfaces are filled by the iron minerals (Fig.4E & 3E). The base of this lithofacies is associated with an erosional contact whereas the upper contact appears gradational accompanied by fining-upward texture. The scoured surface, normal grading and fining-upward texture further suggest deposition by waning energy of the current flow.

(B). Features that suggest diagenetic origin:

1. Replacement: Imbricates and white color represent the cementation, concentric lamination in coated grains with iron rich matrix. Intergranular and replacing cement at depth of 2286.6m (Fig.5A & 5B). Therefore, there is an evidence of secondary deposition that replaced primary lithology. The analyzed sandstone lithofacies is coarse to very coarse grained, subrounded to well-rounded and moderate to very poorly-sorted. The quartz grains are commonly sub-rounded to subangular in shape (Fig.5A & 5B)). This facies is typically consisting of 30% to 50% of quartz grain. The cements of this lithofacies are dominated by iron cements. It is generally fine-grained, and framework grains are composed of quartz grain that are later coated by iron matrix, and rock fragments.

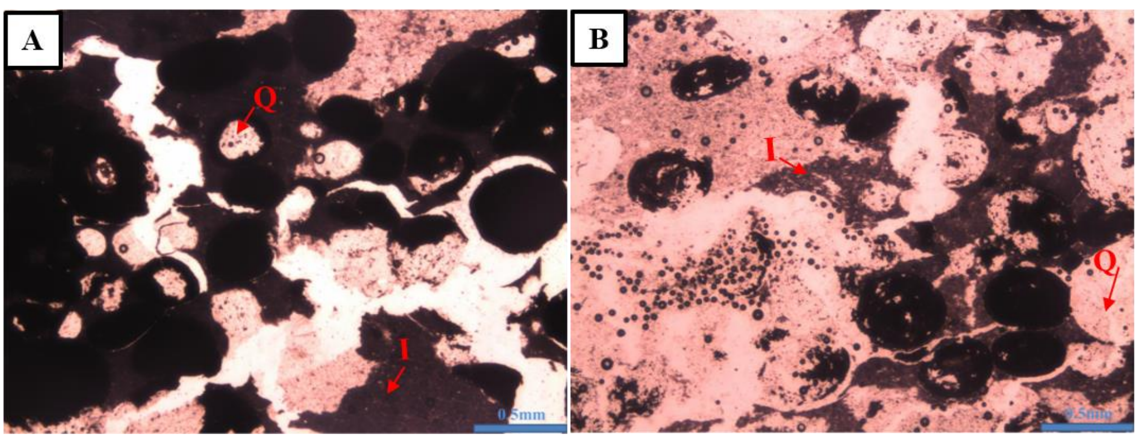

Figure.5. Ferruginous sandstone contains (I) iron cements, quartz grains (Q), and coated grains. (A) and (B) showing intergranular and replacing cement at depth of 2286.6m in well 101/05-15-010-02W2/00.

2. Infiltration: Infiltration of iron minerals in discrete, irregular zones within the bioturbated sandstone (Fig.3A) in 101/05-15-010-02W2/00 well at depth of 2286.6m. Reddish color infiltration is very prominent in the core sample that also proved the diagenetic origin of ferruginous sandstone.

Conclusions

The vertical lithofacies change from highly bioturbated quartz arenite (beneath reddish sandstone) to the less-burrowed and reddish sandstone lithofacies may indicate a sea level drop which caused the exposure and ferruginous weathering of reddish sandstone. The occurrence of the offshore shale on top of reddish sandstone indicates a relative sea level rise condition and cessation of the influx of the coarse-grained facies. This rise did not last long as indicated by the greenish sandstone, highly ferruginous sandstone which accumulated in an environment much shallower than that of shale. The latter may have accumulated in a subaerially-exposed coastal region. This was followed by major flooding which heralded the deposition of the Icebox Member (i.e., the base of the shale above (greenish sandstone). The relative sea level fluctuations and subaerial exposures of the shallow shelf may have developed short hiatus that separates the Black Island Member from the overlying Icebox Member.

Sedimentary features (scour surfaces, coated grains, and imbricated clasts) and limonite mineralogy suggest that the ferruginous sandstone accumulated in a shallow marine high energy, oxygenated environment. However, based on the pyrite contents the previous work suggests diagenetic origin in a reducing environment. Possible reconciliation between the two interpretations is that the ferruginous sandstone accumulated in an oxygenated environment but later diagenetically altered to pyrite. The ferruginous layers have been reported in different places within the province of Saskatchewan and in Manitoba, as well. South-east correlation indicates that ferruginous sandstone lithofacies is thinner toward the south and thicker toward the east of the Saskatchewan province. Further scrutiny of these iron-bearing intervals, their potential usage as marker layers for inter-provincial correlations and their significance in terms of sea level changes within the Winnipeg Formation are in progress.

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