APPLICATIONS OF ICHNOLOGY IN EXPLORATION AND EXPLOITATION OF MISSISSIPPIAN CARBONATE RESERVOIRS, MIDALE BEDS, WEYBURN OILFIELD, SASKATCHEWAN

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ABSTRACT

Few carbonate workers have realized the usefulness of ichnology in reservoir modeling and characterization. This study proposes building on the strengths of the ichnofacies concept for paleoenvironmental reconstructions; and, integration of genetically-significant data derived from use of new petrographic classification schemes for bioturbate textures, and associations of paleobiologically-influenced dolomites and porosity characteristics. For example, at Weyburn Oilfield, bioturbated dolomudstones of the Upper Midale Beds form important hydrocarbon reservoirs. This suggests widespread bioturbation has played an important role in diagenesis and porosity evolution within these reservoirs. Common occurrence of *Zoophycos*, *Planolites* and *Chondrites*, some *Helminthopsis*, *Asterosoma*, *Teichichnus* and *Palaeophycus,* and rare *Siphonichnus* define a diverse ichnofossil suite, characteristic of a distal-*Cruziana* ichnofacies. This trace fossil assemblage suggests deposition of muds occurred in a fully-marine, offshore paleoenvironment that developed in response to a major transgression. Furthermore, such an ichnofossil suite indicates predominance of deposit-feeding activities in responses to flooding.

Organism-sediment interactions by deposit-feeders resulted in nearly complete pelletization of muddy substrates. Petrographic studies on bioturbated dolomudstones show fecal pellets define burrow-fabrics consisting of concentric and tangential alignments, and abundance patterns ranging from clustered-interpenetrating to homogenized textures. These indiscrete fabrics are associated with bioturbate texture-selective dolomites, consistent with reservoir development. Consequently, widespread re-organization of the mud into fecal pellets resulted in development of intergranular voids in otherwise relatively impermeable substrates. This porosity type shows distribution patterns, characteristic of both intraburrow- and interburrow-fabric voids. Both distribution patterns in voids facilitated percolation of fluids in dolomitization, and origin of intercrystalline porosity; and provided conduits for dissolution fluids that leached out skeletal fragments aligned in bioturbation. Hence, distribution of moldic voids suggest morphological elements in burrow-fabrics, including spreiten and wall-structures, enhanced local permeability and insignificantly influenced fluid flow. This concept provides a base for future research on dolomitization, in terms of modeling fluid flow and patterns of crystal growth, and development of fabrics derived from ingrowth (host-to-burrow) and outgrowth (burrow-to-host) mechanisms, and variations in porosity.

INTRODUCTION

Applications of ichnology represents a powerful tool in petroleum geology. Utilization of trace fossils in sedimentology and stratigraphy has proven useful in paleoenvironmental reconstructions, at the centre of many exploration models.

Several works have summarized the conceptual framework of ichnology, where trace fossil data represents integral elements of sedimentary models, including interpretations regarding genetic stratigraphy (Ekdale *et al.,* 1984; Frey and Pemberton, 1984, 1985; Frey *et al*. 1990; Bromley, 1990 1996;Pemberton *et al.,* 1992a, b; Pemberton *et al.,* 2001). Research has been focused primarily on applications of Seilacher's (!964; 1967; 1978), ichnofacies concept to delineate significance of ichnofossil assemblages in siliclastic deposits. Alternatively, genetic interpretations regarding usefulness of indiscrete aspects of bioturbate textures remain controversial amongst both ichnologists and sedimentologists (Keswani, 1999).

Notwithstanding, relatively few carbonate workers have recognized the significance of discrete biogenic structures, nor indiscrete aspects of bioturbate textures. Carbonate sedimentologists tend to utilize only body fossils and physical characteristics in paleoenvironmental reconstructions. The ichnologic record has been commonly disregarded altogether; or bioturbate textures are described in general terms, such as 'burrowed," "burrow-mottled," and "ichnofabrics" (Keswani, 1999). Such descriptions lack significance regarding biotic processes, and relevance to genetic interpretations is rather minimal. Consequently, most carbonate workers have overlooked the inherent significance of textural relationships derived in sedimentary-paleobiological dynamics; and the roles of biogenically-modified substrates in diagenesis and origins of dolomite reservoirs.

PURPOSE

This study builds on traditional approaches used in carbonate sedimentology and ichnology. To demonstrate the usefulness of ichnologic applications to petroleum geology of detrital carbonate deposits, this study has utilized an integrated approach to modeling reservoir strata in the upper Midale Beds. This approach uses the strengths of the ichnofacies concept for paleoenvironmental reconstructions; and, integrates genetically-significant data derived from use of new petrographic classification schemes for bioturbate textures, and associations of paleobiologically-influenced dolomites, and porosity-permeability characteristics. Such an approach provides data useful for reservoir characterization in development geology, where types and distribution patterns in porosity indicate paleobiological controls on fluid flow dynamics that influenced dolomitization and leaching in reservoir development.

At Weyburn Oilfield, the Midale Beds represent one of Canada's most important hydrocarbon reservoirs formed in detrital carbonates. These reservoirs host an estimated oil reserve of 1.4 billion barrels (Burrowes, 2001). Reservoir development occurs within the bioturbated dolomudstones of the upper Midale Beds ("Marly" unit). Origin of prolific reservoirs within these carbonates suggest biotic processes played a significant role in carbonate diagenesis, and origins of porosity and permeability relationships. An improved understanding of inherent paleobiological controls on such economic aspects is significant for modeling reservoir development and characterization. Hence, such information on paleobiological controls provide data useful for implementation of effective exploitation strategies in development geology.

STUDY AREA

This ichnologic study on the Midale Beds is focused on the cored interval at Mobil Roughbark well 2-12-6-14W2. This core shows excellent preservation of trace fossils and sedimentary facies relationships, representative of the Midale Beds at Weyburn Oilfield. These carbonates were deposited on the northeastern flanks of the Willliston Basin in southeastern Saskatchewan (Figure1). In this area, Mississippian carbonates of the Midale Beds define parts of the “Midale trend” in subsurface (Smith, 1980; Fuzesy, 1983). The Weyburn Oilfield represents one of many important pools that straddle this subsurface trend.

STRATIGRAPHIC AND SEDIMENTARY SETTING

Stratigraphic nomenclature for Mississippian strata in the Williston Basin is provided in Figure 2. The Midale Beds form the middle portions of the Mississippian succession. Midale Beds are composed of the basal Frobisher evaporite unit and the Midale carbonates (Smith, 1980; Kent, 1984). The Midale carbonates may be further subdivided into a lower, middle, upper and uppermost units (Fuzesy, 1960; 1983; Smith, 1980). These carbonates are subdivided into an upper "marly" unit and a lower "vuggy" unit (Matiisen and Shehata, 1987). In recent years, Kent (pers. communication) has suggested formal designation for

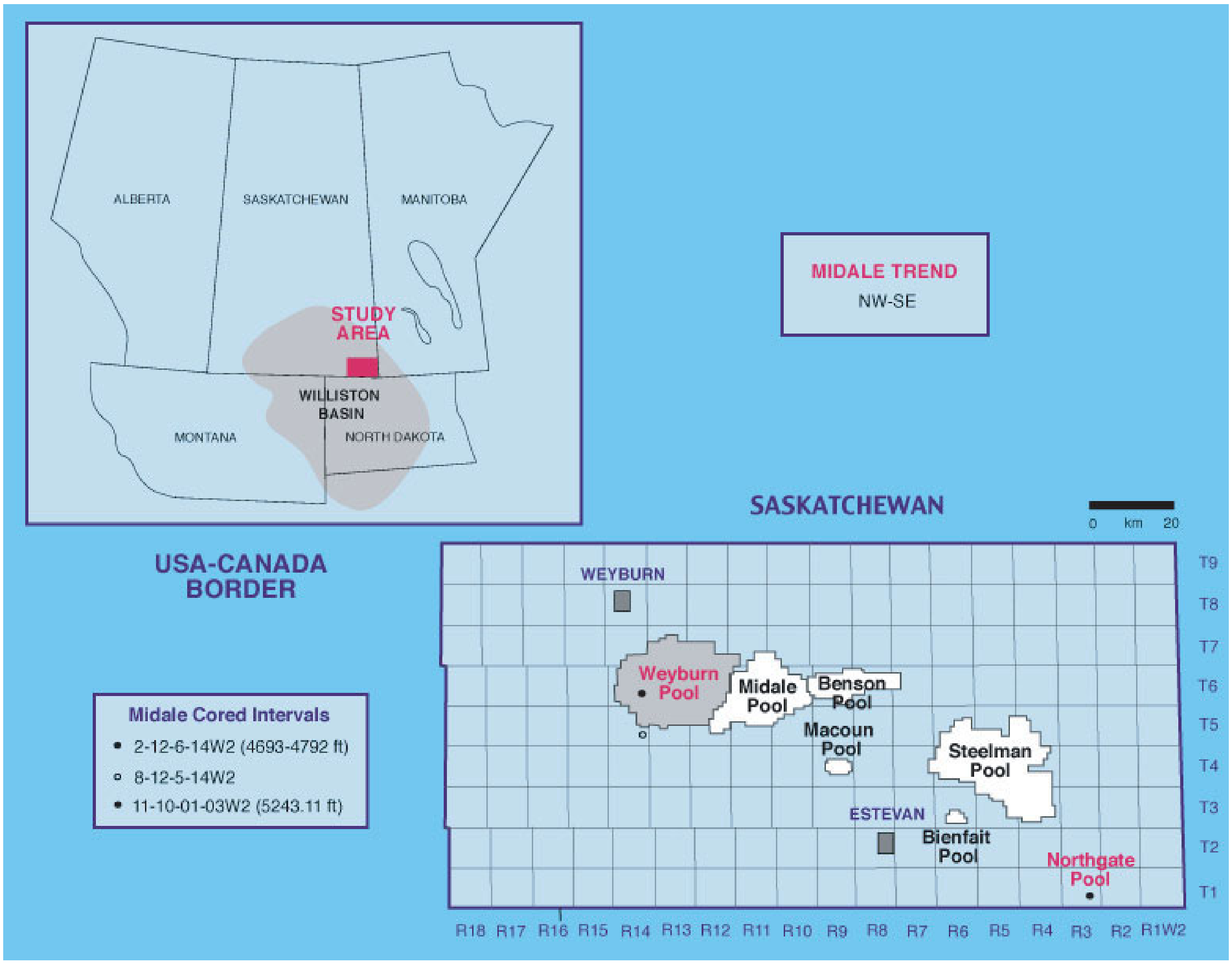


Figure 1. Location Map. Study area shows well locations along the "Midale Trend."

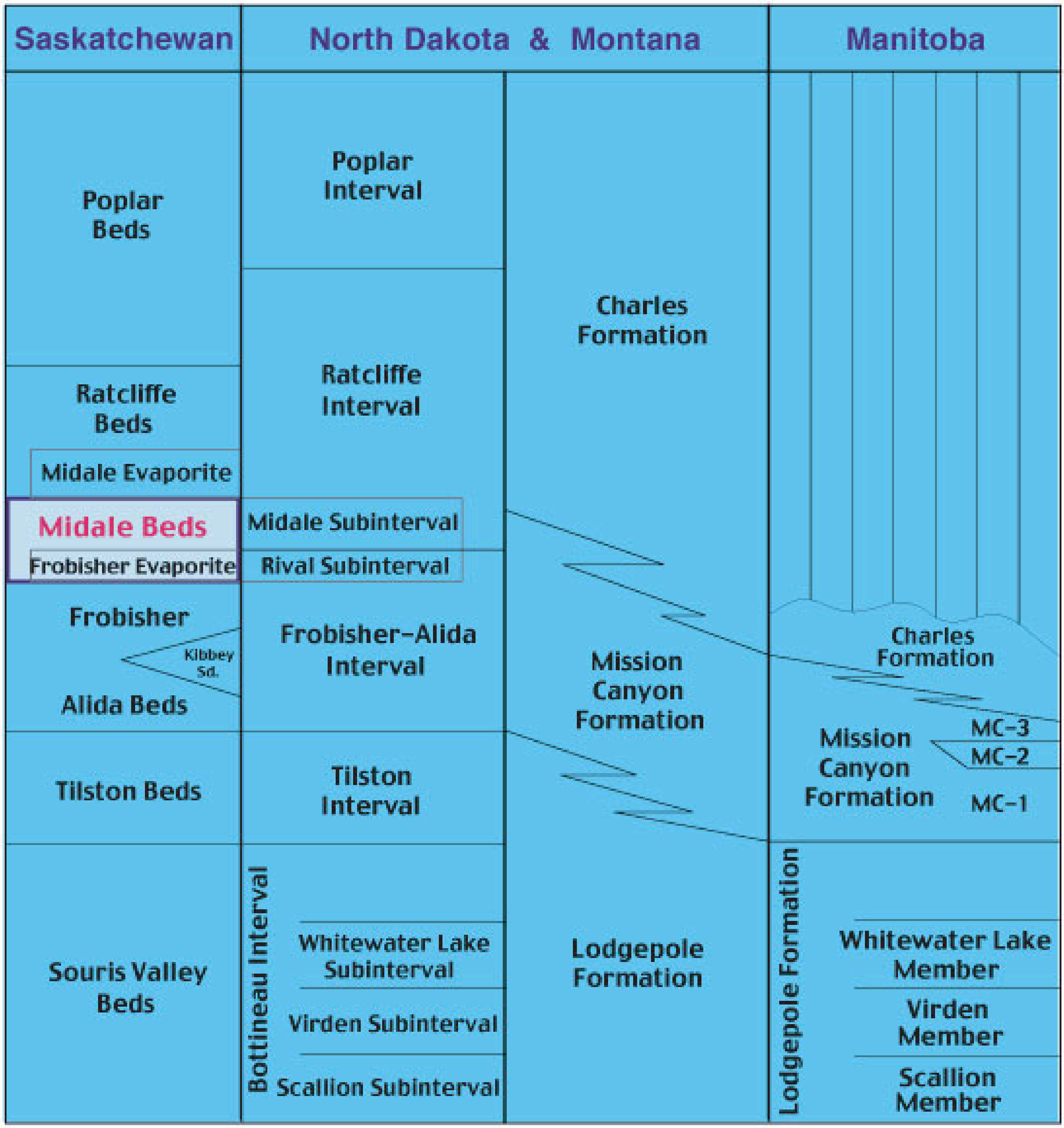


Figure 2. Midale Beds. Mississippian stratigraphic nomenclature, Williston Basin (Kent, 1984).

the “vuggy” unit as lower Midale Beds, and “marly” unit as upper Midale Beds. This paper subscribes to the updated terminology.

Many studies have been focused on aspects of stratigraphy and sedimentology of the Midale Beds (Smith, 1980; Crabtree, 1982; Fuzesy, 1983; Kent, 1984a; Matiisen and Shehata, 1987; Kerr, 1988, and Lake, 1991 Nimegeers and Quing, 2002a,b,c). Mississippian strata are correlated using recurring evaporite marker beds. Regional stratigraphic correlation facilitated development of a basin model (Kent, 1984a, b, 1987a; Kent *et al.,* 1988). Large-scale changes in sedimentary environments, including an overall shallowing-upward trend reflected in characteristics of Mississippian strata have been attributed to basin evolution, fill, and variations in platform configurations from ramp to shelf (Smith, 1980; Lindsay and Roth, 1982; Kent, 1984a b, 1987a; Kent *et al.,* 1988 Lake, 1991). Recently, works on stratigraphic variability and facies relationships have resulted in construction of updated paleoenviromental models, including potential hydrocarbon significance (Kent and Nimegeers, 2002; Nimegeers and Quing, 2002a, b, c; Nickel and Quing, 2004). However, paleoecological investigations on dolomudstones within upper Midale Beds suggest interplays in sedimentary-paleobiological dynamics provide intrinsic controls on dolomitization and development of hydrocarbon reservoirs at Weyburn and Northgate oilfields (Keswani and Pemberton, 2006).

SEDIMENTOLOGY

Sedimentologic and paleontologic characteristics of the Midale Beds at Mobil Roughbark well 2-12-6-14W2 is summarized in a log depicted in Figure 3. An integrated approach analyses has been utilized, including both core studies and thin-section petrography. A brief description is presented for the lower Midale Beds, a bored hardground and the upper Midale Beds. Although two major textural facies are recognized, the reservoir strata of the upper Midale Beds are highlighted in this study on genetic linkages in bioturbation-diagenesis.

Lower Midale

The lower Midale beds is a thick, light-tan colored limestone unit that overlies an evaporite-dolomudstone (Figure 4). This textural facies consist of a peloidal packstone, with local variations in thickness of individual beds, coarse grain-size, and amounts of skeletal fragments. Considerable variability in textural parameters is a characteristic feature of this limestone, including gradual changes to a grainstone in parts. Furthermore, diagenetic bedding is defined by local development of stylolites and incipient solution seams (Figure 4A) . Although textural parameters show variability, peloids represent the predominant constituent in this limestone. Amounts of peloids range between 60%-70%. Calcite spar comprises about 5%-20% and micrice varies in amounts from 5%-10%. Porosity varies from 15%-20%. A low -diversity assemblage of thin-shelled, body fossils is present in this limestone. Skeletal constituents include calcareous

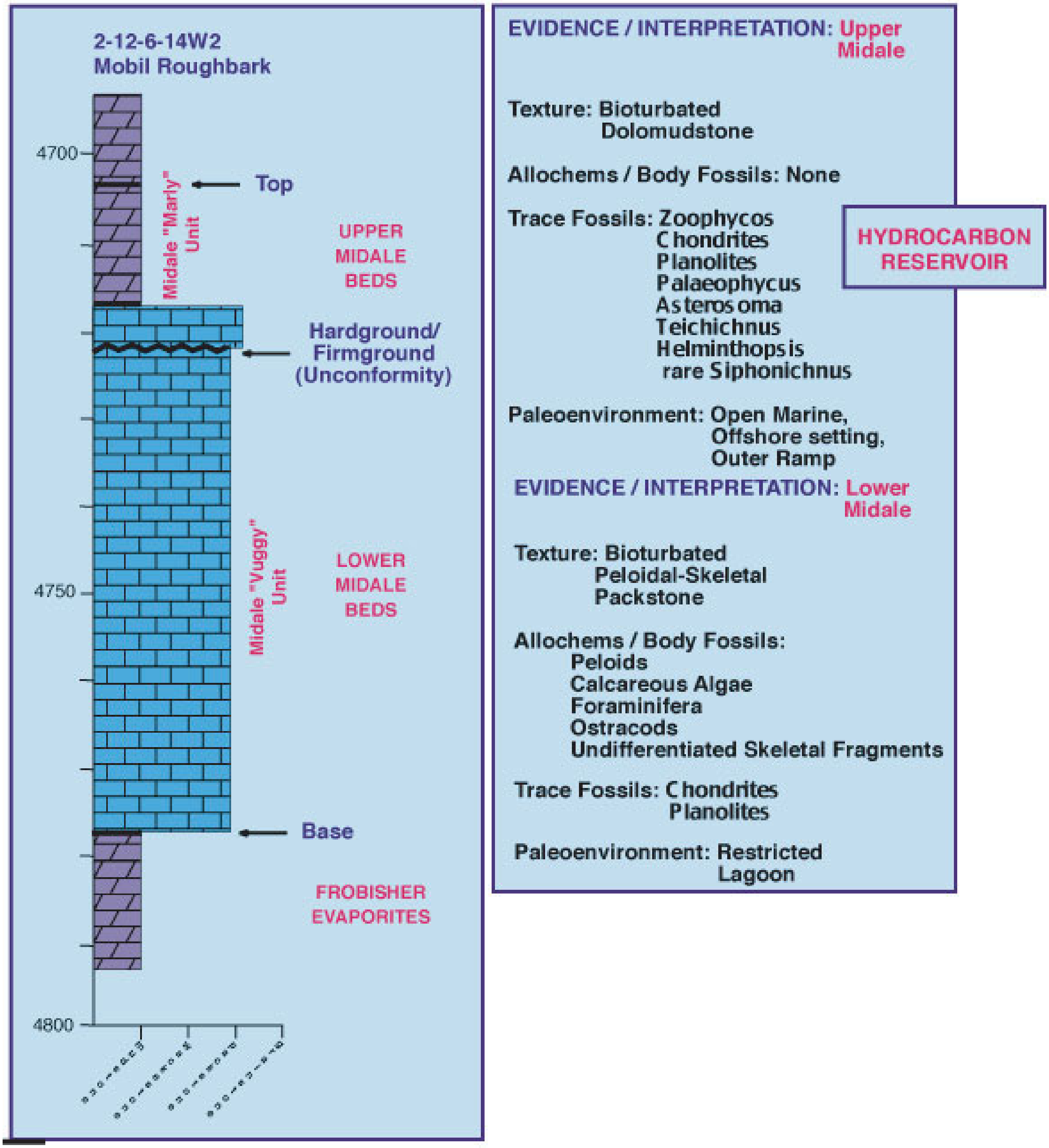


Figure 3. Strip log. Midale Beds, Weyburn Oilfield (well 2-12-6-14W2).

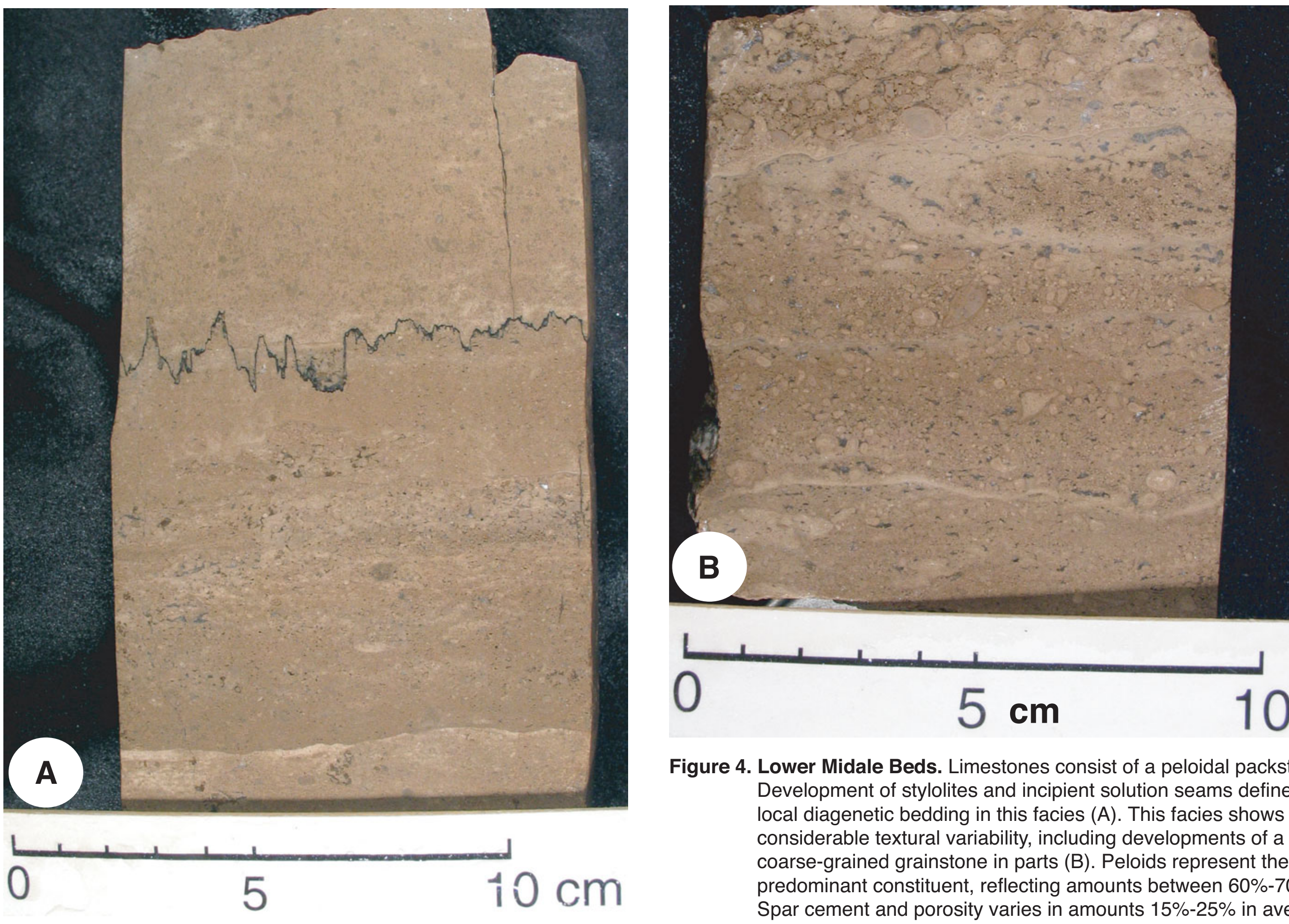


Figure 4. Lower Midale Beds. Limestones consist of a peloidal packstone. Development of stylolites and incipient solution seams define local diagenetic bedding in this facies (A). This facies shows considerable textural variability, including developments of a coarse-grained grainstone in parts (B). Peloids represent the predominant constituent, reflecting amounts between 60%-70%. Spar cement and porosity varies in amounts 15%-25% in average. Although skeletal fragments represent monor components, these packstnes are characterized by a low-diversity body fossil assemblage, including calcareous algae, ostracods, foraminifera and undifferentiated material. Such a low-diversity assemblage of body fossils indicates deposition occurred in a relatively shallow-water, restricted lagoon environment.

algae, ostracods, foraminifera and undifferentiated fragments that amount to a relatively minor 3%-5%.

Although trace fossils are mostly indistinguishable, forms such as *Planolites* and *Chondrites* show local preservation. Absence of physical sedimentary structures suggests complete bioturbation, which produced homogenized textures in most of these substrates. Based on low diversity in skeletal fragments, and dearth of body and trace fossils that otherwise suggest marine conditions, this study proposes the peloidal packstone facies of the lower Midale Beds reflects a restricted lagoon depositional environment. This interpretation is consistent with Flugel (2004, p. 700), where packstone-grainstone comprised of predominantly peloids, and few ostracods, foraminifera and calcispheres suggest a restricted inner platform setting, such as a lagoon. Flugel (2004) attributes many such peloidal deposits to a bioerosional origin.

Bored Hardground

A bored hardground is developed at the top of the lower Midale Beds (Figure 5). The hardground is represented by the sharp contact between the peloidal packstone and the basal parts of overlying skeletal packstone-grainstone unit within the upper Midale Beds. This surface is characterized by vertical borings that penetrate several centimeters into the peloidal packstone. Petrographic analysis of samples from the contact show sharp-walled borings cut into the underlying peloidal packstone. These bioerosional structures contain skeletal fragments that are similar in composition to those in the overlying

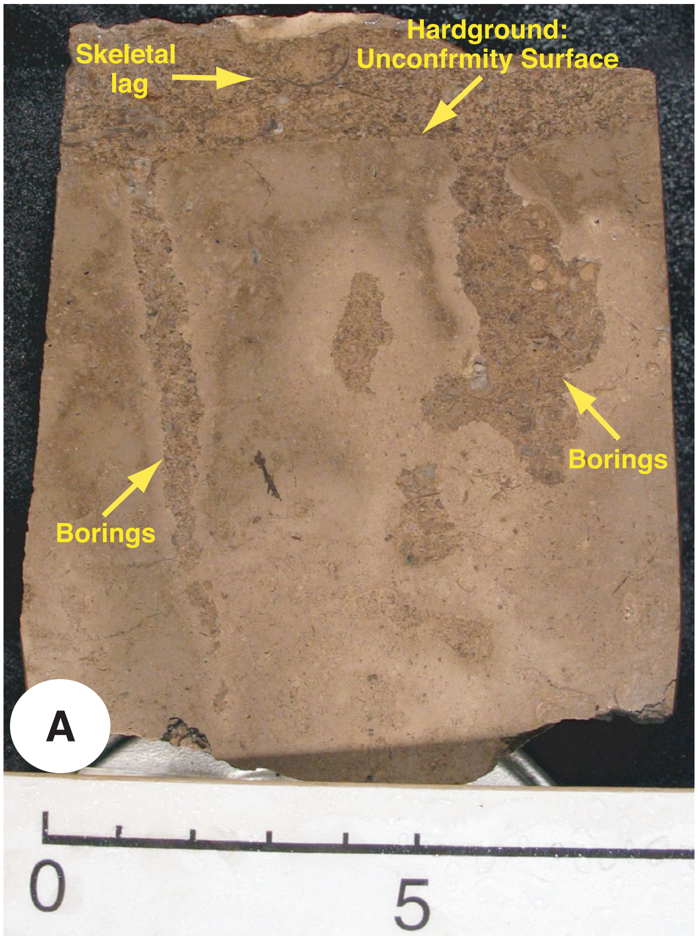
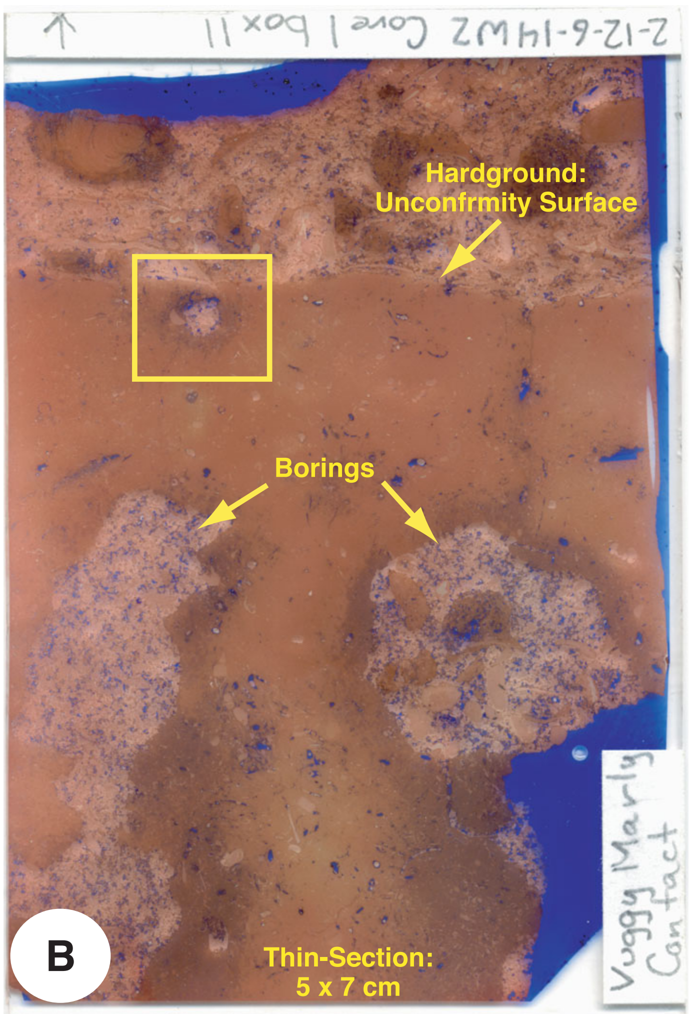
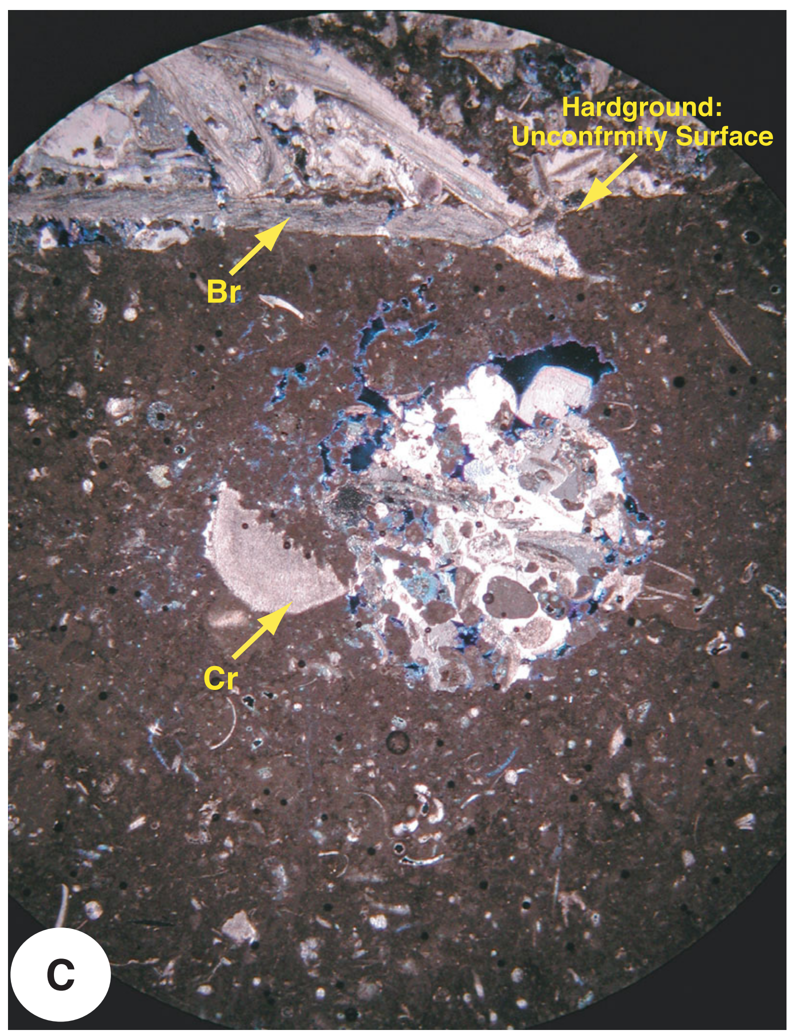


Figure 5. Bored hardground. (A) Core photograph shows the sharp contact between the lower and upper Midale Beds in well 2-12-6-14W2. This surface represents a bored hardground, which reflects a major unconformity at this contact. Borings were open structures at the time of deposition of the overlying strata, which consist of coarse-grained skeletal fragments. (B,C) Thin-section from this contact clearly shows both textural and compositional differences at this contact, indicatiog unrelated facies above and beloew the surface. This break shows peloidal packstones of the lower Midale Beds form host substrates for borings that reflect similar skeletal constituents as those in the overlying packstone-grainstone. This indicates genetic affinity, where borings have been infiled from depositional regime that produced strata above.

(C, inset) Photomicrograph of boring fills and overlying skeletal packstone-grainstone shows similar fossil content in both, including crinoids (Cr) and brachiopods (Br). These constituents reflect deposition in fully marine environments. Conversely, host substrates show fossil remains of calcareous algae, ostracods, foraminifera, and undifferentiated skeletons in predominantly peloidal packstone. These allochems indicate deposition in a restricted lagoon environment.





packstone-grainstone unit. The boring fills consist of coarse-grained allochems such as crinoids and brachiopods, representing a distinct genetic affinity to the overlying skeletal packstone –grainstone (Figure 5C). Alternatively, the host substrates show minor amounts of body fossils, typical of the peloidal packstone within the lower Midale Beds.

The bored hardground represents a major unconformity surface at the contact between the lower and upper Midale Beds. Similar fossil composition within boring fills and the packstone-grainstone above this surface, indicate these skeletons were derived from depositional regimes that produced the overlying unit, and bioerosional structures were open at the time of infill. Development of hard substrates and borings clearly indicates a time gap. Also,body fossils such as crinoids and brachiopods in skeletal packstone-grainstone suggest a fully-marine environment is represented in overlying unit and boring fills. But, skeletons in peloidal packstones indicate a restricted lagoon setting. This change indicated by facies relationships reflects a major unconformity at the contact between the lower and upper Midale Beds. This interpretation is consistent with Walther's Law (Tucker and Wright, 1990).

Upper Midale

The upper Midale Beds are comprised of a basal skeletal packstone-grainstone unit, and a bioturbated dolomudstone. The unconformity surface defines the base of the skeletal packstone-grainstone unit. This unit contains 35%-40% peloids, 20%-25% crinoid fragments; 10%-15% bivalves and brachiopods, 10%-15% undifferentiated skeletal fragments; 5% spar cement, and 10%-!2% micrite. Allochems show poor sorting, and grain-size averaging 0.4 - 1.2 mm. In parts, depositional laminae is preserved in this coarse-grained unit. Characteristic fossils in packstone-grainstone indicate deposition occurred within a fully-marine paleoenvironment. This textural facies is interpreted as a transgressive skeletal lag, consisting of reworked material. This shift in sedimentary dynamics resulted in the basal unconformity surface at onset of marine conditions. This sedimentary regime persists upward in depositional environments that clearly represented a major flooding event. This deepening event produced marine conditions that facilitated development of bioturbated muddy substrates.

Bioturbated dolomudstones represent important reservoir strata within the upper Midale Beds at Weyburn Oilfield. These substrates are characterized by widespread development of bioturbte textures, consisting of discrete trace fossils and indiscrete fabrics. Common occurrence of *Zoophycos*, *Planolites* and *Chondrites*, some *Helminthopsis*, *Asterosoma*, *Teichichnus* and *Palaeophycus,* and rare *Siphonichnus* define a diverse ichnofossil suite, characteristic of a distal-*Cruziana* ichnofacies (Figure 6). This trace fossil assemblage suggests deposition of muds occurred in a fully-marine, offshore paleoenvironment that developed in response to a major transgression. Such a flooding event resulted in a marine incursion, generated reworked skeletal lags, and produced offshore conditions on the Midale platform.

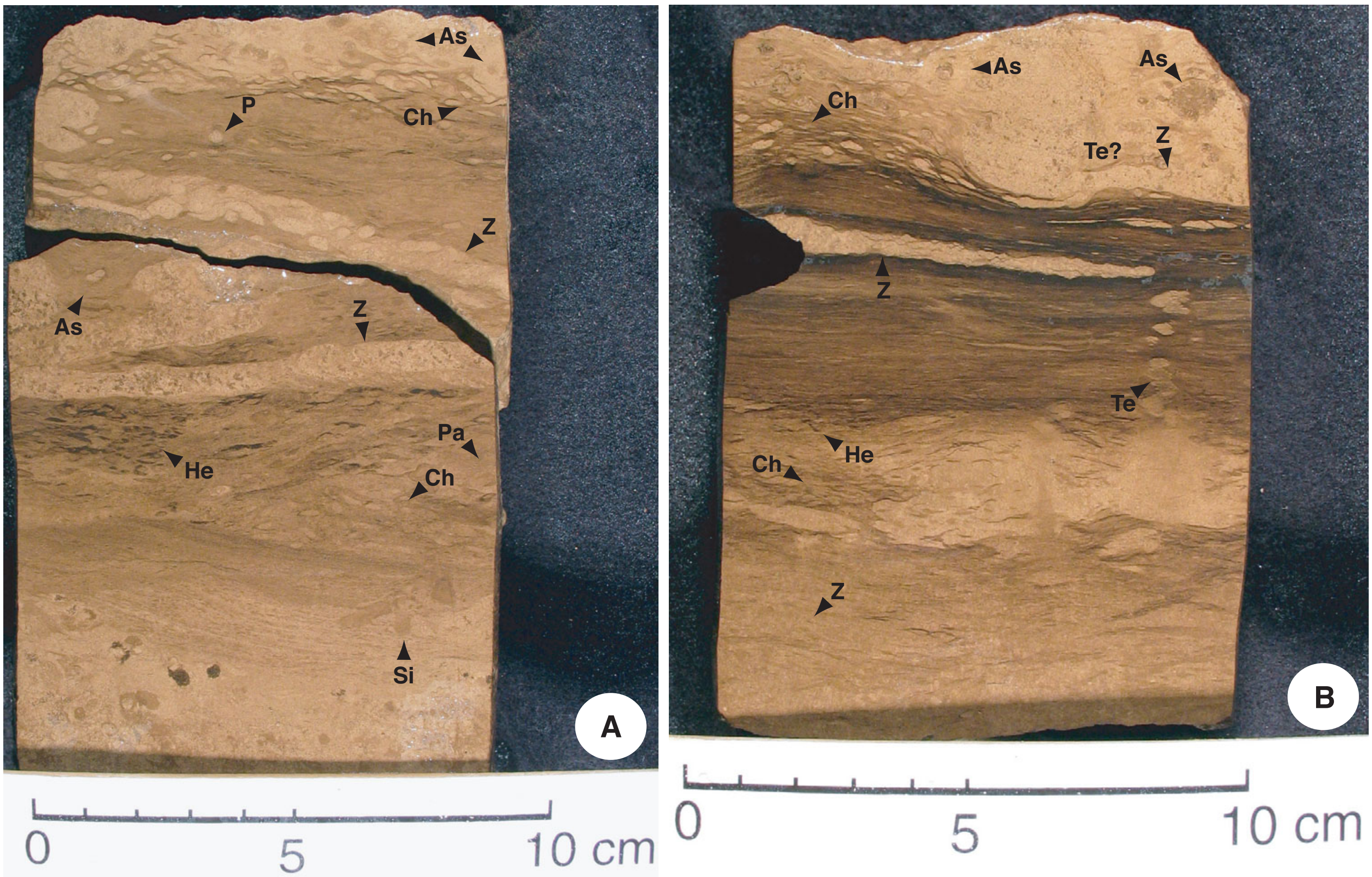


Figure 6. Upper Midale Beds. Bioturbated dolomudstones comprise reservoir strata at Weyburn Oilfield (well2-12-6-14W2). (A,B) A characteristic distal-***Cruziana*** ichnofacies is defined by a diverse ichnofossil suite comprised of common occurrence of ***Zoophycos*** (Z), ***Planolites*** (P) and ***Chondrites*** (Ch), some ***Helminthopsis*** (He), ***Asterosoma*** (As), ***Teichichnus*** (Te) and ***Palaeophycus*** (Pa), and rare ***Siphonichnus*** (Si).This trace fossil assemblage suggests deposition of muds occurred in a fully-marine, offshore paleoenvironment that developed in response to a major transgression. Furthermore, widespread bioturbation has played an important role in dolomitization and porosity evolution.

Indiscrete aspects of bioturbate textures represent the bulk volume of biogenically-modified substrates. Petrographic analysis show these dolomudstones are unfossiliferous substrates, comprised essentially of micrite. Mud content is estimated at 80%-95% total volume (Figure 7). Muddy substrates have been completely dolomitized, and show characteristic intercrystalline and moldic porosity. Estimated range is 5%-20% for average amount of porosity. Although thin-section studies show this unit consists entirely of mud, the distribution of micrite indicates these fine-grained constituents have been organized into fecal pellets in bioturbation (Keswani and Pemberton, 2006).

Petrographic studies on bioturbated dolomudstones show nearly complete pelletization of muddy substrates (Keswani and Pemberton, 2006). Fecal pellets comprise 60%-80% of the total volume of micrite within the bioturbated mudstones. The pellets define burrow-fabrics consisting of concentric and tangential alignments, and abundance patterns ranging from clustered-interpenetrating to homogenized textures (Figure 7). These indiscrete fabrics are associated with bioturbate texture-selective dolomites, consistent with reservoir development.

DISCUSSION

Applications of ichnology represents a powerful tool useful in exploration and development geology. Studies on the upper Midale Beds highlight such applications, including significance of both discrete trace fossils, and indiscrete aspects of bioturbate textures. Such an integrated approach demonstrates the

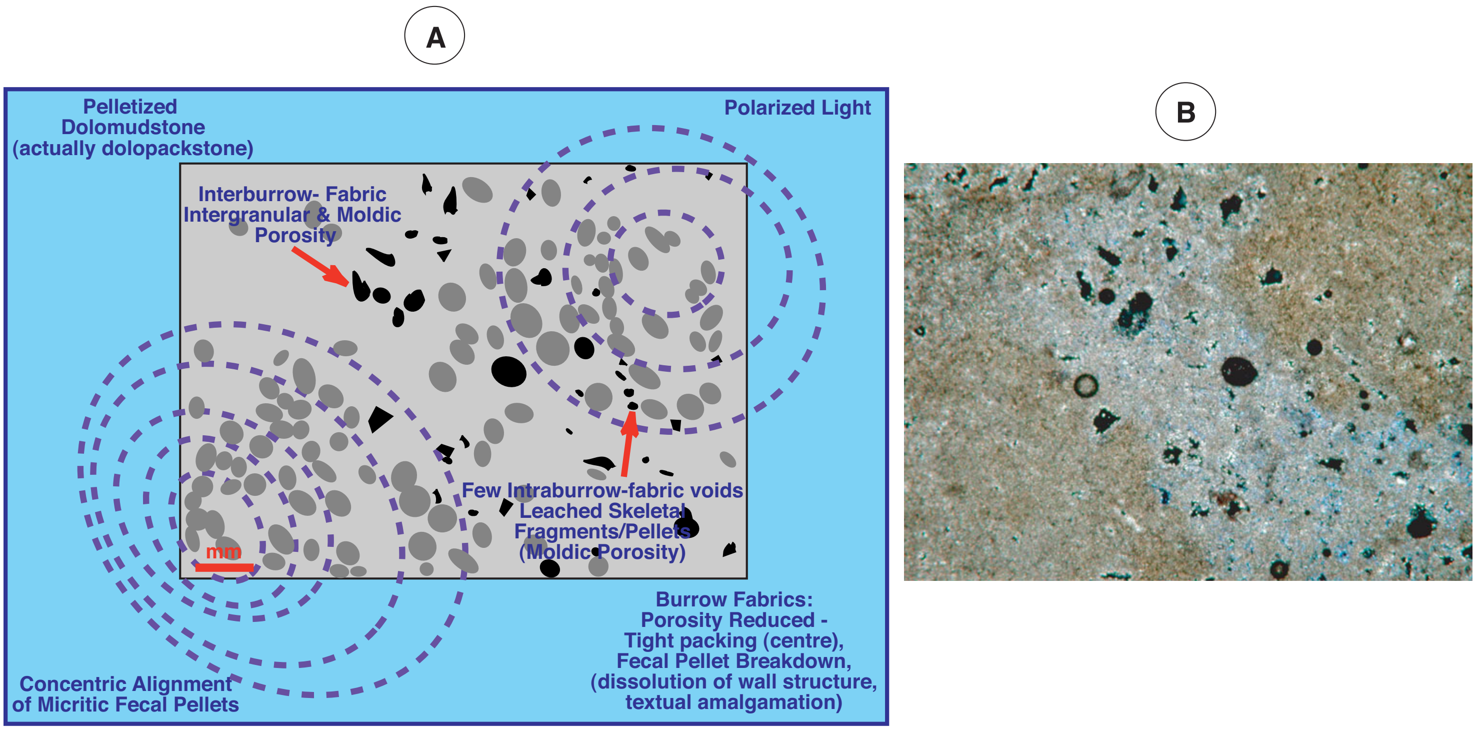


Figure 7. Upper Midale Beds. (A) Schematic and (B) photomicrograph of the reservoir strata at Weyburn Oilfield, These bioturbated dolomudstones show nearly complete pelletization of mud, and early development of intergranular porosity. Such voids facilitated percolation of Mg-bearing fluids in dolomitization, origin of intercrystalline porosiy. Local differences in porosity and permeability influenced development of interburrow-fabric moldic porosity, which enhanced reservoir quality. Hence, biogenically-produced textural heterogeneities have a profound impact on porosity-permeability relationships that influenced fluid flow in diagenesis, and quality of the carbonate reservoir.

strengths of ichnologic studies for understanding origins of detrital carbonate reservoirs.

Discrete Trace Fossils

Significance of substrate-controlled biogenic structures is briefly outlined, including borings and trace fossils. First, characteristics of borings, particularly the nature of constituents in fills, provide insights on the genetic significance of the hardground surface. In petroleum geology, subsurface mapping of this surface is significant in delineating the extent of potential reservoir strata, represented in overlying bioturbated dolomudstones.

Application of the ichnofacies concept to bioturbated dolomudstones provide insights on paleoenvironments. Biotic processes reflected in characteristics of the ichnologic record indicate sedimentary dynamics associated with deposition of upper Midale Beds at Weyburn Oilfield, where body fossils are absent within dolomudstones. lPaleoecological significance of distal-*Cruziana* ichnofacies is documented (Keswani and Pemberton, 1993, 2006). Furthermore, this approach is useful in construction of a sedimentary-paleoecological framework for understanding the roles of bioturbation on carbonate diagenesis in reservoir development. For example, characteristic distal-*Cruziana* ichnofacies show forms that reflect trophic groups consisting of mostly deposit-feeders and grazers (Keswani and Pemberton, 1993). Predominance of deposit-feeding activities reflects paleeobiological response to flooding, and mud deposition in relatively stable outer ramp settings. Organism-sediment interactions resulted in nearly complete pelletization of muddy substrates.

Indiscrete Bioturbate Textures

Rampant deposit-feeding activities and production of fecal pellets represent common behaviors reflected in sedimentary and ichnologic records of offshore marine settings (Cuomo and Rhoads, 1987; Kotake, 1989; Cuomo and Bartholomew, 1991; Ekdale and Lewis, 1991; Ekdale, 1992; Miller and d'Alberto, 2001; Palomo *et al*., 2004). Such paleobiological processes generated textural heterogeneities that have a profound impact on carbonate diagenesis, and reservoir quality. Characterization of heterogeneities within bioturbated dolomudstones provide insights on intrinsic controls on porosity-permeability relationships. Pemberton and Gingras (2005) outlined a range of biogenically-enhanced permeability that affects flow dynamics. In upper Midale Beds widespread bioturbation has resulted in re-organization of the mud into fecal pellets, and introduced intergranular voids in otherwise relatively impermeable substrates. The relatively low permeability characteristics of muddy substrates have been documented (Neuzil,1994; Mallon and Swarbrick, 2002; Mallon et.al.,2005) Fluid flow dynamics associated with dolomitization and leaching have been facilitated by biogenically-enhanced permeability in muddy substrates. Such diagenetic processes resulted in textural changes; and evolution of porosity-permeability relationships, including origin of intercrystalline and moldic voids, respectively.

Application of genetic classification schemes in petrographic analyses show textural heterogeneities are defined by concentric and tangential alignments in fecal pellets, and abundance patterns ranging from clustered-interpenetrating to homogenized substrates. Origin of bioturbate texture-selective dolomites associated with such abundance patterns suggest connectivity in voids facilitated percolation of Mg-bearing fluids. Furthermore, distribution patterns in moldic porosity indicates burrow-fabrics also facilitated percolation of leaching fluids in dissolution of former skeletal fragments aligned by boturbating organisms. Accordingly, paleobiological processes and subsequent diagenetic changes generated textural modifications from mudstone-wackestone to pelletoidal packstone (or pelleted mudstone-wackestone) to dolomudstone within reservoir strata. But, an important question arises: how do characteristics of burrow-fabrics influence fluid flow dynamics associated with carbonate diagenesis and porosity evolution?

Application of genetic classification schemes for porosity and permeability characteristics in bioturbated substrates is useful for understanding the nature of intrinsic paleobiological controls on reservoir development. For example, intergranular porosity associated with widespread pelletization of muddy substrates show characteristic distribution patterns in voids related to bioturbate textures. Such textural heterogeneities indicate fecal pellets arranged in bioturbation has generated two types of intergranular porosity: (1) intraburrow-, and (2) interburrow-fabric voids. Consequently, intercrystalline porosity associated with widespread origin of paleobiologically-influenced dolomites; and moldic porosity linked to alignment of former skeletal fragments in spreiten suggest connectivity of both intra, and interburrow-fabric voids. Such interconections were preserved in porosity evolution. Porosity variations included production of intergranular voids in bioturbation; and origin of intercrystalline and moldic voids in subsequent stages of diagenesis..

Textural classification provides a tool useful in understanding the roles of bioturbation in enhancement of permeability, and percolation of diagenetic fluids in muddy substrates. Classes of burrow-fabrics such as concentric and tangential alignments show connectivity of voids are related to paleobiological modification in grain-size by pelletization of mud; and arrangement of fecal pellets and former skeletal fragments within spreiten and wall-structures. Furthermore, abundance patterns in burrow-fabrics played a key role in enhancement of permeability. Amalgamation of burrow-fabrics in reworking of previously bioturbated substrates has produced interpenetrating and homogenized fabrics. Such genetic classes in burrow-to-burrow relationships have an enhancing effect on permeability, where connectivity of intergranular porosity remains preserved within spreiten and wall-structures. Hence, extent of bioturbation plays a direct role in enhancement of local permeability to amounts that affect fluid-flow dynamics in diagenesis of reservoir strata at ichnofacies scale.

An understanding of biogenically-enhanced permeability is useful for modeling flow dynamics in diagenesis and porosity evolution in bioturbated detrital cabonates; and for implementing effective strategies in exploitation of hydrocarbons from reservoir strata (Gingras *et al.,* 2004a,b; Pemberton and Gingras, 2005; Keswani and Pemberton, 2006). Bioturbated dolomudstones show development of local permeable conduits in burrow fabrics, and abundance patterns ranging from interpenetrating and homogenized textures represent inherent characteristics that enhanced reservoir quality. Since amalgamation resulted from increased abundance and interpenetration of spreiten and wall-structures, these morphological elements manifest in textural relationships facilitated cross burrow-fabric fluid flow (Figure 8). Thus, inherent paleobiological controls played important roles in setup of such a combined flow regime, where fluid migration was influenced by the nature of interconnections in intra- and interburrow-fabric voids.

In future research on applications of ichnology, many ideas outlined in this paper provide a conceptual base for construction of new diagenetic models and improved reservoir characterization. In development of new reservoir models, integration of paleobiological data represents a strengthening of traditional approaches to carbonate sedimentology and diagenesis. Such an integrated approach is useful for understanding fluid flow dynamics and patterns of crystal growth, and development of fabrics derived from ingrowth (host-to-burrow) and outgrowth (burrow-to-host) mechanisms, and variations in porosity-permeability relationships.

CONCLUSIONS

Applications of ichnology provide a tool useful in exploration and exploitation of reservoir strata in detrital carbonate deposits. An integrated approach has demonstrated core studies on discrete trace fossils provide data useful for paleoenvironmental reconstructions in reservoir modeling; and petrographic analyses on indiscrete aspects of bioturbate textures facilitate

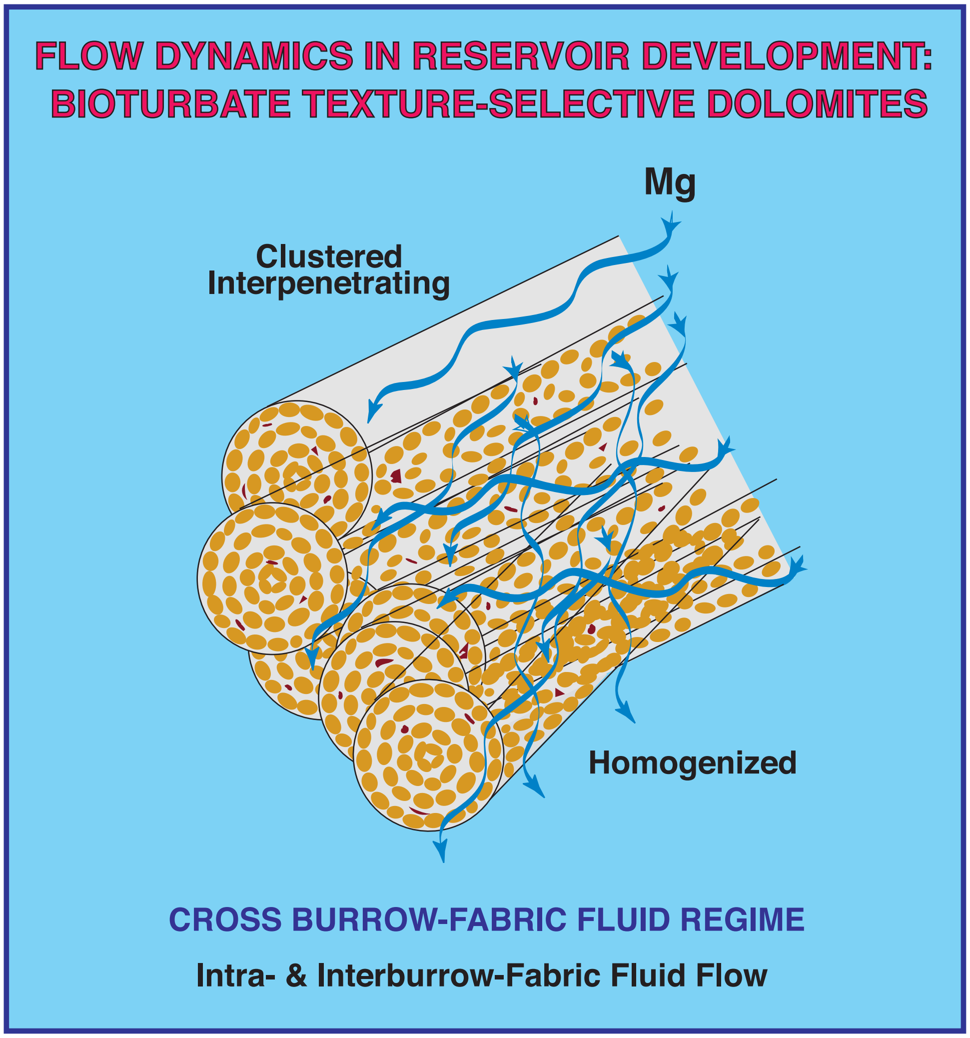


Figure 8. Schematic. Fluid flow dynamics in burrowed substrates of the upper Midale Beds, Weyburn Oilfield (well 2-12-6-14W2). Widespread bioturbation in muddy substrates resulted in nearly complete pelletization of mud. Biogenic arrangements in fecal pellets define burrow-fabrics comprised of concentric and tangential alignments, and abundance patterns range from clustered interpenetrating to homogenized textures. These patterns are associated with bioturbate texture-selective dolomites, consistent with reservoir development. Origin of such paleobiologically-influenced dolomite reservoirs have been linked to fluid-flow dynamics. Mg-bearing fluids percolate in muddy substrates due to formation of intergranular porosity in pelletization; and development of connectivity in voids by alignment of fecal pellets in spreiten and wall-structures. Furthermore, connectivity is enhanced by interpenetration of wall-structures and complete homogenization of substrates. Biogenically-enhanced permeability is a function of tectural controls. These textural heterogeneities influence the degree of cross burrow-fabric fluid flow in dolomitization and leaching at later stages in diagenesis. The setup of a cross burrow-fabric fluid regime, includes both intra- and interburrow flow, in otherwise impermeable muddy substrate.

reservoir characterization, particularly regarding genetic interpretations on porosity evolution, biogenically-enhanced permeability and implications for fluid-flow. This study highlights reservoir strata at Weyburn Oilfield, which consists of bioturbated dolomudstones, characterized by a distal-*Cruziana* trace fossil assemblage. This ichnofacies suggest development of fully-marine conditions in a major transgression.

Petrographic studies on reservoir strata indicate near complete pelletization of mud. These bioturbated dolomudstones show indiscrete textures comprised of concentric and tangential alignments in fecal pellets, and burrow-fabrics range from clustered interpenetating to homogenized relationships in abundance patterns. Biogenically-enhanced porosity consist of intergranular intra- and interburrow fabric voids. Connectivity in such voids define both grain-size and alignment-related permeability in burrow-fabrics. Morphological elements in burrow-fabrics, including spreiten and wall-structures, enhanced local permeability and significantly influenced fluid flow in dolomitization and leaching. Furthermore, abundance patterns facilitated development of a cross burrow-fabric fluid regime, characterized by both intra- and interburrow flow dynamics at ichnofacies scale.

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