Transgressive-Regressive Cycles of the Mississippian Frobisher Carbonate-Evaporite Succession in the Steelman Area, Southeastern Saskatchewan

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Abstract

The Steelman Field in southeastern Saskatchewan, located on the northeastern flank of the Williston Basin, produces oil from Mississippian Midale and Frobisher Beds. In the Frobisher Beds, four transgressive-regressive cycles of sedimentation are recognized, reflecting changes in depositional environments. Up to six lithofacies are commonly present in each cycle with another two lithofacies only locally developed. Their environments of deposition have been interpreted as ranging from subtidal to supratidal. The distribution and continuity of porosity is strongly influenced by the patterns of sedimentation.

Keywords: Frobisher, Steelman Field, carbonate-evaporite, transgressive-regressive, stratigraphy, Williston Basin.

1. Introduction

The Steelman Field is a prolific hydrocarbon producing region on the northeastern flank of the Williston Basin in southeastern Saskatchewan (Figures 1 and 2). Most production in this field is from Mississippian carbonates of the Midale Beds. The Frobisher Beds, subjacent to the Midale Beds, also contain producible hydrocarbons, but have been less extensively studied. In this work, 68 cores have been examined and more than 100 geophysical well logs analyzed to identify sedimentological and stratigraphic characteristics of the Frobisher carbonate-evaporite succession. The area studied covers approximately 746 km^2 (288 mi^2) between Townships 3 to 5 and Ranges 4W2 to 7W2 inclusive, and includes the Steelman Field.

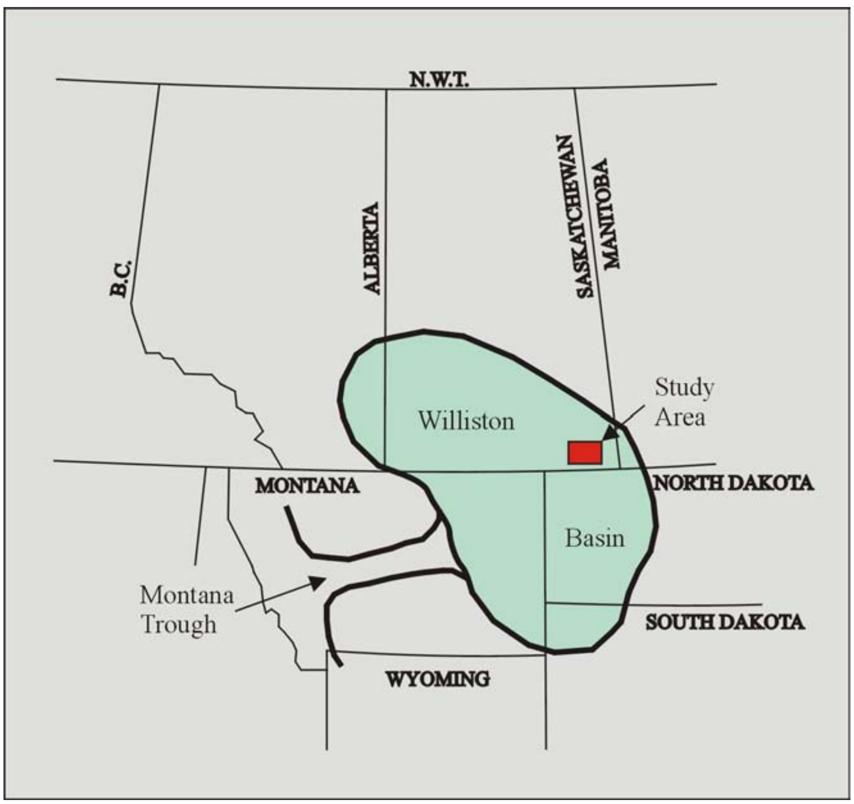

Figure 1 - Regional map showing the locations of the Williston Basin and the Montana Trough during the Mississippian, as well as the location of the study area (modified from Lake (1991) and Wegelin (1984)).

During the Mississippian, the Williston Basin (Figure 1) was at a latitude of approximately 5ºN to 10°N (Storer, 1989) and was relatively shallow, providing an excellent environment for carbonate sedimentation (Storer,

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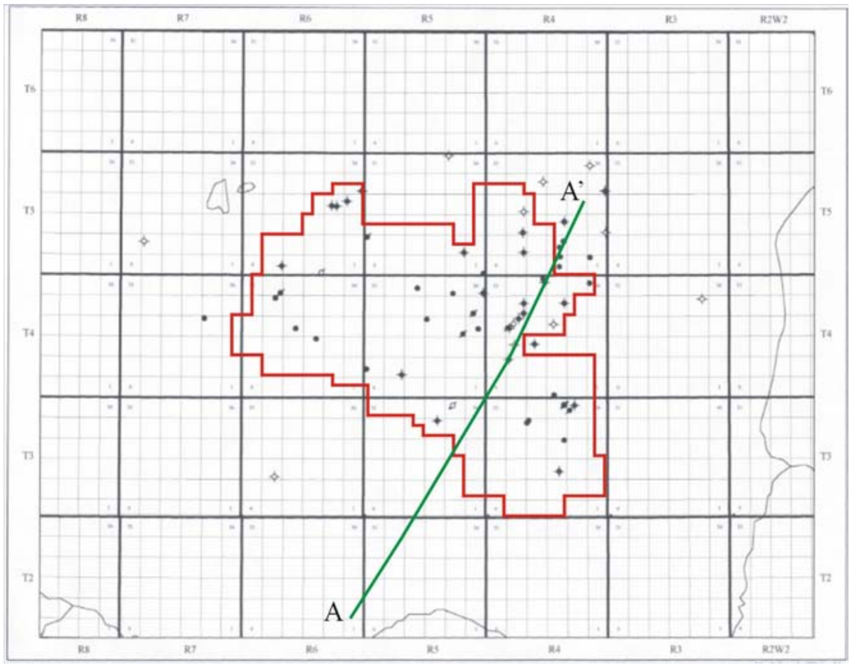

Figure 2 - Base map showing outline of the Steelman Field and location of cross-section A-A'.

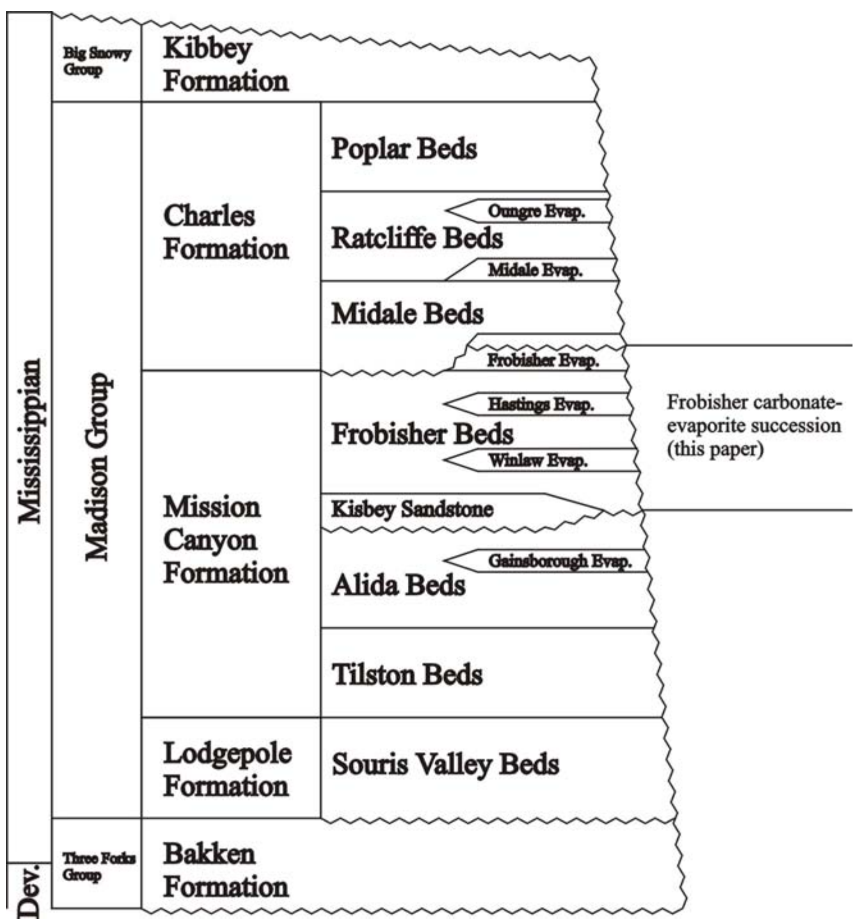

Figure 3 - Stratigraphic column of the Mississippian in southeastern Saskatchewan with particular focus on the Frobisher carbonate-evaporite succession (modified from Kent,1984).

1989; Boggs, 1995; Tucker, 1996). The Mississippian succession in the study area is dominated by shallow-water carbonates with lesser amounts of anhydrite. The Mississippian Madison Group contains three formations which are, in ascending stratigraphic order: the Lodgepole, the Mission Canyon, and the Charles (Figure 3; Fuzesy, 1983; Kent, 1984, 1987; Mundy and Roulston, 1998). Each formation has been subdivided into a succession of 'beds' (Figure 3). The Lodgepole contains the Souris Valley Beds that were deposited unconformably on Devonian shales of the Bakken Formation and are the only subdivision present in southeastern Saskatchewan (Mundy and Roulston, 1998). The Souris Valley Beds are mostly composed of limestone in which carbonate mud-mounds are characteristically developed (Sereda and Kent, 1987; Tucker and Wright, 1996). The Mission Canyon Formation contains (from oldest to youngest) the Tilston, Alida, and Frobisher beds, the last of which are the focus of this study. The Charles Formation contains the Midale, Ratcliffe, and Poplar beds. Portions of the Ratcliffe and Poplar beds have been removed by erosion at the sub-Mesozoic unconformity within part of the study area.

2. Frobisher Stratigraphy

The Mission Canyon Formation is mainly limestone, with the Alida and Frobisher beds being dolomitic in part. Laterally extensive anhydrite beds, identified as the Gainsborough, Winlaw, and Hastings evaporites, are also present (Figure 3) (Kent, 1987; Mundy and Roulston, 1998). The Frobisher Beds are typically separated from the underlying Alida Beds by a regional unconformity. In some areas of the basin, Kisbey Formation sandstones are present at this unconformity, overlying the Alida carbonates (Kent, 1987; Perras, 1990; Mundy and

Roulston, 1998). The Midale, Ratcliffe, and Poplar beds of the Charles Formation also contain limestone, dolostone, and anhydrite, and, in the Poplar Beds, halite (Kent, 1987; Mundy and Roulston, 1998).

Several interpretations of the depositional environment of the Frobisher carbonate-evaporite succession in this part of the Williston Basin have been proposed. The two most common are: 1) a broad carbonate shelf setting (Lake, 1998; Mundy and Roulston, 1998), and 2) a carbonate ramp setting (Kent, 1984, 1987, 1999; Kent *et al.*, 1984; Smith and Dorobek, 1993). Williston Basin subsidence during deposition of these sediments may have been related in part to the reactivation of basement faults, and/or dissolution within the Prairie Evaporite (Sereda and Kent, 1987; Mundy and Roulston, 1998; Kreis and Kent, 2000).

Within the Frobisher carbonate-evaporite succession of the Steelman Field, four progradational transgressive-regressive cycles have been identified based on core and geophysical well log analysis (Figure 4). They onlap the unconformity at the top of the Alida Beds, which forms the lower bounding surface for the Frobisher. The upper boundary is a flooding surface within the lower Frobisher Evaporite of the Midale Beds. Based on this information, the Kisbey Sandstone and the lower Frobisher Evaporite are, in this study, provisionally included within the Frobisher carbonate-evaporite succession (Figure 3). Successive upward shallowing cycles become increasingly thin, possibly in response to a reduction in accommodation space, or due to a decrease in the periodicity of the transgressive-regressive cycles (Walker and James, 1992).

3. Lithofacies of the Frobisher Carbonate-Evaporite Succession

Based on the analysis of core and geophysical well log data, eight lithofacies have been identified, and their depositional environments interpreted from their lithological, compositional, and textural characteristics. Of these, the following six lithofacies are widespread throughout the study area, and typically are present in each cycle in ascending order as listed.

a) Oolitic Peloidal Grainstones and Packstones

Oolitic peloidal grainstones and packstones occur at various intervals within the Frobisher Beds of the study area, but are not typically found within the Frobisher Evaporite. They are pale grey to brown in colour, and contain moderately to well sorted ooids, peloids, oncoids, intraclasts, and shell fragments (Figure 5). The diameter of smaller grains (ooids, peloids, and intraclasts) commonly ranges from 0.5 to 2 mm and that of larger grains (oncoids) from less than 1 cm (typical) to several centimetres. Porosity in this lithofacies is fenestral, vuggy, and interparticulate. Some fenestral pores are infilled with brown metasomatic anhydrite. In places, the vuggy and interparticulate porosity is filled or lined with bitumen. Oolitic peloidal grainstones and packstones are interpreted to have been deposited in bank (shoal) environments.

b) Fossiliferous Peloidal Wackestones and Packstones

Fossiliferous peloidal wackestones and packstones also occur at various intervals in the Frobisher Beds. The lithofacies is characterized by peloidal grains and scattered shell fragments supported by a lime-mudstone matrix (Figures 6 and 7). The peloidal grains are generally less than 1 mm in diameter, well sorted, and often bonded by meniscus cement. In some locations, they are flattened parallel to bedding. The fossiliferous wackestones and packstones are generally pale grey in colour, although oil-stained beds are buff to brown. Porosity is commonly fenestral, vuggy, and/or interparticulate. Fenestral porosity is often filled with anhydrite, while vuggy porosity is either open, or lined with euhedral anhydrite. This lithofacies was probably deposited in back-bank to lagoonal environments.

c) Algal Lime Mudstones

Algal lime mudstones occur at various intervals within the Frobisher Beds, especially within the upper Frobisher Evaporite (lower Midale Beds) where they are interbedded with massive to nodular anhydrite. At many locations, increased gamma-ray readings suggest the presence of argillaceous material. Peloids, ooids, intraclasts, and/or shell fragments (typically less than 2 mm diameter) locally make up less than 5 per cent of some beds (Figure 8). Intercrystalline porosity dominates these grey to buff, commonly oil-stained rocks, but scattered vugs are also present in some places. Algal material, and/or brown metasomatic anhydrite are also commonly found in oil-stained core of this lithofacies. Algal lime mudstones are interpreted as algal marsh deposits.

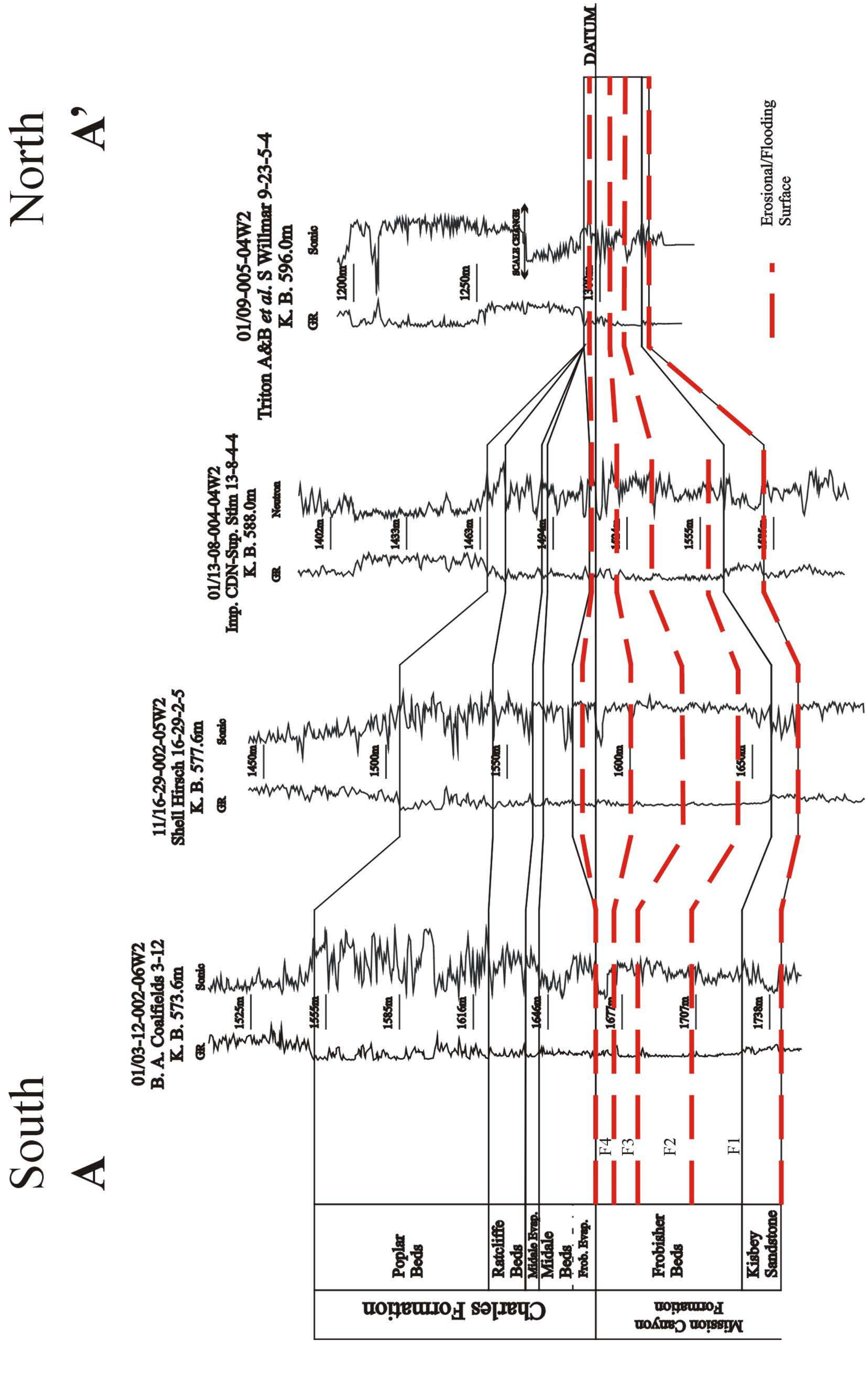

Figure 4 - Regional cross-section A-A' through the upper Mission Canyon Formation and the Charles Formation, showing the four transgressive-regressive cycles (F1 to F4) in, predominantly, the Frobisher Beds.

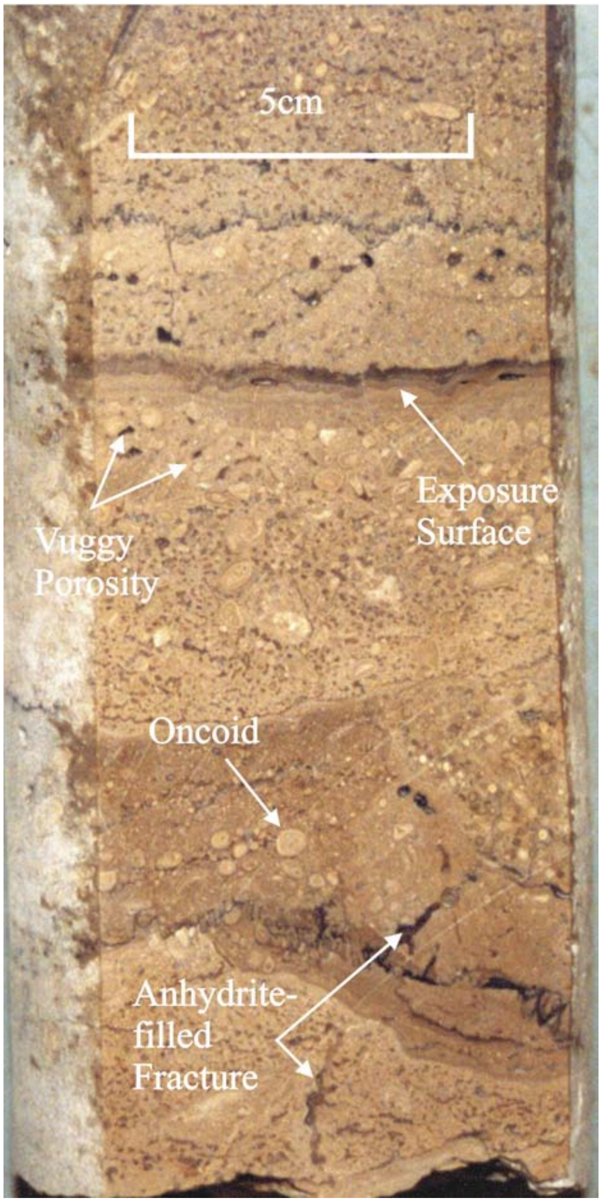

Figure 5 - Photograph of typical oolitic peloidal grainstones and packstones (lithofacies a) from location 1-29-4-4W2 (1394.6 m).

Figure 6 - Photograph of fossiliferous peloidal wackestones and packstones (lithofacies b) showing bivalve and coral fragments and a geopetal gastropod, from location 1-29-4-4W2 (1408.6 m).

d) Argillaceous Dolomitic Mudstones

Argillaceous dolomitic mudstones mostly occur toward the upper Frobisher Beds and are common in the lower Frobisher Evaporite. They are massive to well laminated and are off white to buff, the darker colour often due to oil staining. Porosity is generally intercrystalline, but is vuggy in some intervals. At some locations, scattered peloidal grains (typically less than 1 mm in diameter forming less than 5 per cent of the rock) or algal material and brown metasomatic anhydrite (Figure 9) are present. Within the Hastings and Frobisher evaporites, this lithofacies is associated with nodular anhydrite (chicken-wire anhydrite) or argillaceous lateritic mudstone (patterned carbonate). It is interpreted as tidal flat deposits.

Figure 7 - Photograph of fossiliferous peloidal wackestone and packstone (lithofacies b) showing fenestral and vuggy porosity, and an anhydrite-filled fracture, from location 15-20-4-4W2 (1390.7 m).

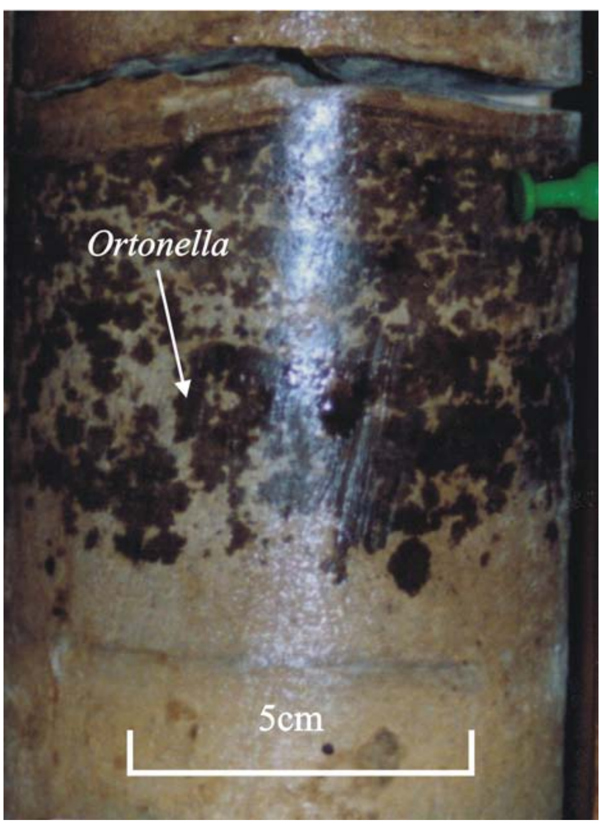

Figure 8 - Photograph of algal lime mudstones (lithofacies c) showing abundant** Ortonella **mixed with argillaceous calcitic mudstone, from location 11-17-4-4W2 (1407.6 m).

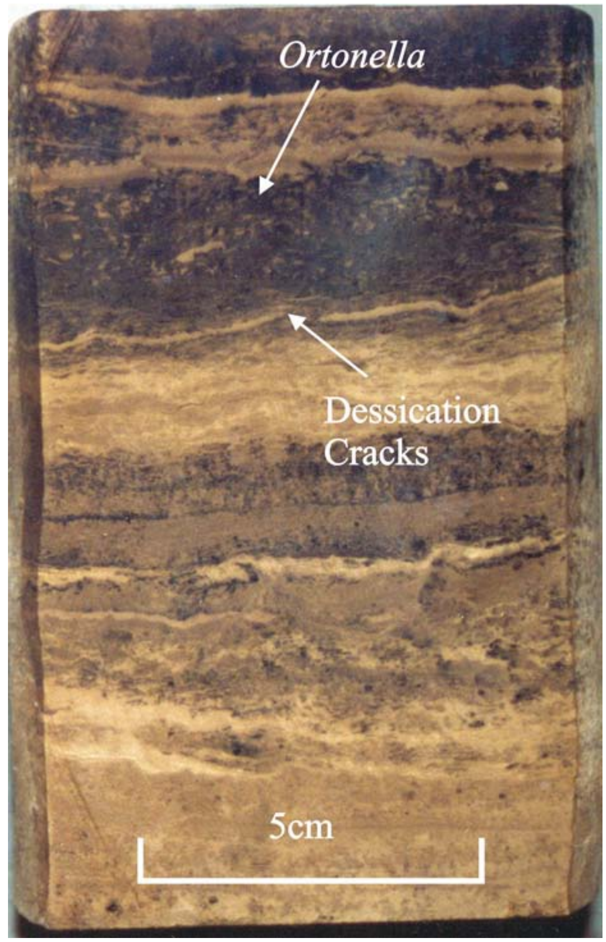

Figure 9 - Photograph of argillaceous dolomitic mudstones (lithofacies d) showing desiccation cracks and abundant** Ortonella**, from location 1-29-4-4W2 (1381.1 m).

e) Variable Nodular to Chicken-wire Anhydrites

This lithofacies (Figure 10) is found as the dominant rock type within the upper Frobisher succession where it forms the Hastings Evaporite and the lower Frobisher Evaporite. These evaporites are characterized by nodular anhydrite that is often partially replaced by argillaceous calcitic, dolomitic, and/or lateritic mudstones (chicken-wire anhydrite). Argillaceous dolomitic mudstones locally occur as stringers between anhydrite nodules and may be oil stained. The anhydrite ranges from white to grey to pink in colour, the variation possibly due to impurities in the brine during precipitation. Nodular to chicken-wire anhydrites are interpreted to have formed in a sabkha environment.

f) Argillaceous Lateritic Mudstones

Argillaceous lateritic mudstones typically occur within the upper Frobisher Beds and are also common within the overlying Frobisher Evaporite. In some locations (e.g. 1-25-5-6W2), they are present in lower zones of the Frobisher Beds. They are massive, laminated or mottled, are characteristically red to pink in colour, and have intercrystalline porosity (Figure 11). At some locations, this lithofacies is associated with argillaceous calcitic or dolomitic mudstone, carbonaceous material, or argillaceous green pyritic mudstone. In the Frobisher Evaporite, it is typically found with massive to nodular anhydrite (chicken-wire anhydrite). Argillaceous lateritic mudstones are considered to have formed as paleosols and terrestrial deposits.

The two more locally developed lithofacies within the study area are:

g) Argillaceous Fossiliferous Mudstones to Packstones

Argillaceous fossiliferous mudstones to packstones are present within two sub-parallel zones trending approximately southwest-northeast. They are best developed in well 7-21-4-6W2 where they make up most of the core. This lithofacies typically is massive in texture (Figure 12), buff to brown in colour, and contains scattered fossil fragments (centimetre-scale rugose corals, bivalves, crinoids, and ostracods) and argillaceous material (recognized by increased gamma-ray values on geophysical logs). Other associated grains are peloids and intraclasts, both normally less than 2 mm in diameter. The texture is dependent on the percentages of fossil fragments and grains that are present. The porosity of this facies generally appears to be intercrystalline. These muddy carbonates are considered to have accumulated in two depositional lows during a relative rise in sea level.

h) Pisolite Grainstones

This facies is found overlying oolitic-peloidal grainstones-packstones within lower intervals of the Frobisher Beds, and is characterized by moderately well sorted pisoids 0.5 to 2 cm in diameter (Figure 13). Faint traces of the precursor oolitic grainstones are visible in places. The pisoids are often bonded by

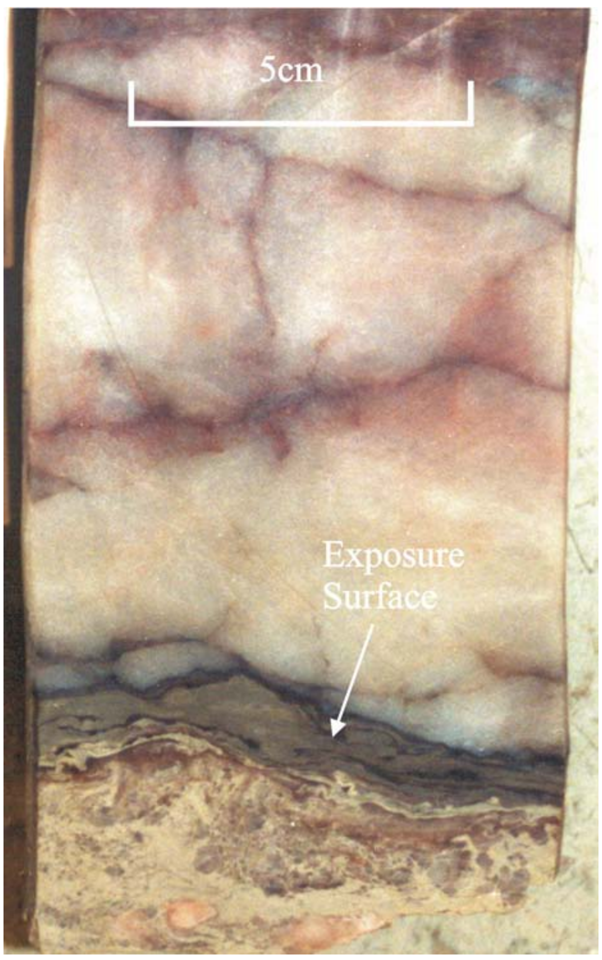

Figure 10 - Photograph of variable nodular to chicken-wire anhydrites (lithofacies e) showing exposure surface on underlying argillaceous dolomitic mudstones (lithofacies d), and typical lower Frobisher Evaporite nodular anhydrite, from location 1-29-4-4W2 (1379.7 m).

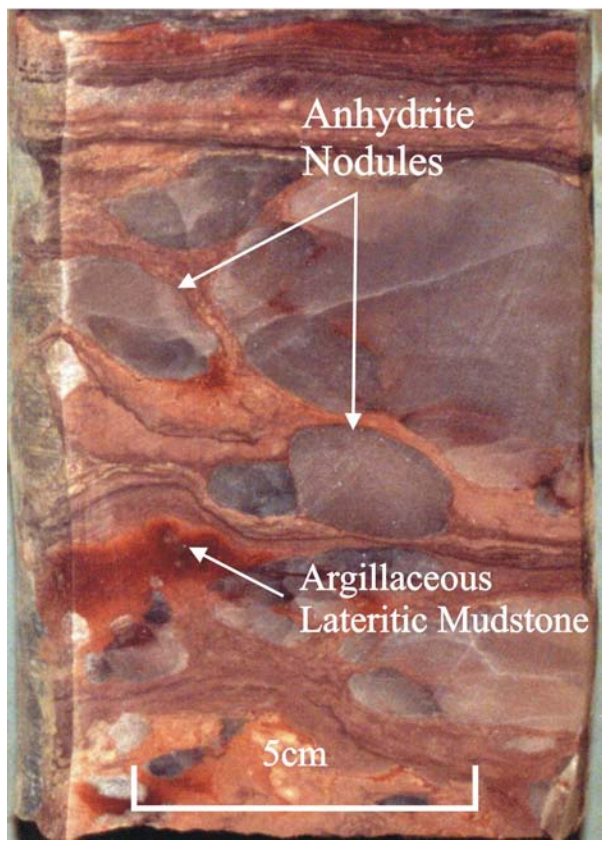

Figure 11 - Photograph of variable nodular to chicken-wire anhydrites (lithofacies e) interbedded with argillaceous lateritic mudstones (lithofacies f) commonly found within the middle Frobisher Evaporite, from location 1-29-4-4W2 (1374.2 m).

meniscus calcite cement and are typically buff in colour. Porosity is commonly interparticulate, and is either open (grainstone texture), or filled with calcite cement or white anhydrite (packstone texture). Pisolite grainstones are interpreted to result from vadose diagenesis of oolitic-peloidal grainstone-packstone banks (shoals) that were exposed during a relative sea-level fall.

The two southwest-northeast-trending depositional lows within the Frobisher Beds of the Steelman Field are sub-parallel to the Nesson Anticline. Along the flanks of these features, vertically offset fractures (Figures 14 and 15) are occasionally observed in core. They may be the result of reactivation of basement faults or salt dissolution within the Prairie Evaporite (Sereda and Kent, 1987; Mundy and Roulston, 1998; Kreis and Kent, 2000).

Figure 12 - Photograph of argillaceous fossiliferous mudstones to packstones (lithofacies g) showing bivalve fragments, anhydrite-filled vug, and pyrite grains. Taken from location 7-21-4-6W2 (1493.6 m).

4. Future Work

Possible revision of stratigraphic nomenclature within the Madison Group will be a major focus for future work. For example, the lower Midale Beds, as currently defined, contain the Frobisher Evaporite, although the lower two thirds of the Frobisher Evaporite form the supratidal facies of the uppermost cycle of the Frobisher Beds. The identification and correlation of the flooding surface above the supratidal facies of the Frobisher Evaporite is difficult where the photo-electric curve is not available. Also, the basal cycle of the Frobisher succession should include the

Figure 13 - Photograph of typical pisolite grainstones (lithofacies h) from location 15-15-4-6W2 (1492.7 m).

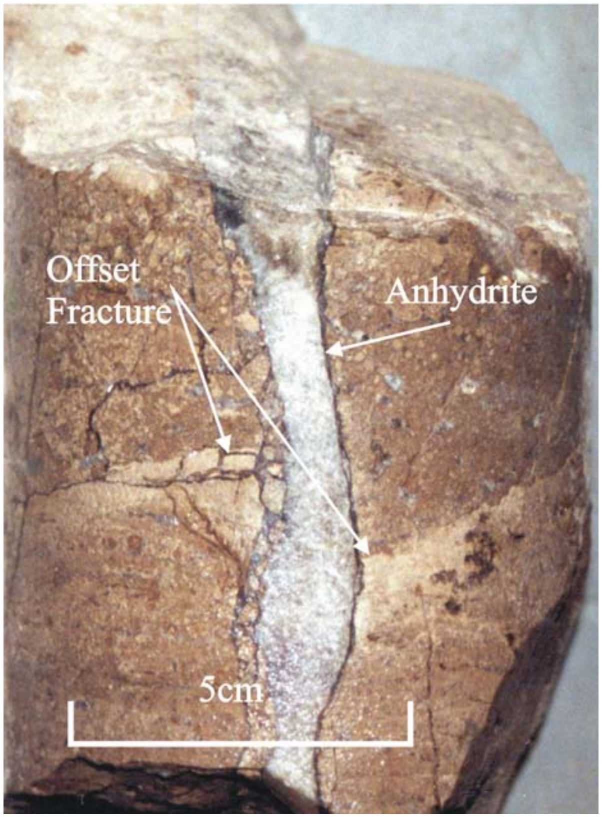

Figure 14 - Photograph of anhydrite-filled offset fracture, from 15-15-4-6W2 (1476.5 m).

Kisbey Sandstone, which is the initial transgressive deposit overlying the Alida unconformity.

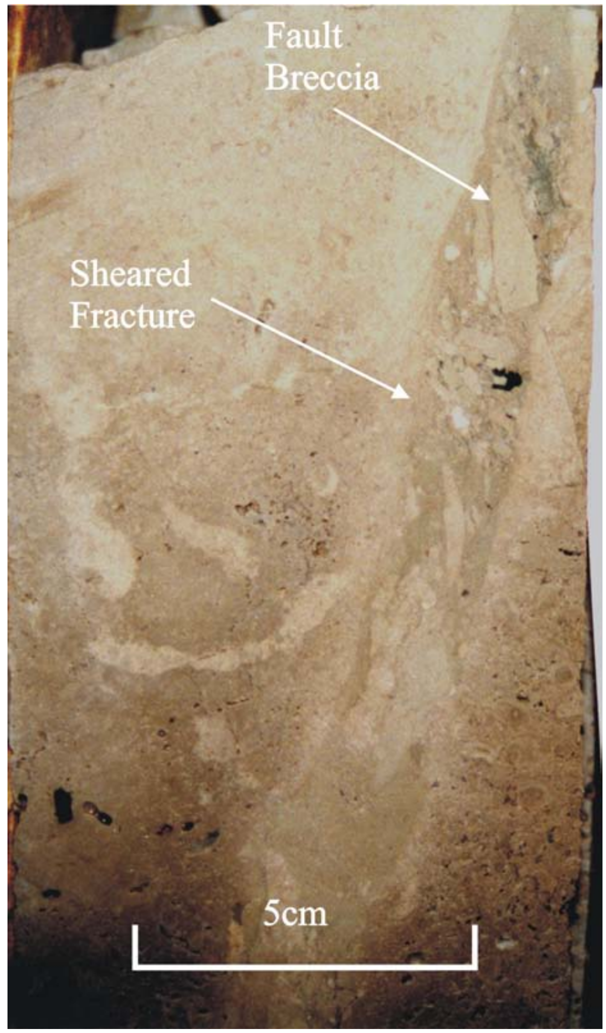

Figure 15 - Photograph of sheared fracture filled with brecciated material, from location7-33-4-5W2 (1426.5 m).

5. Conclusions

The cyclic carbonate-evaporite successions in the Mississippian Frobisher Beds and the Frobisher Evaporite at the Steelman Field were deposited within subtidal, intertidal, and supratidal environments. This complex progradational succession formed during four transgressive and regressive cycles that had significant effect on reservoir continuity.

6. Acknowledgments

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