Waulsortian Lithofacies of the Mississippi an Souris Valley Beds (Lodgepole Formation), Williston Basin, Southeastern Saskatchewan, Canada

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Abstract

Waulsortian lithofacies identified in the subsurface of the Williston Basin of southeastern Saskatchewan are contained in the slope-to-basin transition of the Souris Valley Beds (Lodgepole Formation). Cores from three wells, 07-11-013-30W1M, 12-08-009-30W1M and 05-07-009-30W1M, are characterized by four objective (OL) and subjective (SL) lithofacies: interbedded bryozoan grainstone-packstone and wackestone-packstone (OL1), mud-mound core (SL1); crinoidal and stromatactis mudstone-packstone (OL1), mud-mound drape (SL2); rubified crinoidal mudstone (OL3), saprolitic mud-mound drape (SL3); and cherty dolostone (OL4), pedogenic groundwater dolocrete (SL4). These lithofacies reflect the evolution of carbonate accumulation from deep-water settings to pedogenic modification as a result ofsubaerial exposure. Lithofacies 1 (OL1/SL1), the mud-mound core fades, was analyzed further with the aid of optical microscopy, elemental microprobe WDX analyses and stable-isotope mass spectrometry. OL1/SL1 was chosen for these analyses because it is the main reservoir elsewhere in the Williston Basin and is the least modified by pedogenic alteration.

Around the world, Waulsortian accumulations comprise sparry lime mudstone lithosomes with scattered crinoid and bryozoan fossils. Lithosomes have a variety of depositional geometries ranging from tabular where they lacked relief over the surrounding seafloor, to mounded where they had significant relief on all sides above the surrounding seafloor, to clinoforming sheets that had relief over the surrounding seafloor but grew laterally and in a preferred direction. The three Saskatchewan cores examined in this study have the characteristic Waulsortian sparry lime mudstone lithofacies, and have been interpreted by other workers to represent mounded accumulations. These cores contain abundant crinoids and bryozoa, organisms that, in life, were filter-feeding and would have baffled currents, assisting in the trapping and stabilizing of muddy particulate materials. They would not, however, have provided a rigid organic framework. In this context, therefore, Waulsortian mounds were stabilized and aggraded by biologically mediated sediment trapping. This trapped sediment became firm by precipitation of syndepositional calcite cement in early, complex cavity systems that we believe were products of fluid venting and seeping that originated below the mounds. Later, as particulate material continued to settle in the immediate area of the mound, fluids vented through the mounds.

In the Saskatchewan mounds, calcite cements filling these early, complex cavity systems are common and typically are characterized by three phases of spar: Phase 1 - neomorphosed, bladed, dusty calcite; Phase 2 - neomorphosed, multigenerational, fibrous, dusty calcite; and Phase 3 - equant, clear calcite. Phase 1 spar binds grainstones and packs tones and nodular micrites. Phase 2 cement infills vugs, cross-cutting veins and fissures. Phase 1 and 2 cements together account for greater than 50% of the total volume of the mound and must have played an important role in maintaining the relief of the mound. They were formed early in any given mound's development. We interpret the distribution and arrangement of phase 1 and 2 spars in continuous fissure and vein systems to be an infill of conduits through which fluids exited the mounds. Active venting of fluids and expulsion of materials onto the seafloor would have contributed to the development of the mounds, provided an environment where filter-feeding organisms would have thrived, and led to synsedimentary cementation of surrounding sediments.

Waulsortian mud-mounds are known to be prolific petroleum reservoirs in the Williston Basin with production from them starting in 1993 when Conoco developed the Dickinson Field, North Dakota. Since the initial find, several additional fields have been discovered in the Lodgepole Formation of North Dakota. This type of play yields wells that typically produce 1000 to 2500 bbl (ca. 160 to 400 m^3) of oil per day with reserves of 0.5 to 3.0 million bbl (ca. 79,500 to 477,000 m^3) oil. To date, however, no Waulsortian mounds in southeastern Saskatchewan have shown suitable reservoir characteristics, but further research on controls of porosity and additional exploration in this area for undiscovered Waulsortian mud-mounds could create a new Souris Valley Beds/Lodgepole play capable of adding substantial reserves. In this context, in the Williston Basin, Waulsortian mud-mounds are geologically interesting and a potentially productive play when conditions are right. Detailed geological studies that assist in unravelling their origin and their development into reservoirs are needed.

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1. Introduction

Waulsortian lithofacies and lithosomes often occur as lense-like accumulations of carbonate mudstone and spar with abundant crinoid and bryozoa fossils (Wilson, 1975; Lees and Miller, 1995). Across the globe, in outcrop and in core, Waulsortian mud-mounds have been recognized and described from Lower Carboniferous (Mississippian) marine rocks (Wilson, 1975; Lees and Miller, 1995; Pratt, 1995; Krause *et ah,* 2004). Recently, in their detailed study of Waulsortian build-ups, Lees and Miller (1995, p259) have cautioned that the term "Waulsortian mud-mound" has to be applied with care and that a Waulsortian mud-mound is a built-up accumulation "dominated by an association of polymuds with at least one of the grain-type assemblages A-D[3] (and the accompanying macrofaunas) and lying in the upper Tournasian or lowermost Visean". Notably this new definition seems to downplay the association of carbonate mudstone and spar. Significantly, the Waulsortian lithofacies in the subsurface of the Williston Basin of southeastern Saskatchewan first described by Sereda and Kent (1987) and identified by them as Waulsortian mud-mounds not only match this newer definition, but also the original concept identified in the opening sentence.

The Saskatchewan Waulsortian lithofacies are thought to have developed as part of a prograding carbonate-shelf to shale-basin sequence and occur in the lower slope of this transition (Figure 1) (Kent, 1984; Sereda and Kent, 1987; Kent 1994; Kent and Christopher, 1994; Richards *et al,* 1994). The slope deposits that enclose the mud-mounds are rhythmically bedded, fining-upward couplets of skeletal grainstone, packstone and wackestone that were interpreted by Sereda and Kent (1987) and Kent and Christopher (1994) to be tempestites. They also identified the basinal deposits as being organic rich, lime-mudstone laminites, interbedded with thinly bedded, argillaceous lime mudstone and chert layers (Sereda and Kent, 1987; Kent and Christopher, 1994). Importantly, the Waulsortian mud-mounds are not confined to southeastern Saskatchewan and occur elsewhere in the Williston Basin in outcrop and subcrop in similar depositional settings (Cotter, 1965; Stone, 1972; Sereda and Kent, 1987; Montgomery, 1996).

[3] Grain type assemblages A-D of Lees and Miller (1995, their Figure 21) include crinoids, fenestrate bryozoa hash and fronds, hyalosteliid spicules, and foraminifera. Assemblages A-C accumulated in the aphotic zone while assemblage D was deposited in the photic zone.

2. Methods

a) Core Logging

All samples analyzed were obtained from drill core stored at the Subsurface Geological Laboratory of Saskatchewan Industry and Resources in Regina. Cores logs for the samples studied are available in Miller (2006).

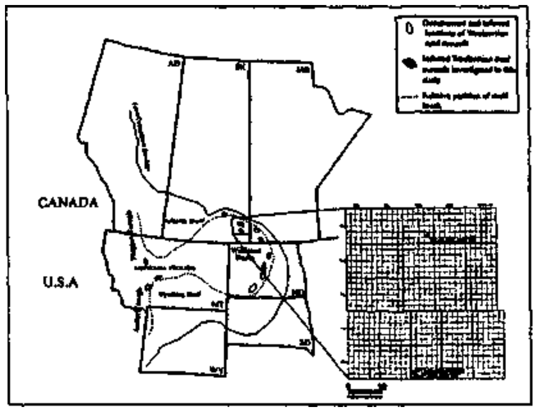

Figure 1 - Location, index and paleogeographic maps. Index map of the Northwest Plains of North America and location map of southeastern Saskatchewan emphasizing the position of three cored wells examined for this study. The erosional edge of Lower Carboniferous rocks in die Western Canada Sedimentary and Williston basins, the relative position of the Lower Carboniferous shelf break, and the locations of mud-mounds with Waulsortian lithofacies that have been identified in outcrop and in the subsurface are also indicated on the index map (figure modified from Sereda and Kent (1987) andBlakey (2006)).

b) Stable-Isotope Analysis

Carbonate powders for carbon and oxygen stable-isotope analyses were milled from selected areas with a hobby drill. Isotope measurements were conducted at the Isotope Science Laboratory (ISL) at the University of Calgary (Alberta, Canada). Results are reported in per mil (‰) using the usual 8 (delta) notation relative to IAEA standards:

(0 8_{sample}(%o) = {(.RswJRsUntei) -1 }x1000

where *R* is the $^{13}C/^{12}C$ or $^{18}0/^{16}0$ ratio of the sample or an internationally accepted standard. $6^{13}C$ and 8 0 are reported relative to PDB. Accuracy and precision of the measurements were assured by repeated analyses of reference materials and by calibrating all measured carbon and oxygen isotope ratios to 8 C-NBS 18 = -5.1±0.1‰, $8^{13}C$-NBS 19 = 1.95‰ (b.d.), $8^{3}C$-IAEA CO-1 = 2.5‰, $8^{13}C$-IAEA CO-8 = -5.8‰, $8^{13}C$-IAEA CO-9 = -47.1‰; and $8^{18}0$-NBS 18 = -23.2±0.1‰, 8^{,8}0-NBS 19 = -2.2%o (b.d.), 5^{18}0-IAEA CO-1 = -2.4±0.1%o, 5^{18}0-IAEA CO-8 = -22.7±0.2%o, 8^{,8}0-IAEACO-9 = -15.6±0.2%o.

We describe in this paper the lithological and penological characteristics of four Waulsortian lithofacies that are typically developed in the subsurface of southeastern Saskatchewan, and we provide preliminary stable-isotope and microprobe analyses of components of these lithofacies.

c) Microprobe Wavelength-Dispersive X-ray Analysis

Microprobe analyses were conducted at the University of Calgary Laboratory for Microbeam Analysis (UCLEMA) with a JEOL JXA-8200 electron microprobe using a 15 kV accelerating voltage, beam diameter 5, 20 nA beam current, peaks were measured for 20 s, and 10 s on bkg+ and bkg-. Standards used were calcite for Ca, apatite for P, Kakanui hornblende for Fe, almandine for Si and Al, barite for Ba and S, dolomite for Mg, strontianite for Sr, orthoclase for K, spessartine for Mn and pyromorphite for Pb. X-ray mapping conditions were 15k V and 50 nA focused beam, pixel resolution was 1024 x 1024, pixel size 12 urn and dwell time 12 ms per pixel. No standards are required for X-ray mapping, except to establish peak positions.

3. Lithofacies

Waulsortian mud-mound deposits, as highlighted by Lees and Miller (1995), are accumulations that contain a variety of lithologies and include different depositional geometries. Mounded accumulations are only one of a number of lithosomal geometries recognized, others including "tabular", "knoll-form" and "sheet-form" deposits (Lees and Miller, 1995, pi95-197). The lateral lithosomal relationships are also an integral component in the development of transitional geometries of Waulsortian deposits, because flanking lithofacies may be greatly reduced or absent, or may be common and extensive (Lees and Miller, 1995). These authors indicate further that Waulsortian accumulations are not always muddy throughout. Thus to establish the nature of these accumulations, it is necessary to identify at the outset the lithofacies that comprise these accumulations. In this study, we recognize lithofacies following a set of objective criteria that include the following: bedding, colour, composition, grain size, fossils (both body fossils and trace fossils), mineralogy, sedimentary structures (physical, biological and diagenetic) and sorting. Each lithofacies is identified with an **objective name** that is based on these observational criteria, and a ***subjective name*** that is contingent on the interpreted depositional environment and/or subenvironment.

In southeastern Saskatchewan, three wells (07-11-013-30W1M, 12-08-009-30W1M and 05-07-009-30W1M) intersect and core Mississippian deposits of the Souris Valley Beds. We have identified the following four **objective** and ***subjective*** lithofacies from these cores: **OL1** - Interbedded bryozoan grainstone-packstone and wackestone-packstone, *SL1 - Mud-mound core;* **OL2** - Crinoidal and stromatactis mudstone-packstone, ***SL2*** *- Mud-mound drape;* **OL3** - Rubified crinoidal mudstone, ***SL3*** *- Saprolitic mud-mound drape;* and **OL4** - Cherty dolostone, ***SL4*** *- Pedogenic groundwater dolocrete.*

a) Lithofacies 1

Objective Name (OL1): Interbedded bryozoan grainstone-packstone and wackestone-packstone.

Subjective Name *(SL1): Mud-mound core.*

Description: Rocks of this lithofacies are creamy to light tan in colour with cements typically displaying lighter colours than the surrounding mudstone. Common bioclastic fossil fragments are crinoids and fenestrate biyozoa. While bryozoa fragments typically are comminuted and millimetres in size, large fronds that are several square centimetres in diameter are also present. Crinoids are represented by ossicles that commonly are 5 to 15 millimetres in size. Both bioclasts comprise 2 to 20% of the rock and are poorly sorted. Other less common fossils include rugose corals, brachiopods and ostracods.

Carbonate mudstone, while typically lacking distinct bedding, appears to be multigenerational and, in places, occurs as subrounded clasts or nodules surrounded by calcite cement. Mudstone clasts or nodules often have reddish centres and light grey to pale green reduction haloes (Figure 3). Also common are multiple zones of centimetre-scale vugs and fissures that often are interconnected. Cement typically has precipitated from free surfaces provided by mudstone walls and bioclasts. The cement is multigenerational and most often consists of crystalline blades and, less frequently, fibres. Cements are dusty, dirty in appearance and contain abundant inclusions. Identification of this lithofacies is based on the predominance of calcite cement (> to 30% cement). While micrite and bioclasts comprise 5 to 20% and 5 to 30%, respectively, calcite cement accounts for 40 to 85% of the primary components. Late fractures occasionally cross-cut the rocks and are often filled with anhydrite or gypsum.

Interpretation: Lithofacies 1 represents the core of the Waulsortian mud-mounds and is typical of similar lithofacies identified by other researchers who have examined Waulsortian mud-mounds elsewhere in the Williston Basin and the world (Johnson, 1995; LeFever *et al,* 1995; Lees and Miller, 1995; Longman, 1996). Sediment accumulation must have taken place in areas of low current power because carbonate mud is abundant and large bryozoan fronds are well preserved. Had these materials had been exposed to strong wave agitation or current activity, not only would carbonate mud have been washed out and removed, but fragmentation and comminution of bryozoan fronds would probably have been commonplace. On the other hand, areas rich in cement seem to represent an interconnected system of passages that opened following the deposition of carbonate muds and

Figure 2 - Depositional and early diagenetic relationships observed in lithofacies 1 between micrite and primary calcite-cement phases 1 and 2. While phase 1 cement surrounds micrite and fossils stabilizing the rock framework, phase 2 cements are found infilling fissures and veins. Label A points to a micrite clast that has a smooth roof and a digitate base, a pattern that is common for micrite masses in this rock type. Abundant geopetals are useful to define stratigraphic orientation. Polished core slab, well 12-08-009-30W1M, sampleWOS, depth 921.25 to 921.43 metres.

accompanying larger particles, possibly as a result of erosion by fluids that vented through the mounds. In this instance, the mounds are considered to have formed as drifts of fine-grained carbonates that were colonized and stabilized by filter-feeding crinoids and bryozoa. As the drift evolved over time and fluid flux diminished, passages and carbonate muds were further stabilized by early cementation. While exact analogs to Waulsortian mud-mounds are not known from modern oceans, mounded muddy carbonates have been described from the toe of slope of Little Bahama Bank in the Florida Straits and from areas where active venting of fluids takes place such as at hydrocarbon seeps and zones of gas clathrate hydrate formation (*e.g.*, Neumann *et al,* 1977; Roberts, 2001; Suess *et al,* 2001). While in these mounds irregularly networked spar-cemented vents have not been documented, hardgrounds, irregular nodules, sparry vugs, and mineralized cones and chimneys are common (Greinert *et al,* 2001; Roberts, 2001; Suess *et al,* 2001).

b) Lithofacies 2

OL2. Crinoidal and stromatactis mudstone-packstone.

SL2. Mud-mound drape.

Stratigraphically this lithofacies is found above lithofacies 1. It is composed predominantly of carbonate mud and crinoid ossicles with minor amounts of other bioclasts. This lithofacies is subdivided into two sub-facies based on the abundance of crinoid particles. Intervals with > 30% crinoids are placed in subfacies 2WP (crinoid and stromatactis wackestone and packstone) and intervals with < 30% crinoids are identified as subfacies 2MW (crinoid and stromatactis mudstone and wackestone).

Description: Rocks are characteristically light cream to light grey f.id pale green in colour. The bulk composition of this facies is lime mudstone with bioclastic interbeds 5 to 20 cm thick that may be horizontal to slightly inclined. Dark grey zones, when present, are chert. The most common bioclasts are crinoid ossicles that are 4 to 20 mm in diameter and poorly sorted. Other fossils include fenestrate bryozoa, brachiopods and sponge spicules. Lime mud comprises 20 to 90% of the material in this facies with crinoid ossicles contributing 10 to 85%, and bryozoa and calcite cements making up the remainder to a limit of about 10%. Vugs 10 to 30 mm in diameter and fractures decimetres long and up to 2 mm wide are also present. Cemented stromatactis cavities 10 to 20 mm long and 5 to 8 mm high are filled with creamy, tan-coloured, blocky calcite. Syntaxial cements are common on crinoid ossicles. Anhydrite nodules that on average are 10 mm in diameter are common throughout. Red, fine-grained, infiltrated material is present along small fractures and scattered through the facies, giving the rock a mottled appearance. Anhydrite and gypsum may also occur in these fractures.

Interpretation: The juxtaposition of lime mudstones with poorly sorted beds containing bioclastic granule- to pebble-size particles is indicative of accumulation in quiet-water and low current-power conditions. The bottom does not appear to have been reworked frequently and repeatedly by strong currents, particularly those associated with shallow water and frequent wave reworking. On the other hand, the accumulation of bioclastic debris in layers is indicative of either occasional reworking by currents as was proposed by Sereda and Kent (1987), or layering resulting from sloughing of materials down slope as mound flanks built up beyond the angle of repose for sediments. Alternatively, venting of fluids from the mounds may have resulted in fiuidization of sediment and displacement of this sediment as gravity flows as has been observed on modern seafloors (e.g., Roberts, 2001).

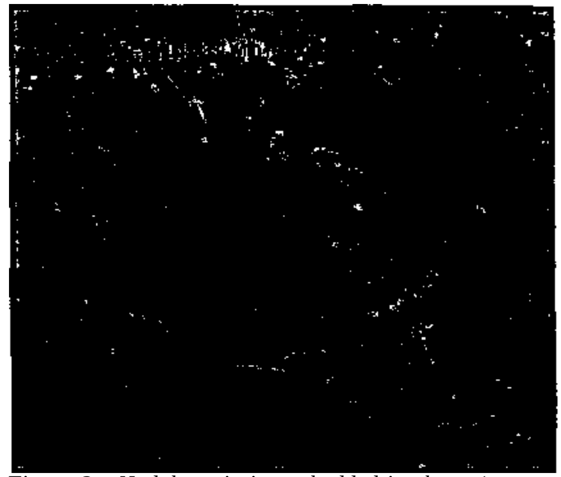

Figure 3 - Nodular micrite embedded in phase 1 cement Micrite nodules appear to float in the cement In outline, micrite nodules are irregular and often have wispy projections. Enlargement illustrates common reduction haloes, where cores are reddish and margins are pale greenish grey in colour. Label A identifies a delicate fenestrate bryozoa branch that crosscuts the micrite and the cement Polished core slab, well 05-07-009-30W1M, sample 11/0S, depth 928.28 to 928.50 metres.

Interestingly, the dominant groups of organisms observed - crinoids, bryozoa, brachiopods and sponges -are filter feeders capable of living well below the photic zone as noted by Lees and Miller (1995), so they would also be common in deep, quieter water. If, however, the mounds were buildups around vents, these filter-feeder organisms would have avoided areas of abundant particulate expulsion that may have accompanied seafloor vents with high fluid fluxes unless currents acted on the bottom, diluting the suspensions and transporting nutrients necessary to sustain these organisms. Fluid fluxes from the vents, over time, may also have waned. Moderate fluid fluxes would not have interfered with these organisms, as can presently be observed in the Gulf of Mexico where vents with moderate fluid fluxes are colonized by many organisms (Roberts, 2001). Seafloor areas of low fluid flux and seepage also become rapidly mineralized and cemented with authigenic carbonates as has been noted in the Gulf of Mexico and off the coast of Oregon, U.S.A. (Roberts, 2001; Greinert *et al*, 2001). It is therefore possible that Waulsortian mounds with cemented and complex cavity systems are mounded vents that became cemented as fluid fluxes waned, the mounds having built up during earlier stages when fluid fluxes and particulate venting were high.

c) Lithofacies 3

OL3. Rubified crinoidal mudstone.

SL3. Saprolitic mud-mound drape.

Description: Deposits of lithofacies 3 are bright creamy tan, reddish brown and medium grey in colour. Lime mudstone is the dominant lithology with up to 10% fossils, most of them being crinoid ossicles with lesser amounts of brachiopods. Crinoid ossicles are 2 to 8 mm in diameter, coarse sand to small pebble in size. Anhydrite nodules 2 to 5 mm in diameter are randomly distributed through the lithofacies interval. Subangular blocky peds 90 mm long and 40 to 100 mm high and columnar peds 100 mm long are present at specific horizons (Figure 4). A reddish iron stain overprints the interval and gives a mottled appearance to the rock.

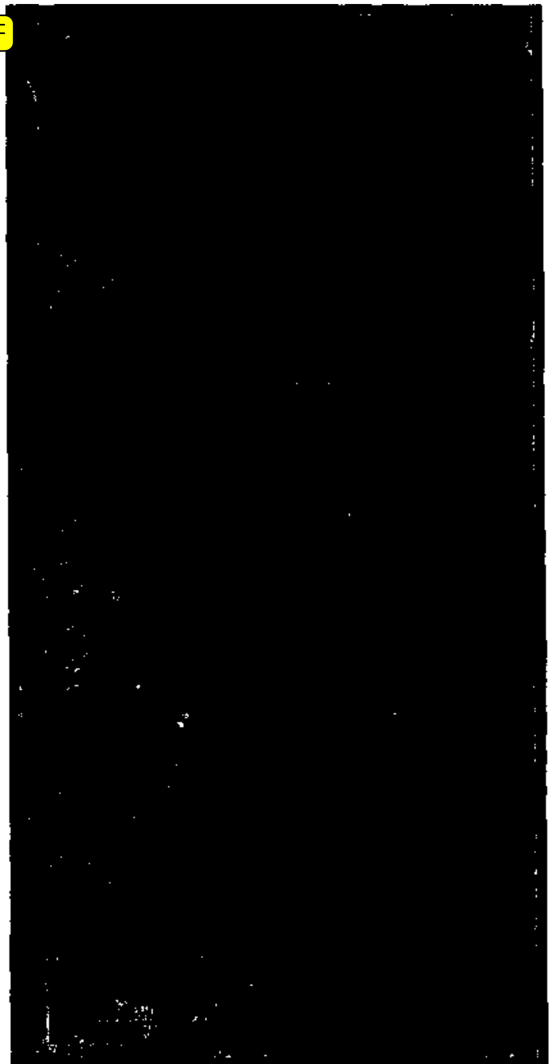

Figure 4 - Lithofacies 3 with pedogenic overprint Note subangular blocky peds with red illuvial deposits. Polished core slab, well 12-08-009-30W1M, sample 04/05, depth 912.49 to 912.76 metres.

Interpretation: This lithofacies is overprinted by soil features, but still displays fabrics of the parent rock. The original rock reflects quiet-water deposition with fossils from filter-feeding and nonphototropic organisms. Thus, the rock may have originally accumulated below zones of intense wave agitation. However, subsequently the rocks were subaerially exposed and weathered as is indicated by the presence of peds and pedogenic alteration. These soil features are indicative of soil shrinkage, swelling and translocation processes associated with soil development. Rubification and anhydrite glaebules (nodules) are indicative of aridity and saline soil development (Rettalack, 1990).

d) Lithofacies 4

OL4. Cherty anhydritic dolostone and crinoidal mudstone.

SL4. *Pedogenic groundwater dolocrete.*

Description: Colours of this lithofacies typically are mottled and creamy pink, reddish brown and medium grey. The rock is predominantly a dolomitic mudstone with silt- to fine sand-sized crystals. In addition, nodular chert, tripolitic chert and anhydrite nodules 20 to 100 mm in diameter are common (Figure 5). Chert is creamy tan-coloured and anhydrite is medium grey. Anhydrite is also observed in layers 20 to 100 mm thick within a matrix of carbonate mudstone (Figure 5). Fossils are uncommon and those observed are brachiopods and ossicles from crinoids.

Interpretation: Lithofacies 4 is heavily overprinted by pedogenesis, which occurred as a result of subaerial exposure in the presence of lenses of saline groundwater over an extended period of time either during a relative sea-level drop following growth of the mound or during the development of the sub-Jurassic unconformity. The latter explanation is more compatible with the surrounding stratigraphy and is most likely the cause of this groundwater-influenced diagenetic event. However, evaporitic conditions enabled dolomitization to proceed, and nodular chert and anhydrite to precipitate and replace the rock. The parent material may have been similar to lithofacies 2, but at present this possibility is no more than a guess.

e) Depositional and Pedogenic Lithofacies Associations

Depositional Lithofacies: Lithofacies 1 and 2 are characteristic of Waulsortian mud-mounds described previously by other researchers who have studied these types of deposits {*e.g.,* Lees and Miller, 1995), and are related to mound development. The mounds formed in quiet-water conditions that allowed mudstone accumulation. All macrofossils observed (crinoids, bryozoa, brachiopods and sponges) are filter-feeding organisms which can obtain nutrients outside the photic zone and can therefore survive in deep water. The presence of abundant mud and filter-feeding organisms, the lack of wave-reworked structures, and the enclosing dark black shales described by Sereda and Kent (1987) together indicate that the mounds formed below storm wave base in quiet water and probably well below the photic zone. The presence of abundant masses and fissure-infills largely made up of fibrous and bladed spar indicates that mud-mound mudstones had cavities and open fractures that filled with this spar. The origin of these cavities is at present unknown, but may have been the result of fluid seepage and escape or clathrate hydrate consolidation and dissociation, as is being recognized with great frequency in studies of modern ocean floors *(e.g.,* Roberts, 2001; Suess *et al,* 2001).

Figure S - Lithofacies 4 with layered anhydrite and irregular white chert nodules surrounded by dolomitic and bioclastic mudstone. Polished core slab, well 12-08-009-30W1M, sample 01/05, depth 908.11 to 908.30 metres.

Pedogenic lithofacies (Pedofacies): Lithofacies 3 and 4 are typical of paleosols and are related to the development of phreatic and vadose zones and accompanying phenomena within a soil profile. The paleosoils appear to have been aridisols. They display features commonly observed in the evolution and development of evaporitic profiles such as those seen in sabkhas where nodular anhydrite and layered anhydrite are common, as are chert nodules. The significance of these observations is that the mud-mounds were subaerially exposed at some time in their geological history.

4. Cements

It is common for Waulsortian lithofacies to be extensively cemented. Not only did Waulsortian mounds develop as a result of biologically mediated sediment trapping and baffling, but sediment was stabilized by syndepositional calcite-cement precipitation. Cements accumulated in complex cavity, fissure and dyke systems of unknown origin. In the Saskatchewan mounds, calcite cements filling these early cavity systems are also common and typically are characterized by three phases: 1. Neomorphosed, bladed dusty calcite; 2. Neomorphosed, multigenerational fibrous dusty calcite; and 3. Equant clear calcite. Phase 1 spar binds grainstones and packstones. Phase 2 cement infills vugs, cross-cutting veins and fissures. Both phases 1 and 2 account for greater than 50% of the total volume of the mound and must have played an important role in maintaining the relief of the mound. Lastly, equant clear calcite, phase 3, fills or partially fills the remaining small voids. Thus, while the mounds lacked frame-building organisms that would have facilitated the development of a stable structure above the surrounding seafloor, they were stabilized and maintained their relief because of the all-embracing calcite cementation that occurred early in their history.

a) Phase 1. Neomorphosed, Bladed Dusty Calcite

Description: These cements are beige coloured, consist of bladed, low-magnesium calcite and are particularly common in lithofacies 1 *(mud-mound core).* Bladed calcite is widespread in grainstones and packstones where it occurs as cement around fossil fragments, intraclasts and very irregular patches or nodules of micrite. Crystals are bladed in longitudinal section, but are equant in transverse section. The cement is also neomorphosed, and intercrystalline boundaries are commonly subhedral to anhedral. In some larger patches of spar, bladed cements are seen to become fibrous and, in places, grade into fibrous phase 2 cements.

Bladed cements are also continuous around bryozoa fragments and fronds, making centripetal envelopes around the bryozoan colonies. Similarly, bladed cements commonly surround crinoid ossicles and stems, a pattern that contrasts markedly from the classical syntaxial overgrowth that is typically observed on particles of this type. Bladed cements are present in widespread and interconnected sparry grainstone mosaics where bladed spar surrounds large masses (centimetres to decimetres across) of irregularly shaped micrite.

Interpretation: Phase 1 cements appear to have precipitated rapidly as they envelop patches and nodules of mudstone, wackestone and packstone that are irregular in shape and commonly have finger-like projections. In many instances, micritic carbonates are completely surrounded by spar. It is unlikely that the muddy carbonate nodules are transported clasts, because clasts with these shapes would have been abraded or ground down by repeated collisions during transport by flowing currents or as sediment gravity flows. Preservation of delicate arms and wispy projections may be indicative of weathering as is observed with karsts for example, or may possibly be a result of erosion from venting and seeping fluids. Cement features commonly associated with karsting such as stalactitic, pendant and meniscus fabrics have not been observed with these rocks. While pedogenesis is notable in lithofacies 3 and 4 and is a late phenomenon in the history of the mounds, rocks of lithofacies 1 and 2 have not been affected significantly by processes of exposure. In addition, the fossils observed in lithofacies land 2 are all marine and isotopic signatures (described below) do not indicate re-equilibration with subaerial fluids. Instead, it appears that these features are probably the product of sediment erosion from seeping and venting fluids exiting onto the seafloor. Fluid-venting and -seepage are well-recorded phenomena in modem seafloors, and are associated with precipitation of carbonate cements (Roberts, 2001; Suess *etal,* 2001).

b) Phase 2. Neomorphosed, Multigenerational, Fibrous Dusty Calcite

Description: Phase 2 cement is typically present in irregular veins, fissures and neptunian dykes (Figure 6). This cement is most common in lithofacies 1 *(mud-mound core)*. In plane-polarized light, crystals are dusty in appearance because they contain a large number of inclusions or irregular microcavities. In reflected light, inclusions are creamy white. While fibrous crystals have neomorphosed and comprise subhedral to anhedral subcrystals, fibres widen distally and larger subcrystals display sweeping extinction with cross-polarized light (Figure 7). Veins, fissures and neptunian dykes are seen to cut through phase 1 cements, through patches and clasts of micrite, and, while they may have layered internal sediments, typically they have few associated particles or fossils. Microprobe analyses indicate that the cements are low-magnesium calcites (Figure 8).

Interpretation: While phase 2 cements typically postdate phase 1, they occur in close association with the earlier cement phase and, therefore, would also have been products of fluid seepage and venting onto the seafloor and surrounding water column as noted with phase 1 cements. Veins, fissures and neptunian dykes filled with phase 2 cements represent a late phenomenon in the evolution of the seafloor vents because they crosscut previous materials. In these openings, opposing free surfaces follow each other's outline crudely and, while exact fits are not possible, indicate that facing walls define fissure and vein systems that permitted the movement of fluids. Incomplete matches may be the result of movement of the enclosing materials or slight erosion of the free surfaces by moving fluids following the development of the fissures. The unusually small amount of particulate material in the veins and fissures filled with phase 2 cements may result from the fact that flows exited the fissures with enough speed to prevent the accumulation of particles in the fissures.

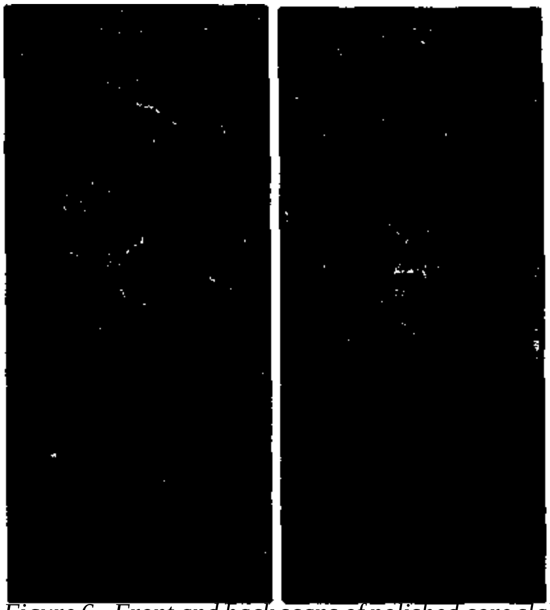

Figure 6 - Front and back scans of polished core slab illustrating vein filled with cement phase 2. Note that the vein changes in dimension between front and back, and that it cross-cats micrite and phase 1 cement Well 05-07-009-30W1M, sample 09/05, depth 925.59 to 925.91 metres.

c) Phase 3. Equant Clear Calcite

Description: These cements stand out because they lack inclusions. The cements are equant, blocky, clear calcite. This cement phase is commonly seen as a partial or complete fill of openings between phase 2 cements.

Interpretation: Cements of phase 3 appear to be a late-stage precipitate. While this cement is notably different to the other two cement phases, it is not abundant and may reflect precipitation of carbonates during the subaerial exposure stage of the mounds. Additional work will be required to elucidate their origin.

5. Stable-Isotope Analyses

Carbon and oxygen stable-isotope analyses were completed on five samples of lithofacies 1. This lithofacies was chosen because, even though it would have been affected by pedogenesis, it did not show the obvious signs of extensive modification by subaerial diagenesis that were observed in lithofacies 3 and 4. To test this notion, five samples were obtained from the following components of lithofacies 1: two crinoid ossicles, one micrite and two phase 2 cements (neomorphosed, multigenerational, fibrous dusty calcite). For these samples, $8^{13}C_{PD}B$ and $5^{18}O_{PD}B$ values are, respectively, 7.3‰ and 7.8‰ and -2.1‰ and -2.2.‰ for the crinoid ossicles, 5.3‰ and -0.18‰ for micrite, and 4.4‰ and 4.9‰ and -1.0‰ and -2.0‰ for phase 2 cements (Figure 9). Interestingly, $S^{13}C_{P}DB$ and $8^{18}0pDB$ for Lower Carboniferous seawater based on samples from brachiopods are, respectively, about 3‰ and -3.5‰ (Veizer *et al,* 1999). Thus, our isotopic data do not appear to be indicative of major re-equilibration of carbon and oxygen stable isotopes as a result of meteoric diagenesis.

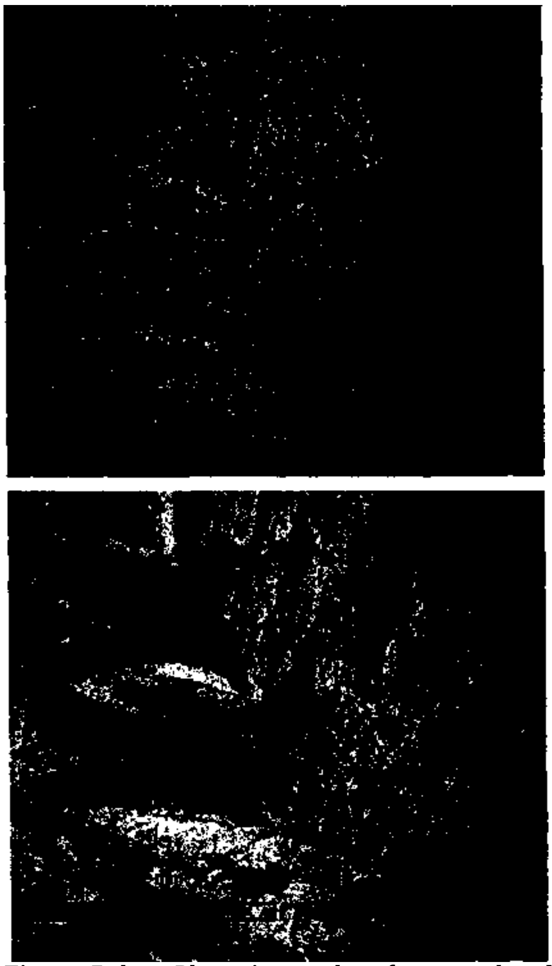

Figure 7a,b - Photomicrographs of neomorphosed, multigenerational, fibrous dusty calcite (phase 2 cement) in PPL (7a) andXPL (7b). Dusty, fibrous crystals meet along a complex compromise boundary in the centre of the image (black arrow, 7a). Undulose extinction and neomorphic fabric (black arrow, 7b) is readily apparent in XPL Well 0S-O7-009-30W1M, sample 13/05, depth 930.05 to 930.16 metres.

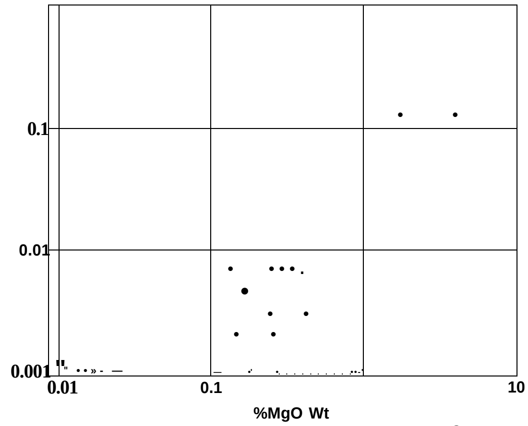

Figure 8 - Fe and Mg weight % analysis of phase 2 cements. Note that Mg typically appears to be an order-of-magnitude more abundant than Fe.

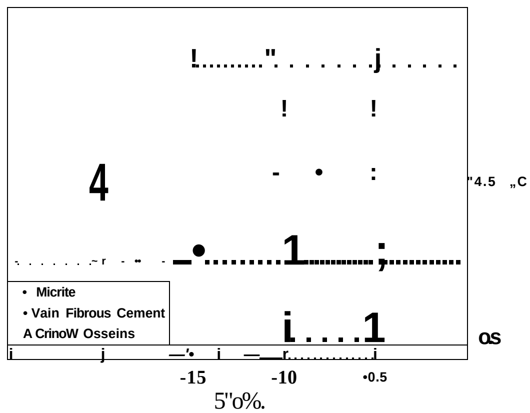

Figure 9 - Bivariate plot of C and O stable-isotope ratios for selected samples from wells 05-07-009-30W1M and 12-08-009-30W1M.

Interestingly, values for $8^{13}C_{P}p_{B}$ and $8^{18}0_{PDB}$ in lithofacies 1 are similar to equivalent stable-isotope ratios from six Mississippian age mud-mounds from the Sacramento Mountains of New Mexico, which range from 2.5‰ to 4.7‰ (mounds) and from 4.396o to 5.2‰ (Muleshoe Mound neptunian dykes) for $8^{13}C_{PDB}$, and from -5.3‰ to -2‰ (mounds) and from -3.5‰ to -0.5‰ (Muleshoe Mound neptunian dykes) for $8^{18}O_{PD}B$ (Wu and Chafetz, 1999). The $8^{13}C_{PDB}$ and $8^{18}0_{PDB}$ ranges for crinoid ossicles from lithofacies 1 of the Saskatchewan mounds falls outside those reported for the Sacramento Mountains mounds, and the ossicles appear to be enriched in ^{13}C. It is, however, unknown if this condition also exists in Sacramento Mountains mounds as stable-isotope data from ossicles analyses were not separately reported by Wu and Chafetz (1999). The $8^{\cdot 3}C_{PDB}$ values for the Saskatchewan mounds are approximately l‰ to 4‰ above the sinle average value for Lower Carboniferous seawater reported by Veizer *et al.* (1999). Enrichment in ^{13}C was also noted in the Sacramento Mountains mudmounds by Wu and Chafetz (1999), which they attributed to precipitation from C-enriched fluids that were seeping from the seafloor, where enrichment was a result of bacterially mediated fractionation during bacterial fermentation of organic matter by methanogens. It is possible that similar processes may have been active in the evolution of the Saskatchewan mud-mounds, but additional work will be required to confirm or deny this possibility.

6. Conclusions

Carbonate cores from three wells that intersect Waulsortian (Lower Mississippian) lithosomes in southeastern Saskatchewan are characterized by four lithofacies that we have recognized by applying a specified set of defined geological criteria. We provide the following objective and *subjective* names to identify them: OL1. Interbedded bryozoan grainstone-packstone and wackestone-packstone, *SLI. Mud-mound core;* OL2. Crinoidal and stromatactis mudstone-packstone, *SL2. Mud-mound drape;* OL3. Rubified crinoidal mudstone, *SL3. Saprolitic mud-mound drape;* and OL4. Cherty dolostone, *SLA. Pedogenic groundwater dolocrete.* These lithofacies mark the evolution of carbonate sediment accumulation from deep-water settings to pedogenic alteration during subaerial exposure.

Waulsortian lithofacies 1 and 2 are cemented extensively. We recognize three cement phases: Phase 1. *Neomorphosed, bladed dusty calcite;* Phase 2. *Neomorphosed, multigenerational fibrous dusty calcite;* and Phase 3. *Equant clear calcite.* Phase 1 spar binds grainstones and packstones. It is also found in networked masses of spar and around wispy and rounded micrite nodules. Phase 2 cements typically occur in irregular vugs, veins and fissures. In several core intervals, phases 1 and 2 account for greater than 50% of the total volume of mound material. Thus, while the mounds lacked frame-building organisms that would have facilitated the development of a stable structure above the surrounding seafloor, mounds were stabilized and relief was maintained by all-embracing calcite cementation early in their development. Carbon and oxygen stable-isotope ratios from cements, micrite and crinoid ossicles are similar to isotopic signatures recorded by others for Lower Carboniferous marine settings.

In these mounds, the presence of widespread cement networks, cemented wispy micrite nodules, and cemented veins, fissures and neptunian dykes are indicative of early and complex cavity systems. Cavities may initially have formed by erosion of carbonate mudstones as fluids and particulate material plumes were venting from the seafloor. Subsequently, as fluid fluxes waned, mudstones and cavities became progressively cemented and fracturing occurred. Moderate and low fluid fluxes would have allowed filter-feeding organisms such as crinoids, bryozoa and brachiopods to colonize the mounds. Fluid venting, particulate plumes and abundant carbonate cementation have been identified on modern seafloors and are known to be commonplace in these settings.

Later in their history, these rocks were subaerially exposed and were modified by pedogenetic processes. The effects of this exposure and modification are observed in lithofacies 3 and 4 that occur near the top of the stratigraphic interval. Exposure appears to have taken place under evaporitic and arid conditions as anhydrite and gypsum nodules and beds are common, and the rocks are extensively overprinted by iron oxides. Groundwaters at the time of exposure must have been saline. Pedogenesis appears to have had few visible post-depositional effects on lithofacies 1 and 2.

7. Acknowledgements

We thank the Petroleum Geology Branch of Saskatchewan Industry and Resources and their personnel for their support. In particular, we are grateful to Fran Haidl, Chris Gilboy and Erik Nickel for helping to make our visit to Regina productive and for encouraging and facilitating our work. We greatly appreciate Don Kent's help for the same reasons. Robert Marr enabled our microprobe analyses at the UCLEMA facility of the Department of Geology and Geophysics, University of Calgary. Steve Taylor oversaw the stable-isotope analyses at the Isotope Science Laboratory (ISL), University of Calgary. Louise Klatzel-Mudry of the Sedimentary Geology Laboratory of the Department of Geology and Geophysics, University of Calgary, was most helpful in arranging the microscopes and equipment needed for our work in Regina. Calgary Rock and Material Services Inc. prepared the double-polished thin sections used in this study. Lastly, Cody also extends a special thank you to his laboratory mates, Alex Haluszka, J.P. Derochie, Breanne Graham and Andrea Mellor, for the friendly and supportive environment in the lab during the long hours of his Honours Thesis work.

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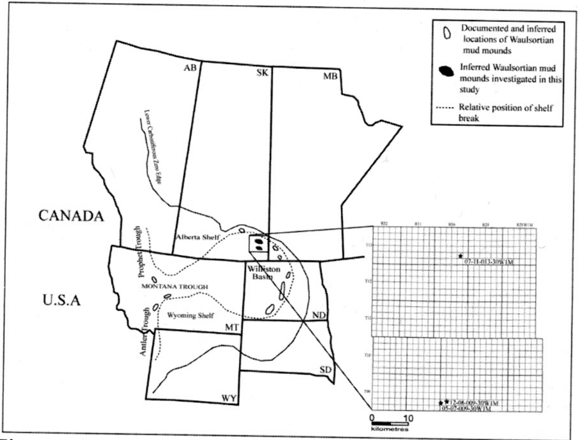


Figure 1 - Location, index and paleogeographic maps. Index map of the Northwest Plains of North America and location map of southeastern Saskatchewan emphasizing the position of three cored wells examined for this study. The erosional edge of Lower Carboniferous rocks in the Western Canada Sedimentary and Williston basins, the relative position of the Lower Carboniferous shelf break, and the locations of mud-mounds with Waulsortian lithofacies that have been identified in outcrop and in the subsurface are also indicated on the index map (figure modified from Sereda and Kent (1987) and Blakey (2006)).

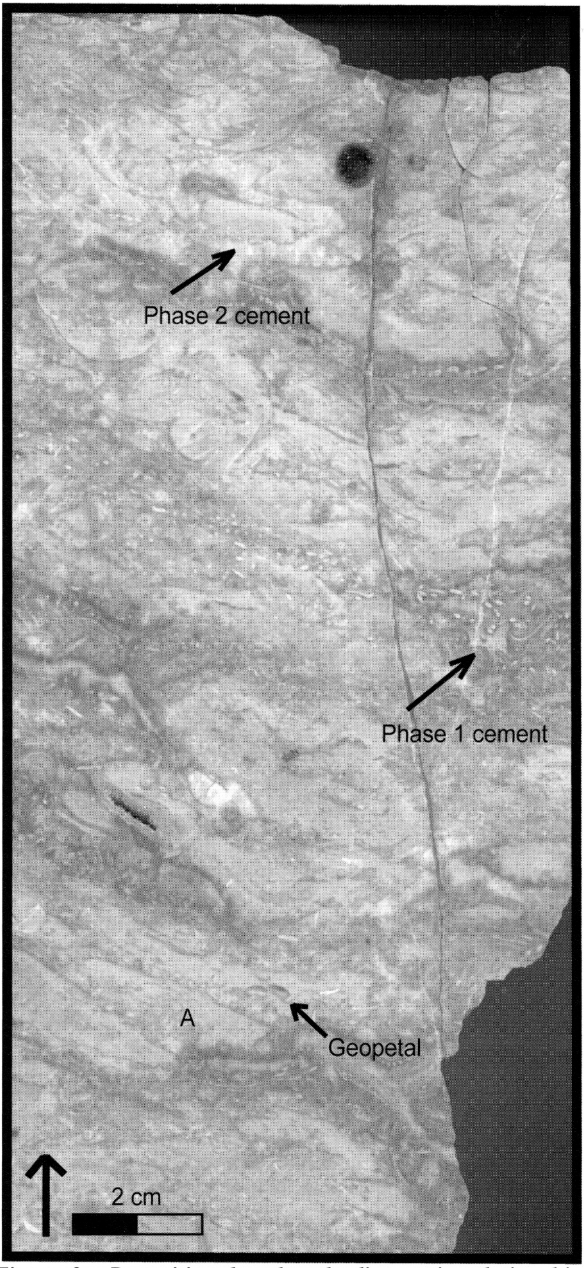
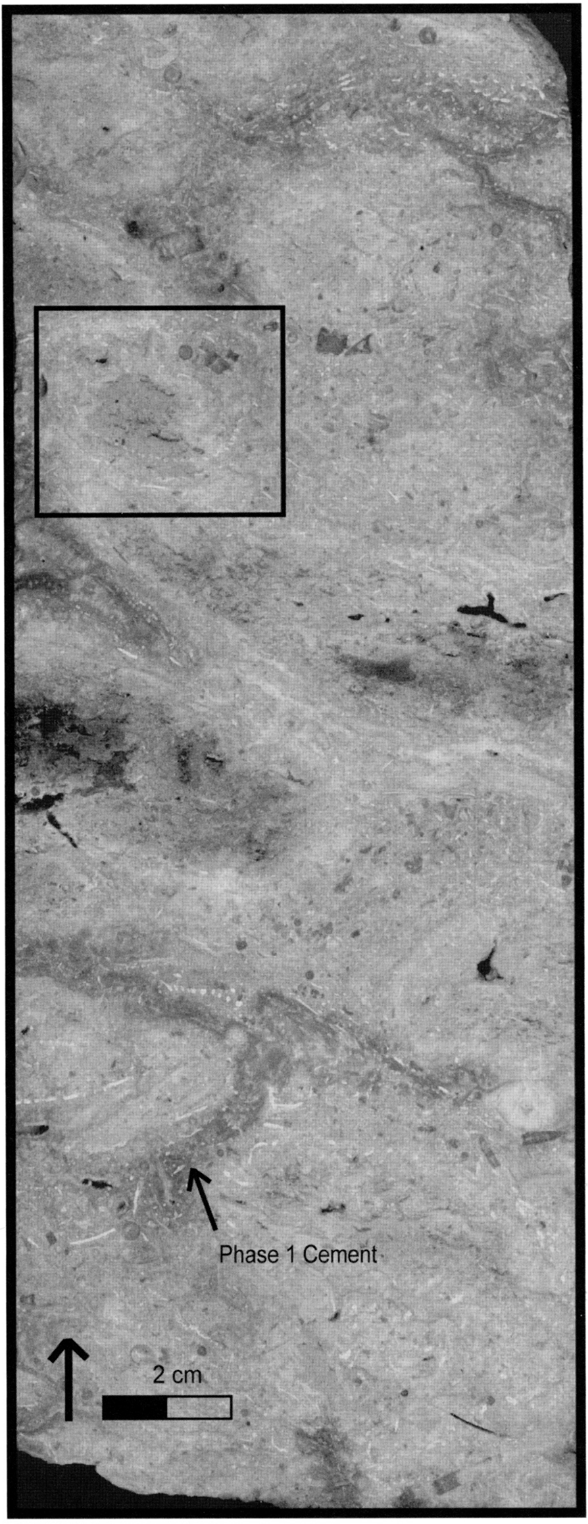


Figure 2 - Depositional and early diagenetic relationships observed in lithofacies 1 between micrite and primary calcite-cement phases 1 and 2. While phase 1 cement surrounds micrite and fossils stabilizing the rock framework, phase 2 cements are found infilling fissures and veins. Label A points to a micrite clast that has a smooth roof and a digitate base, a pattern that is common for micrite masses in this rock type. Abundant geopetals are useful to define stratigraphic orientation. Polished core slab, well 12-08-009-30W1M, sample14/05, depth 921.25 to 921.43 metres.


Phase 1 Cement
2 cm

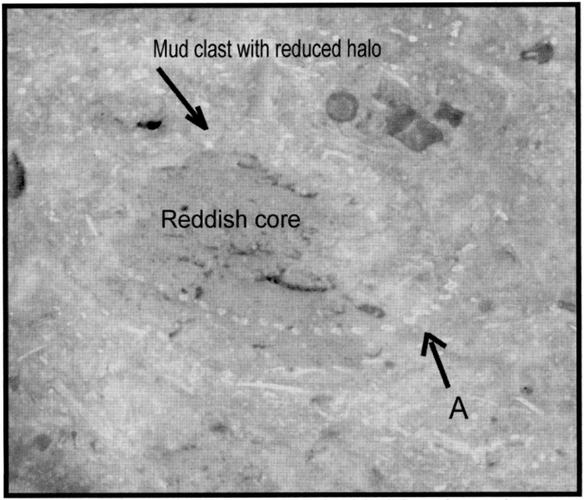


Figure 3 - Nodular micrite embedded in phase 1 cement. Micrite nodules appear to float in the cement. In outline, micrite nodules are irregular and often have wispy projections. Enlargement illustrates common reduction haloes, where cores are reddish and margins are pale greenish grey in colour. Label A identifies a delicate fenestrate bryozoa branch that crosscuts the micrite and the cement. Polished core slab, well 05-07-009-30W1M, sample 11/05, depth 928.28 to 928.50 metres.

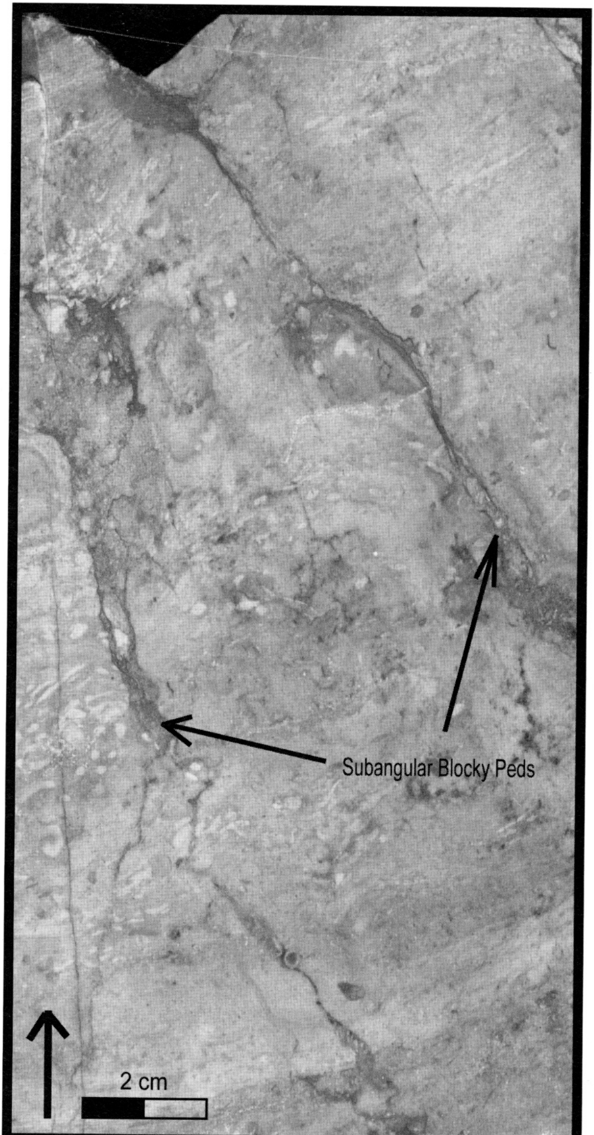


Figure 4 - Lithofacies 3 with pedogenic overprint. Note subangular blocky peds with red illuvial deposits. Polished core slab, well 12-08-009-30W1M, sample 04/05, depth 912.49 to 912.76 metres.

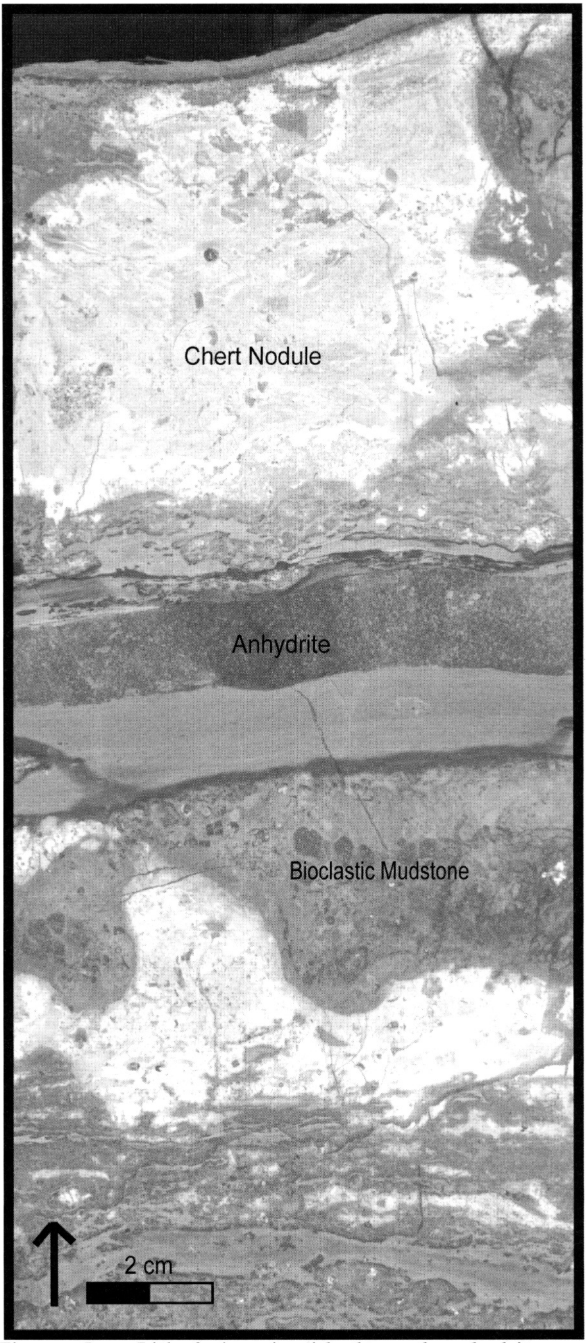
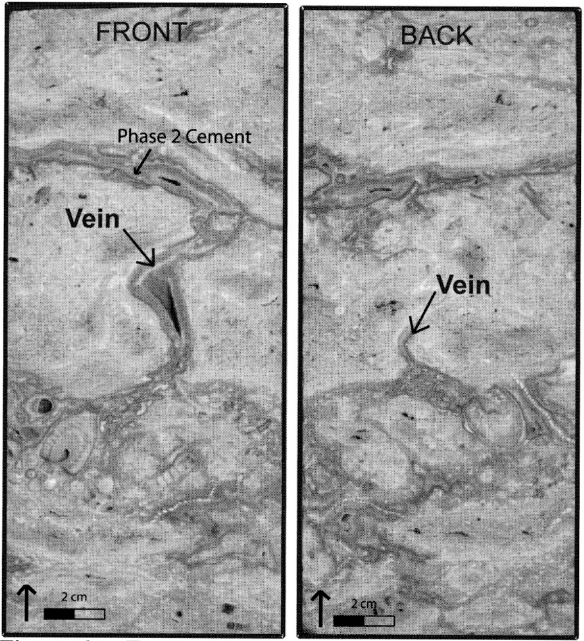


Figure 5 - Lithofacies 4 with layered anhydrite and irregular white chert nodules surrounded by dolomitic and bioclastic mudstone. Polished core slab, well 12-08-009-30W1M, sample 01/05, depth 908.11 to 908.30 metres.



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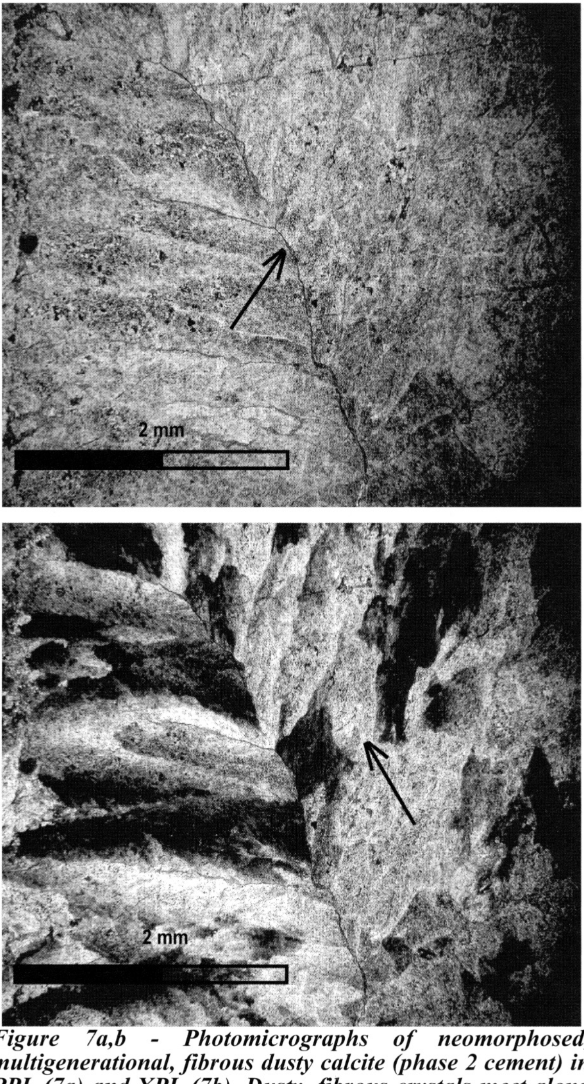

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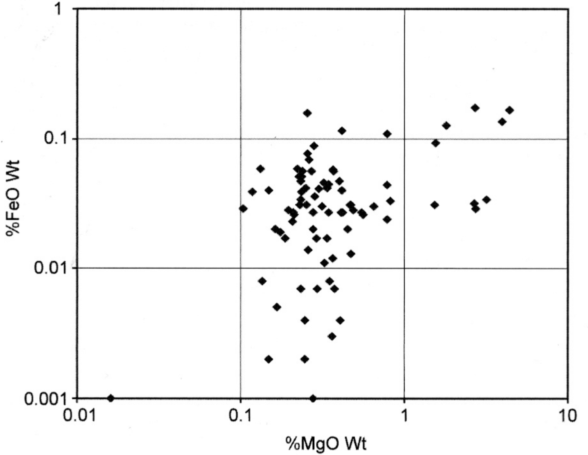

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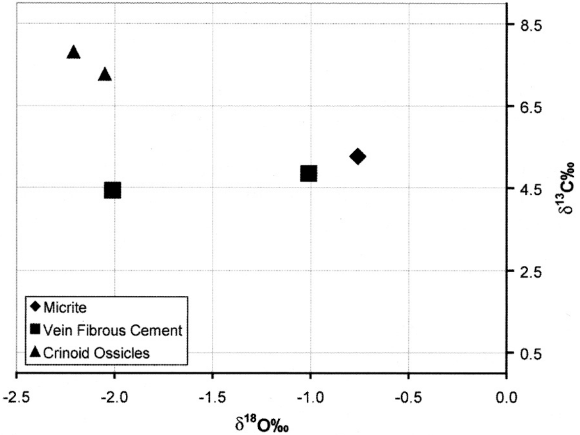

Figure 9 - Bivariate plot of ^{13}C and ^{18}O stable-isotope ratios for selected samples from wells 05-07-009-30W1M and 12-08-009-30W1M.

Interestingly, values for $\delta^{13}C$ and $\delta^{18}O$ in