Sedimentology and Ichnofacies, Uppermost Three Forks Formation (Fammenian), Williston Basin, North Dakota and Montana – A Storm Dominated Intrashelf Basin

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ABSTRACT

The recent economic interest in the unconventional Three Forks Formation in the Williston basin has allowed sedimentological analysis of this low porosity, low permeability mudrock dominated unit. A regional database of polished drill core slabs and petrographic thin sections allowed for detailed analysis of texture, sedimentary structures, and ichnology.

The uppermost Three Forks carbonate intrashelf mudstones facies consist of the following lithofacies: (F1) **disturbed claystones** that contain moderate abundance of mobile feeding traces and syneresis cracks; (F2) **laminated mudstones**, and (F3) **dolomudstones** that include the previous features plus escape burrows and opportunistic suspension feeding colonies. These facies demonstrate scouring, high depositional rate, storm, and wave features. Syndepositional deformation through dewatering, evaporite precipitation and dissolution and bioturbation is interpreted to produce (F4) **brecciated to distorted mudstones**. Storm-generated deposits are preferentially preserved over fair-weather deposits. Variable storm strength and resultant geomorphology can result in high vertical facies variability.

INTRODUCTION

Dumonceaux (1984) initially suggested for the Three Forks a predominance of wind-derived wave reworking in a shallow epicontinental sea. Recently workers have reinterpreted the Three Forks as a tide-dominated, intertidal to supratidal depositional system (Karasinski 2006; Berwick 2008; Gantyno 2010; Bottjer et al. 2011; Berwick and Hendricks 2011; Guttierrez 2013; Bazzell 2014). This seeming consensus belies problematic sedimentological features presented here. Extensive ancient epicontinental sea deposits covering cratonic settings are poorly understood and lack modern analogs. The low accommodation potential and subtle depositional slopes of less than 0.01° produce a broad lithofacies distribution that requires extensive data sets to develop a complete understanding of these broad shallow seas (Shaw 1964, Irwin 1965, Laporte 1969; Lukasik et al. 2000). Despite these complexities, understanding these systems is essential to the global interests in hydrocarbons associated with epicontinental carbonate platforms (e.g. Wang et al 1992; Bourquin et al. 1997; Ziegler 2001; Palermo et al. 2010).

Unlike modern carbonate platforms and ramps, epicontinental platforms lack sharp shelf breaks or continuous reef trends. This prevents shallow areas from being protected from swell, waves, and storms (Aigner 1985). Sedimentological data confirm that epicontinental platforms were indeed hydrodynamically unique from modern carbonate settings (Bertrand-Sarfati and Moussine-Pouchkine 1988; Bose and Chaudhuri 1990).

This study characterizes and interprets the petrologic features of Fammenian aged deposits contained in the sub-surface of Montana and North Dakota, USA. This provides information on the most landward preserved deposits of a larger carbonate platform system that have not been documented throughout the entire stratigraphic section at a regional intraself basin scale (Figure 1).

GEOLOGIC SETTING

The Late Devonian, Famennian transgression inundated a 1500 km2 area of the craton resulting in carbonate production and deposition along a slowly subsiding platform in the distal foreland basin with an overall declivity less than 0.005° (Peterhänsel and Pratt 2008) (Figure 1). The Palliser (Wabamum in subsurface) platform deposits include five broad facies belts (Halbertsma 1994; Peterhänsel and Pratt 2008). The four storm-dominated facies belts along the distal foreland basin from deepest to shallowest (northwest to southeast on the platform) include: the argillaceous mud, bioturbated mud, dasycladacean-crinoid meadow, and microbial mud belts (Peterhänsel and Pratt 2008). The most landward deposits during this time comprise a fifth facies belt of siliciclastic enriched sediments that comprise the Three Forks Formation and are preserved in the Williston basin (Figure 2).

METHODS

Visual examination of seventy-two slabbed and polished subsurface drill cores laid the foundation for detailed petrologic study. Thirty-nine cores were described in detail at a one meter to three centimeter resolution. High-resolution core photos done immediately after slabbing were compiled from a variety of sources. Two hundred petrographic thin sections were impregnated with blue epoxy to illuminate porosity. Dual staining with alizarin red-S and potassium ferricyanide allowed for differentiation of carbonate mineralogy. Samples were sorted by lithofacies and mineralogy and plotted to identify rock type.

A ternary classification for mixed detrital siliciclastic and carbonate mudstones is used (after Boak et al. 2013). Rocks with greater than fifty percent dolomite are called dolomudstones, greater than fifty percent clay are claystones, and greater than fifty percent quartz and feldspars (silicates) are considered siltstones or sandstones. Modifiers such as siliceous, dolomitic and argillaceous denote relative abundances of other components.

Ichnological elements are named either for their ethology, i.e., what the organism was doing within the sediment, or for the species name when the traces are distinct enough. The relative proportions of these traces are described using the bioturbation index (BI) of Taylor and Goldring (1993). In this scheme numerical grades range from zero to six, where zero corresponds to absent bioturbation and six to complete bioturbation where sediment is totally homogenized by biogenic activity.

STORM-DOMINATED SHALLOW, SCHIZOHALINE INTRASHELF BASIN LITHOFACIES ASSOCIATION

The uppermost Three Forks carbonate dominated interval comprises a set of lithofacies that are interpreted here to represent a shallow intrashelf basin that was storm-dominated and had fluctuating levels of salinity (Franklin Dykes, 2014); Franklin and Sarg, in press (Figures 2 and 3). This paper will focus on the carbonate facies of a larger mixed carbonate-siliciclastic-evaporite depositional system. Lithofacies are defined by sedimentary structures, primary lithology, biologic features and early diagenetic associations. In general, the upper Three Forks is

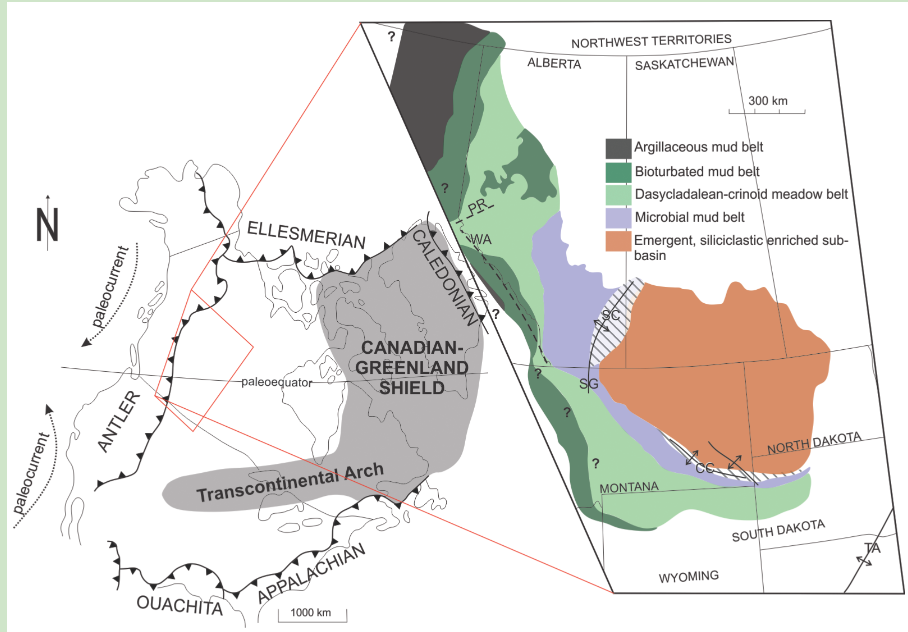

Figure 1: Upper Devonian paleogeography of the Three Forks Formation modified from Patchett et al. (1999) (left). Facies belts of the Palliser Platform (inset) modified from Halbertsma (1994) Root (2001) and Peterhänsel and Pratt (2008). Frasnian structures include the Peace River Arch (PR) and Western Alberta Ridge (WA). Major structures active during Three Forks time include the Sweetgrass Arch (SG), Swift Current Platform (SC), and Cedar Creek Anticline (CC). The Transcontinental Arch (TA) was emergent southwest of the greater platform.

predominantly dolomite with lesser amounts of clay and detrital silica. This facies association is composed of five lithofacies. Assuming a constant wave base, they are in order from deepest to shallowest: F1-disturbed claystones, F2-dolomudstones, F3-sandstones, F4-laminated mudstones, and F5-distorted mudstones (Figure 3).

F1: Disturbed Claystone

This dark green to grey facies ranges in composition from a claystone to a dolomitic siliceous claystone (Figure 4). The matrix is composed of illite clay. The dolomitic mud and siliceous silt may be mottled, preserved as a layer, or infilling syneresis cracks in this facies. The disturbed claystones either have a mottled texture or are moderately bioturbated (BI 3). Poorly preserved horizontal ellipses reflect mobile sediment ingesting organisms, fodichnia, and contribute to the mottled texture (Pemberton et al., 2013). Lined, horizontal, oblong and non-contrasting filled *Palaeophycus* are the most common and distinguishable traces (Pemberton et al., 2013). This facies also commonly contains syneresis cracks associated with the lamina and bed tops. In some cases, preserved normally graded laminations are present. This facies occurs in units that range from 10 centimenters to one meter in thickness. Units may be separated into individual beds on the scale of tens of centimeters by intervening dolomudstone layers. The upper and lower surfaces are sharp.

Origin: Disturbed claystones are interpreted as fluid mud deposits in a hypersaline environment. Common, silt-filled syneresis cracks at the tops of packages of these facies indicates that during mud deposition conditions were saline and were later followed by a freshening pulse associated with the overlying dolomudstones. Additionally, low diversity traces imply stressed chemical conditions. Poor preservation of fodichnia suggests that before compaction and dewatering, the substrate consistency was still “soupy” while infauna fed within it.

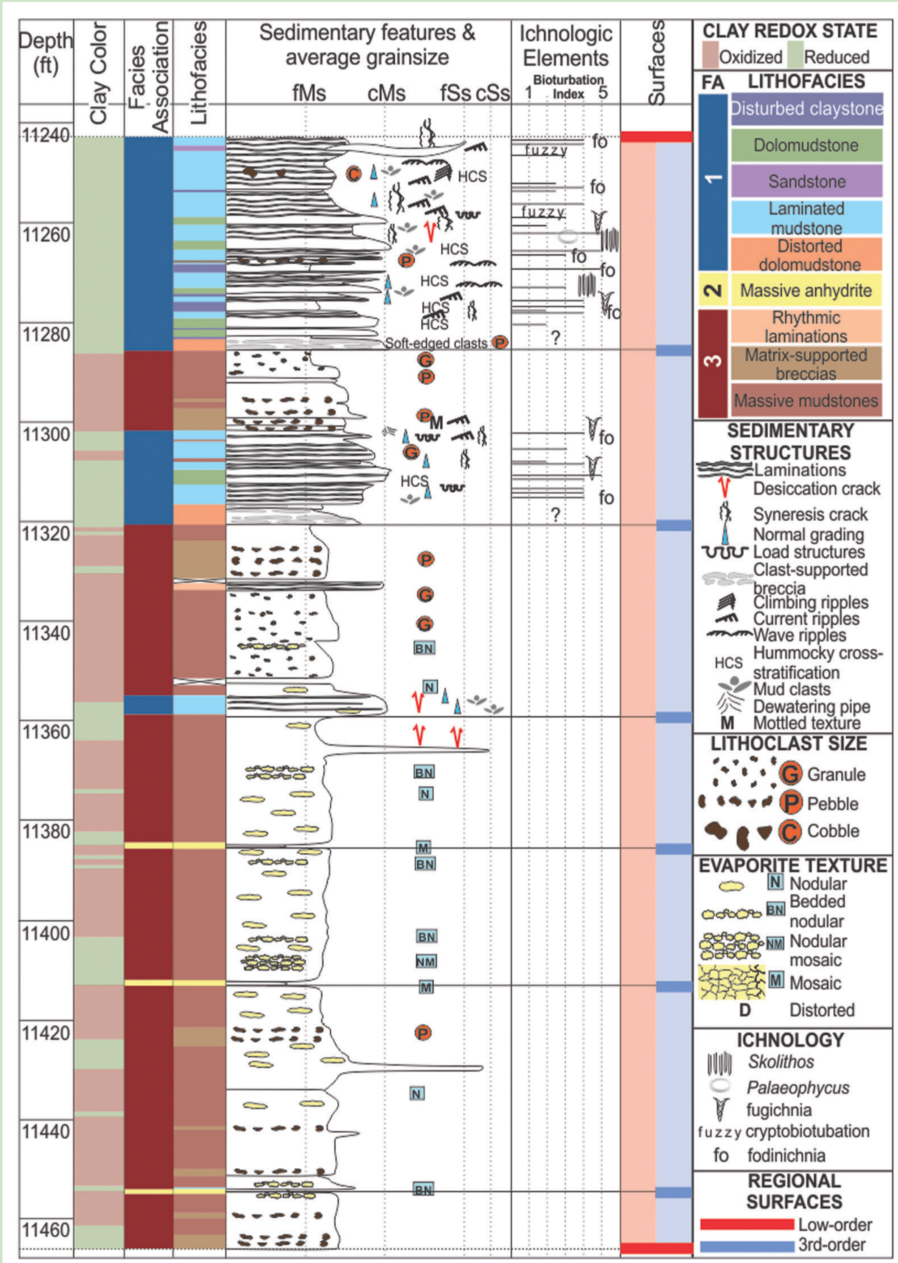

Figure 2: Stratigraphic section through the Hess Corporation Hovden 15-1H well demonstrating vertical facies trends through the section within the context of regional surfaces.

F2: Dolomudstone

This beige to brown facies is primarily a siliceous dolomudstone that ranges in composition up to dolomitic siltstone, and dolomitic very fine sandstone. Detrital components include silt to very fine sand sized, well-rounded, well-sorted, quartz and feldspars. These matrix constituents are commonly surrounded by small displacive crystals and nodules of dolomite and patchy anhydrite. The dolomudstone facies contains several sedimentary features in common with the laminated mudstone facies (Figure 5 and 6). Scour surfaces often amalgamate dolomudstone packages. Climbing ripples, and pinch and swell laminations with onlap interpreted as HCS, are common in this facies. Some current and oscillatory ripples are also present. Abundant syndepositional soft-sediment deformation includes ball-and-pillow, dish, and dewatering structures in addition to convolute bedding.

Ichnological elements are relatively diverse in this facies (Figures 5 and 6). Fugichnia, escape traces, defined by downward v-shaped lamina within a rectangular shape are sparse (BI 1) and commonly transect up through the sediment. These features form as an organism moves through overlying sediment and leaving a vacuum behind itself that pulls the lamina downwards (Buck and Goldring 2003). Dolomudstone and siltstone layers overlying muddy laminations commonly demonstrate a relationship between poorly preserved mobile feeding traces (fodinichnia) within the mud connecting up to overlying escape traces (fugichnia) moving out of the muddy layer through the dolomudstone. Fugichnia contrast with *Skolithos* burrows that are passively filled (Pemberton et al. 2013). Moderate to common (BI 3-4) *Skolithos* may dominate a package or individual traces ranging from 0.5 mm to 3 cm in width can be identified. Lined *Palaeophycus* are uncommon to moderate (BI 2-3) within discrete sections not associated with other areas. Rare (BI 1-2) "vertical series of concave upwards concentric laminae", are present indicative of *Teichichnus* (Pemberton et al. 2013) dwelling to feeding activity.

In general, this facies has much thicker layers of dolomudstones and dolomitic siltstones than the laminated mudstones. Dolomudstone beds range in thickness from five cm to two meters and may contain internal surfaces, clay drapes or layers (common), or soft clast lags (infrequent) that intermittently divide the package. The basal contact of these layers can be sharp and scoured, often overlying massive mudstones. The upper contact either grades into laminated mudstone or is sharp and scoured. Components of this facies have also been described in Christopher (1961), Dumonceaux (1984), Karasinski (2006), Berwick (2008), Gantyno (2010), Bottjer (2011), and Berwick and Hendricks (2011).

Origin: Hummocky cross stratification indicated by parallel

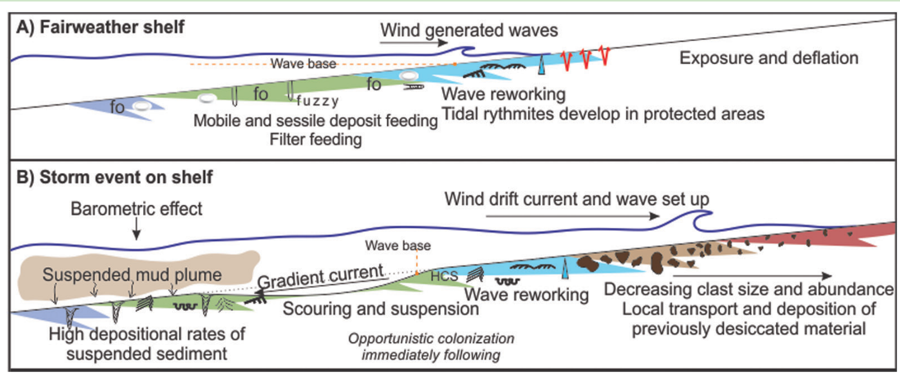

Figure 3: Schematic diagram contrasting fair-weather (A) and storm event (B) processes inferred from lithofacies for a storm-dominated shelf and adjacent mudflats (colors for lithofacies as in Figure 2). Times of increased bioturbation, minor wave interaction and desiccation in may be obliterated by storm-wave set up pushing the strandline landward, depositing intraclasts and muds. Lowered wave base significantly influences sediments producing wave-ripples and HCS. Off-shore directed gradient currents provide erosive power that may eliminate evidence of fair-weather activity, amalgamate sediment packages, and produce suspended muds that settle out leaving evidence of high depositional rates and organism escape.

to sub-parallel laminations with onlapping surfaces, provides strong evidence for storm-processes in the dolomudstone facies (Brenchley et al. 1979; Cant 1980; Mount 1982). Abundant scour features, though in places, difficult to identify due to the lack of contrast, indicates an onset of strong erosive power that is able to scour and erode the substrate, as well as carry soft clasts. Scouring becomes especially prevalent with the waning of the storm that produces off-shore directed currents (Brenchley et al. 1979; Hamblin and Walker 1979; Myrow 1992). The onset of landward wind drift currents also result in amalgamation of sediments (Aigner 1985).

Convolute bedding, dewatering structures, soft sediment deformation features such as ball and pillow structures and abundant climbing ripples all indicate high depositional rates of the dolomitic siltstones. Fugichnia supports this interpretation (Saunders et al. 1994; MacEachern et al. 2009). Mobile deposit feeding is favored over farming, grazing, and sessile deposit feeding. The nature of this bioturbation also supports high depositional rates (MacEachern et al., 2009) associated with storm deposition processes.

High frequency changes between distinct trace fossil assemblages at the lamina to thin bed scale indicate these erosive and high depositional rare storm events were episodic. The three assemblages include: the fair-weather traces, the escape traces, and the opportunistic recolonization traces. Relatively high abundance of mobile and sessile feeding traces, fodichnia, and *Palaeophycus* represent times of equilibrium when organisms are able to thrive within the sediments (Pemberton and Frey 1984; Pemberton et al. 1992). These fair-weather times are interrupted by

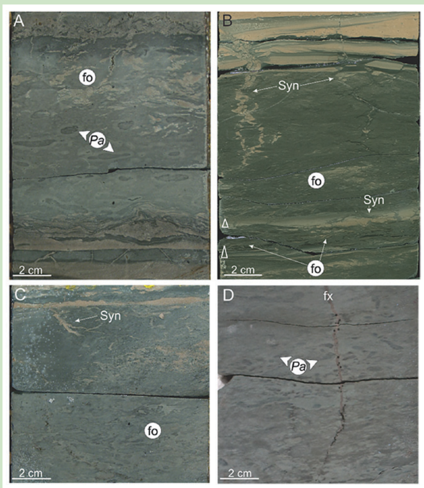

Figure 4: Key features of the disturbed claystone facies include syneresis cracks (Syn) and moderate biological disturbance (BI 3). A) EOG Resources, Inc. Sidonia 1-06H 8796 ft. (2681 m) demonstrating poorly preserved mobile feeding traces, fodichnia (fo), infilled with silt from above and definitive, lined and passively filled Palaeophycus *(Pa). This bed overlies a mudstone below. (Photo courtesy North Dakota Industrial Commission (NDIC)). B) Hess Corporation Hovden 15-1H 11265 ft. (3433 m) another example of fodichnia and syneresis. Note the normally graded laminations that occur intermittently within the package indicated by the triangles (Photo courtesy Hess Corporation). C) EOG Resources, Inc. Sidonia 1-06H 8802 ft. (2683 m) indicating biological disturbances, most likely fodichnia in association with syneresis. D) Whiting Oil and Gas Corporation Johnson 21-25 9805 ft. (2988 m) containing poorly preserved* Palaeophycus *and a late stage filled vertical fracture (fx) (Photo courtesy Whiting Oil and Gas Corporation.*

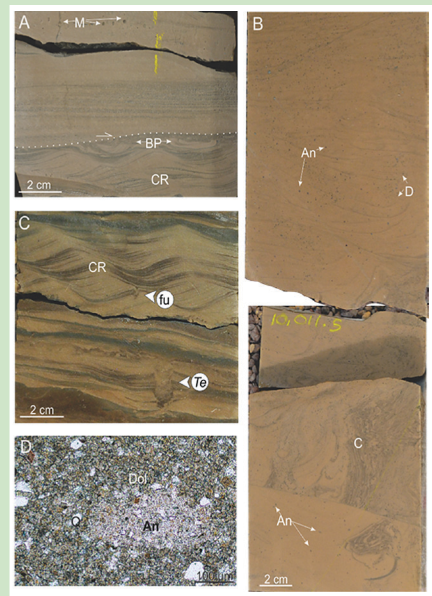

Figure 5: Common sedimentary features of dolomudstone (beige) highlighted by gray to black hydrocarbons. A) From Whiting Oil and Gas Corporation Braaflat 11-11H 9975.8 ft., (3040 m) shows climbing ripples (CR) covered with ball and pillow (BP) structures truncated by a scour surface. Hummocky cross stratification (HCS) with moldic porosity (M) overlies the truncation surface. B) Dramatic convoluted bedding (C) and dish structures (D). Disseminated patchy anhydrite cement centers (An) are light grey specs, from QEP Energy Company MHA 2-05-04H-148-91 10011 ft. (3051 m) (Photo courtesy NDIC). C) Uncommonly bioturbated (BI 2) example from Petro-Hunt, LLC Fort Berthold 152-94-13B-24-1H 10717 ft. (3266m) that demonstrates a Teichichnus (Te) burrow through some subparallel laminations beneath a downward V-ing escape burrow (fu) within climbing ripples (Photo courtesy NDIC). D) Plane polarized light photomicrograph of typical early, patch of anhydrite cement within the dolomudstone facies from Whiting Oil and Gas Corporation Cherry State 21-16TFH 11076 ft. (3375 m).

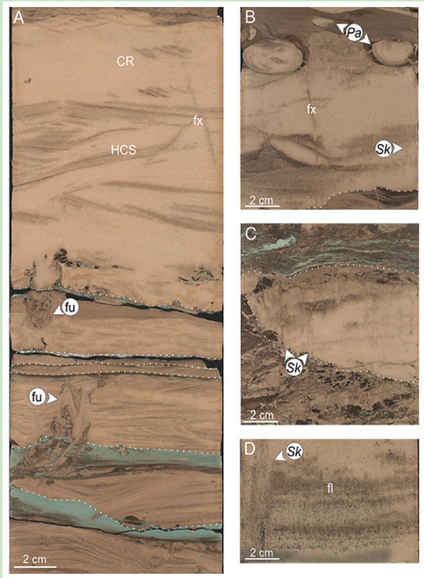

Figure 6: Typical ichnological elements and sedimentary structures of dolomudstones highlighted in Hess Corporation EN Person 11-22 by solid reservoir bitumen (Photos courtesy Hess Corporation). A) 10200 ft (3109 m) demonstrating current ripples (CR), hummocky cross stratification (HCS), and downward V-ing escape burrows (fu, fugichnia) (B.I. 2). B) 10187 ft. (3105 m) a moderately bioturbated **Skolithos** *siltstone bed with Palaeophycus (Pa) traces (BI 3-4). C) 10188 ft. (3105m) an example of a moderately bioturbated (B.I. 3-4) massive filled* **Skolithos** *dolomitic siltstone bed (bound by two sharp contacts of mud clast bearing intervals. D) 10193 ft. (3107m) a relatively large* **Skolithos** *trace on the left is adjacent to fuzzy laminations (fl) where pyrite and solid reservoir bitumen are abundant.*

storm events that erode and deposit sediments at high rates, affecting the benthic community. This necessitates organism escape (fugichnia) to survive the event. Following the event, opportunistic recolonization occurs, indicated by the high abundance of simple suspension feeding traces (Pemberton and Frey 1984; Pemberton et al. 1992). These concentrations of *Skolithos* suggest that after the storm event and during fair-weather conditions, waters were clear enough for suspension feeding. The dolomudstone deposits represent interbedded high depositional rate storm events, fair-weather reworking of these deposits, and subsequent erosion or additional high deposition rate storm events.

F3: Laminated Mudstone

This lithofacies is composed of green or red siliceous dolomitic claystone lamina that alternate with beige argillaceous siliceous dolomudstone or argillaceous dolomitic siltstone lamina (Figure 7). The detrital silt grains are composed of well-rounded and well sorted quartz and feldspars. These detrital constituents are well-mixed with dolomicrite. This facies is also identified in Christopher (1961), Dumonceaux (1984), Karasinski (2006), Berwick (2008), Gantyno (2010), Bottjer (2011), and Berwick and Hendricks (2011).

Dolomudstone lamina range from one to five cm thick, and claystone lamina range from one to two cm thick. Laminae contain a diverse suit of sedimentary structures (Figure 7). Scour surfaces bracket contrasting lithologies or amalgamate the same lithology packages. Normal grading from dolomudstones into claystones is common. Dolomudstone layers also demonstrate a range of physical structures including from most to least abundant: oscillatory, current, climbing, and bidirectional ripples. Parallel to subparallel, pinch and swell laminations, with onlapping lamina suggest hummocky cross stratification (HCS). Ripples or pinch and swell laminations in the dolomudstone often grade into the overlying claystone lamina.

Scour-bound packages of completely mottled sediments occur intermittently between physically reworked packages. These bioturbated packages (BI 4-5) contain mottled to poorly preserved, unlined fodichnia (Figure 7) or well preserved millimeter-scale horizontal traces (Figure 8). These traces on the larger end of the cryptobioturbation spectrum are suggestive of *Macaronichnus* (Pemberton et al. 2008; Pemberton et al. 2013). Diminutive, lobate, sheet-like spreite of *Zoophycos* (Pemberton et al. 2013) are rare (Figure 7).

The most common syndepositional

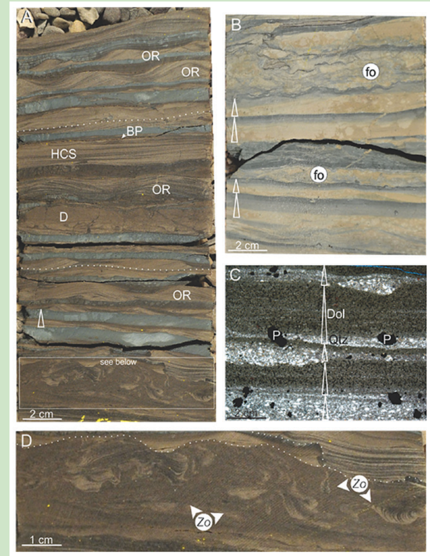

Figure 7: Typical features associated with the mudstone lamina of F4 highlighted with dark brown and black SRB. Normally graded laminations denoted by white triangles. White dotted lines indicate scour surfaces that amalgamate silts. A) From Enerplus Resources USA Corporation Danks 17-44H at 10685 ft (3257 m) showing oscillatory ripples (OR), suggestive hummocky cross stratification (HCS), ball and pillow stuctures (BP), desiccated intervals (D) (Photo courtesy NDIC). B) From QEP Energy Company MHA 2-05-04H-148-91 at 9993 ft (3045m) demonstrating well defined fining upwards laminations with two mottled units intermixed. These mottled units are interpreted as poorly preserved and abundantly bioturbated (BI 5) fodichnia (fo) traces (Photo courtesy NDIC). C) Thin section plane polarized photomicrograph of EOG Resources, Inc. Liberty 2-11H 9709 ft (2959 m) demonstrating successive scours followed by normally graded laminations of silt and dolomicrite, with disseminated pyrite (P). D) An inset of A indicated by white box. An amalgamated scour surface truncated the upper edge of an abundant (BI 5) bioturbated zone that displays diminutive **Zoophycos** *(Zo) traces within mottling.*

alterations of this facies include soft sediment deformation, desiccation and syneresis cracks. Soft sediment deformation features such as ball-and-pillow structures may be present at interfaces between mud and silt dominated units. Syneresis cracks are common. Desiccation cracks are infrequent. These two features can be distinguished based on morphology (Figure 9). Desiccation cracks are generally wider, not highly ptygmatic, and also taper in diameter

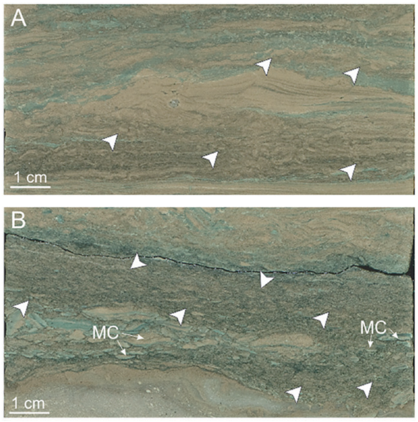

Figure 8: Abundantly bioturbated (BI 5) millimeter-scale horizontally elongate ellipses (white arrows) suggest mobile deposit feeding of diminutive fauna, most likely some type of nematode (Pemberton et al. 2008). A) Hess Corporation Hovden 15-1H 11244 ft. (3427 m). B) 11248 ft. (3428 m) mud clasts and ripples preserved amidst an abundantly bioturbated interval (Photos courtesy Hess Corporation).

downwards. Syneresis cracks are highly ptygmatic because they form before muds are dewatered, and they often intersect one another at random angles. Their diameters remain relatively consistent vertically.

Sharp surfaces are abundant within the laminations, and generally bound the upper and lower surfaces of units of this facies. Units are 10 cm to 10 m thick. Generally thicker units have high frequency interbedding at a meter scale with the dolomudstone lithofacies.

Origin: The laminated mudstone lithofacies is interpreted to represent shallow, storm and wave reworked deposits alternating with fair-weather conditions. Fluctuations between hyper- and hyposaline environments and periods of exposure are evident.

Common parallel to sub-parallel laminations with onlap indicative of hummocky cross stratification, represent storm-dominated events (Brenchley et al. 1979; Cant 1980; Mount 1982). Variations between current and oscillatory ripples reflect the range of processes including wave oscillations, geostrophic currents and density induced flows that develop with different magnitudes during storms (Arnott and Southard 1990; Myrow and Southard 1996). HCS, oscillatory, uni- and bi-directional ripples indicate significant wave-influence (de Raaf et al. 1977). Normal grading is present in some lamina laminations suggesting suspended load deposition with waning storm-generated currents (Reineck and Singh 1972; Pedersen 1985; Schieber 1990) (Figure 7C). Common transition from hummocky cross stratification to claystone lamina also suggests waning flow associated with these storm events.

Abundant scour surfaces attest to the erosive potential of these storm events where landward wind drift currents and off-shore currents both can generate such features (Aigner 1985). Soft pebble clast deposits associated with this facies may be generated in a similar manner.

The common biogenic reworking of lamina alludes to fair-weather processes. Fodichnia, mobile feeding traces, and sessile feeding traces such as *Zoophycos* with elevated abundance of reworking indicate that in between storm events there was sufficient time for these infauna communities to move in and thrive in the sediment (Pemberton and Frey 1984). The presence of some fair-weather deposits within abundant evidence of storm deposits attests to the episodic nature of the storm events.

Ball-and-pillow features and climbing ripples indicate high depositional rates. Irregular occurrences of syneresis and desiccation features suggest episodic exposure, and salinity fluctuations.

F4: Distorted and Brecciated Mudstone

The distorted and brecciated mudstone facies is composed of beige to brown argillaceous siliceous dolomudstone to argillaceous dolomitic siltstone that commonly form clasts, and variable amounts of green siliceous dolomitic claystone. Detrital components are well-rounded to well-sorted silt-sized quartz and feldspar grains. The overall appearance of the distorted mudstone facies is a fitted appearance of dolomudstone to siltstone clasts and mottles or matrix with variable amounts of claystone. This facies includes a variety of associated distinct textures including clast-supported breccia, and mottled textures to stratiform clasts. These textures may intermix vertically within single sections of drill core.

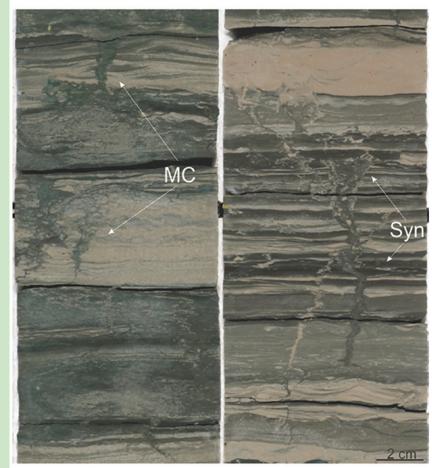

Figure 9: Contrasting nature of mud cracks (MC), downward tapering versus compacted and cross-cutting syneresis cracks (Syn), both of which are common, from Whiting Oil and Gas Corporation Chitwood 44-36TFH 11075 and 11077-78 ft (Photos courtesy Whiting Oil and Gas Corporation).

The distorted mudstones demonstrate a range of textures indicating ductile and brittle deformation (Figure 10). The pebble-sized clasts generally have contact with one another, are fitted, moderately sorted, and angular. Dewatering structures in this facies are defined by upward v-ing angular clasts appearing to have ductile response and deformation (Figure 10A) (Buck and Goldring 2003). Tightly packed angular, sharp-edged clasts with minimal matrix indicate brittle deformational responses (Figure 10B). Angular, fitted, ductile deformed clasts ranging to mottled textures also are common (Figure 10C). “Clasts” or layering may not always form coherent regular layers and appear mottled (Figure 10C).

Three syndepositional alteration features associated with the distorted dolomudstones include cone-in-cone pyrite growth (Figure 10A and 10B), gas bubble escape, and synsedimentary evaporites. Preserved synsedimentary evaporites appear to push apart, distort, or separate dolomudstone and claystone layers. Cone-in-cone pyrite in underlying massive mudstones are inferred as syndepositional features related to the downward movement of supersaturated fluid gradients associated with these stratiform to clast-supported breccias (Carstens 1985). Gas bubble escape features (Berner 1971; Martens and Val Klump 1980; Santschi et al. 1990) are also associated with this breccia facies and result in brittle and ductile deformation features.

The distorted dolomudstone facies is bound by sharp lower surfaces and grades into claystone and siltstone laminations or into dolomitic siltstone. Packages can range from 10 cm to 2 m in thickness, with variable internal heterogeneities.

Origin: Distorted and brecciated mudstones are interpreted to have formed through a variety of in-situ processes, and were not formed by clast transport. Fitted, angular, soft- and sharp-edged clasts and preserved but deformed lamina indicate in-situ processes. Based on sedimentological evidence, mechanisms of deformation to produce the distorted mudstones include dewatering, syndepositional evaporite precipitation and dissolution, bioturbation, soft sediment deformation, and gas escape. Variable proportions of these mechanisms in concert can produce a wide range of textures.

This facies is interpreted as early deformed laminated mudstones and dolomudstones based on composition and association with these other facies. Dewatering pipes captured in core associated with ductile soft-edged clasts imply the importance of this process. Dewatering and soft sediment deformation features in the laminated mudstones and dolomudstones indicate the role of high deposition rates in this depositional system.

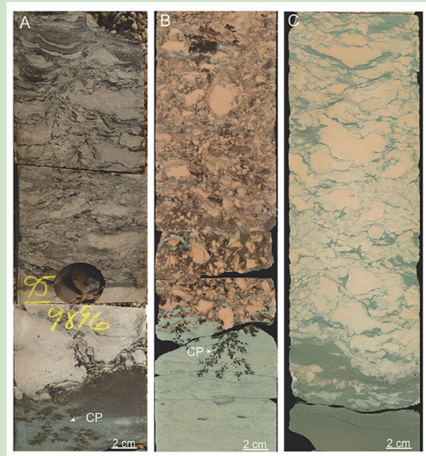

Figure 10: Textural features of distorted dolomudstones. All clasts are angular, fitted, in the pebble to cobble size range. A) Headington Oil Company LLC Sakakawea Federal 13X-35 9895-9896 ft. (3016 m) (Photo courtesy NDIC) with upwards curving, primarily ductile responding siltstone clasts due to dewatering. Compacted, cone-in-cone dendritic pyrite (CP) showing downward growth into underlying mudstone. B) Hess Corporation EN Person 11-22 10212 ft. (3112 m) with a distinct dendritic, cone-in-cone structure (CP) developed in the underlying mudstones. This siltstone breccia indicates brittle deformation with highly angular and sharp clast boundaries (Photo courtesy Hess Corporation). C) Ductile deformation producing large, very angular siltstone clasts in Hess Corporation Hovden 15-1H 11282 ft. (3439 m) (Photo courtesy Hess Corporation). Contacts around clasts are highly angular with soft-edged clast boundaries.

DEPOSITIONAL MODEL

The connection between the intrashelf Williston basin and the Palliser carbonate platform was presumably variably restricted through time due to syndepositional structural movement along the Sweetgrass Arch and Swift Current structural complex (Figure 1). Schizohaline, storm-dominated developed in the basin and at the basin margin. Ephemeral to seasonal and unconfined and confined fluvial flows over the mudflats provided siliciclastic sediments and freshwater inputs to the basin through time. Rapid changes in water chemistry are not unusual in restricted intrashelf basins that get flooded by heavy rains carrying freshwater and detrital material and that undergo periods of drought (Folk and Siedlecka 1974).

The Three Forks Formation carbonate lithofacies exhibits a range of sedimentary textures and proportions of lithologies in a mixed sedimentary system in an epicontinental intrashelf basin (Figure 3). These represent storm event deposits with some preserved fair-weather elements in a shallow intrashelf basin with fluctuating salinities. Green illitic ***claystones*** contain distorted *Palaeophycus* and fodichnia traces. This facies is uncommonly preserved and may contain syneresis cracks. The low abundance and diversity of traces and syneresis cracks indicate a harsh chemical environment with changes between hyper and hyposaline. ***Laminated mudstones***, 1-5 cm thick, contain infrequent, abundantly bioturbated layers with mobile and sessile feeding traces. These layers are interbedded with layers containing oscillatory, current, and climbing ripples, hummocky cross stratification, and normal grading. There are abundant scour surfaces within this facies. Syneresis, desiccation and soft pebble conglomerates are associated with this facies. These features imply fair-weather processes occasionally preserved within storm-dominated dominated deposits. High frequency changes in salinity and base level result in distortion of these fabrics and associated conglomerates. Laminated mudstones and ***dolomudstones*** often contain discrete layers of distorted mobile feeding traces associated with overlying escape traces. Additionally, dolomudstones contain cryptobioturbation and *Skolithos* beds. All of these ichnological elements demonstrate the interplay between fair-weather communities, escape events, opportunistic recolonization and ultimate return to fair-weather processes. Additionally, dolomudstones contain abundant evidence for high depositional rates in climbing ripples, soft sediment deformation features, convolute bedding and dewatering features. Storm processes are evident in hummocky cross stratification and ripple structures. ***Distorted and brecciated mudstones*** are interpreted to be deposited as laminated mudstones and dolomudstones. Syndepositional alteration occurred through dewatering from high depositional rate events, evaporite precipitation and dissolution associated with the schizohaline setting, and possibly bioturbation.

ACKNOWLEDGEMENTS

The authors would like to thank Steve Sonnenberg and the Colorado School of Mines Bakken Consortium for their financial support of the first author in her initial work on this project; to Lyn Canter and Mark Sonnenfeld at Whiting Oil Company for their encouragement and providing access to core material; and to the North Dakota Industrial Commission for providing access to core, and core photos.

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Accepted June 2017