geoconvention
Calgary • Canada • May 13-17 2019

Applied Ichnology In Reservoir Geology: A New Biogenic-Diagenetic Model For Dolomites In Mississippian Upper Midale Beds, Weyburn Oilfield, Saskatchewan

Arjun D. Keswani and S.George Pemberton
Department of Earth & Atmospheric Sciences

Summary

Bioturbated dolomudstones of the Mississippian Upper Midale Beds at Weyburn Oilfield, Saskatchewan, has been selected to highlight applications of ichnology in reservoir geology. This study is based on an integrated genetic approach to applied ichnology that utilizes the traditional ichnofacies concept for mapping reservoir strata at upscale observations in cores; yet, the study includes genetic data on such bioturbate textures at downscale observations in thin-section petrography. Such petrographic studies on genetically-significant aspects of the ichnologic record in dolomudstones provide an independently-derived paleobiological data set useful for interpretations of intrinsic controls on dolomitization and reservoir development; and, variations in quality, which define internal architecture and performance. Such an integrated approach builds on genetic significance of the ichnofacies concept, and expands on applications of bioturbate textures to reservoir modelling, particularly regarding significance of modified fabrics in shaping fluid dynamics during diagenesis, and post-dolomitization, also. These links in biogenic-diagenetic relationships represent controls on dolomitization; and influences on characterization and compartmentalization of the reservoir. Hence, an integrated paleobiological approach in construction of a new biogenic-diagenetic reservoir model includes both aspects of the ichnologic record, discrete trace fossils in upscale studies, and indiscrete bioturbate textures in downscale petrographic analyses; and local variations in associated dolomite fabrics, which influence fluid-flow, and construction of baffles and barriers. This model clearly highlights applications of ichnology extend beyond traditional approaches of using trace fossil assemblages within an ichnofacies framework for paleoenviromental reconstructions in sedimentology and genetic stratigraphy.

Since widespread distribution of bioturbate textures within dolomudstones indicate significant paleobiological controls on diagenesis, and origin of reservoir heterogeneities, the Upper Midale Beds was selected for construction of an integrated biogenic-diagenetic model. Reservoir strata are characterized by trace fossils consistent with a distal-*Cruziana* ichnofacies, which suggests mud deposition occurred in stable, deeper-water, marine settings on outer areas of a carbonate ramp (Keswani and Pemberton, 1993, 2007; Nimegeers and Qing, 2002; Qing and Nimegeers, 2008). These dolomudstones show a diverse ichnofossil suite, comprised mostly of *Zoophycos*, *Planolites* and *Chondrites*, some *Helminthopsis*, *Asterosoma*, *Teichichnus* and *Palaeophycus,* and rare *Siphonichnus.* These forms indicate extensive deposit-feeding activities were facilitated by stability in paleoecological conditions that were conducive to

grazing behaviours in organic-rich substrates that produced significantly modified textural characteristics, including completely pelletized mud, and much spreiten-defined fabrics (Keswani and Pemberton, 1993, 2007).

To evaluate diagenetic effects of biogenic re-organization of mud into fecal pellets, and introduction of intergranular porosity-permeability variations associated with local textural heterogeneities, thin-section petrographic analyses is required. However, extension of genetic principles in applied ichnology to thin-section scale requires new tools to investigate biotic processes, which are consistent with the strengths of the ichnofaceis concept. Since bioturbate textural characteristics and dolomite fabrics are inherently linked, a genetically-integrated framework facilitates both forward and reverse interpretations on origins of the reservoir, and variations in its economic parameters. Yet, this study on utilization of an integrated approach to modelling reservoir development and quality, suggests no one-to-one links between genetic classes of burrow-fabrics in thin-sections and trace fossils. Because these petrographic schemes are based on genetic criteria related to biotic processes, paleobiological data sets derived from textural characteristics in thin-sections are consistent with ichnofacies concept of mappable units in fossil behaviours; and predictability associated with recurrent ichnofacies in bioturbated dolomudstones at reservoir scale. Notwithstanding, an evaluation of various reservoir parameters linked to biogenic-diagenetic processes is inevitably dependent upon the extent to which dolomites reflect burrow-fabrics (reverse interpretations), and *vice versa* (forward interpretations).

Since organism-sediment interactions produced local textural heterogeneities from pelletization of muddy substrates, and introduced intergranular porosity; and biotic processes interconnected such voids, which permeable conduits for percolation of diagenetic fluids, the characteristics of biogenically-modified fabrics provide insights on setup of fluid regimes in dolomitization within otherwise impermeable mudrocks. Hence, an understanding of fossil behaviours manifest in bioturbate textural characteristics is significant in modelling reservoir quality and performance. Petrographic analyses of reservoir strata show bioturbated dolomudstones are predominantly comprised of fecal pellets, which define burrow-fabrics consisting of concentric and tangential alignments, and abundance patterns ranging from clustered-interpenetrating to homogenized textures. Such indiscrete fabrics are associated with bioturbate texture-selective dolomites, which are genetically consistent with reservoir development. However, the setup of a cross burrow-fabric fluid flow regime in dolomitization was facilitated by biogenically-produced intergranular porosity showing distribution patterns, characteristic of both intraburrow- and interburrow-fabric voids; and, grain-size change, and alignment-defined permeable conduits. Also, growths of paleobiologically-influenced dolomites were facilitated by abundance of fecal pellets providing nucleation sites for widespread crystallization, and origin of intercrystalline porosity-permeability in diagenetic evolution of the reservoir. Furthermore, enhanced characteristics are associated with local distributions of burrow-fabrics, where permeable-conduits percolated dissolution fluids that leached out skeletal fragments aligned in bioturbation. Such locally-enhanced zones in reservoir quality are indicated by distribution of moldic voids that reflect alignment-defined burrow-fabrics imprinted previously. Therefore, mapping such bioturbate textural heterogeneities using new genetic classification schemes provide insights on developments of permeability flow-units. These mappable textural units comprised of biogenic-diagenetic fabrics are useful for modelling compartmentalization of giant dolomite reservoirs, including effective porosity-permeability characteristics defining productive zones; and, local variations controlling internal architecture, such as parameters comprising baffles and barriers.

An important question arises on construction of predictive models for reservoir architecture in dolomudstones showing significant biogenic-diagenetic controls: how is paleoecological significance of bioturbate textures applied in deciphering mappable fluid-flow units? To illustrate this concept, a mappable flow-unit is defined as genetically-linked textural heterogeneities outlined by common biogenic-diagenetic fabrics that formed similar porosity-permeability qualities, and distribution patterns linked to biotic processes. Since new genetic classification schemes provide tools for understanding roles of such paleobiological processes in reservoir development, the characteristics of biogenic-diagenetic fabrics and associated porosity-permeability relationships are inherently linked to marine benthic paleocommunity dynamics. Hence, applications of traditional paleoecological concepts facilitate construction of models on reservoir architecture, defined by mappable textural units that vary in quality and performance. For purposes of building such reservoir models based on biogenic-diagenetic fabrics, and textural relationships in porosity-permeability variations, new classification schemes are applied for understanding both quality and distribution patterns of fluid-flow units in paleobiologically-influenced dolomites. Typically, such mappable bioturbate textural units within reservoir strata show anisotropy in porosity-permeability data, where parts of burrowed substrates highlight locally-enhanced, or -reduced quality (Gingras *et al*., 1999; Pemberton and Gingras, 2005). However, distribution patterns among units of bioturbated textural heterogeneities, and dolomites characterized by similar fluid-pressure levels, indicate compartmentalization of the reservoir. Thus, applications of traditional paleoecological concepts on spatial relationships in biotic processes, provide insights on reservoir structure and function.

Since deposit-feeding activities resulted in structured paleocommunities in outer-ramp settings, distribution patterns in bioturbate textural heterogeneities, and associated dolomites and diagenetic signatures, produced a layout of flow-units varying in economic quality, where relationships in fabrics and permeable conduits comprise baffles and barriers (Keswani and Pemberton, 1993, 2007). Such variations in biogenic-diagenetic fluid-flow units, and textural aspects of permeability characteristics influenced compartmentalization of the reservoir. Aspects of internal structure, such as baffles and barriers within a reservoir are defined essentially by variations in textural heterogeneities, including morphological elements and grain-size characteristics of burrow-fabrics, and burrow-to-burrow relationships; and by the characteristics of paleobiologically-influenced dolomite fabrics. Therefore, applications of new genetic classification schemes provide tools for interpretations on origin of reservoir architecture, where characteristics of mappable flow-units have been defined by distribution patterns in bioturbate textures, dolomites and diagenetic fabrics. These inherent relationships in biogenic-diagenetic fabrics control aspects of quality and performance of permeable conduit systems in reservoirs. However, such an approach to construction of biogenic-diagenetic models on reservoir architecture and performance are limited by the extent to which bioturbate textural heterogeneities provide a blueprint for mappable fluid-flow units in altered substrates.

To evaluate bioturbate textural controls on reservoir quality and performance, this study proposes a paleoecology-based scheme for deciphering mappable flow-units associated with biogenic-diagenetic fabrics. Applications of such a textural classification scheme on variations in quality, and distribution patterns in permeability are useful for interpretations on reservoir compartmentalization. This scheme is based on the notion that textural variations reflect differences in deposit-feeding-behaviours in paleoecommunity dynamics; and, distribution patterns in burrow-fabrics and associated dolomites define quality and characteristics of permeable flow-units. These paleoecologically-controlled variations in mappable flow-units are inherently linked to the characteristics of bioturbate textural heterogeneities that outline distribution patterns among baffles and barriers, which parameterize reservoir architecture. An understanding of such parameters in reservoir structure and function have economic significance regarding performance, and calculations of reserve volumes in hydrocarbons.

This study proposes a textural classsification scheme for reservoir quality and distribution patterns, where paleoecology provides a foundation useful for understanding bioturbation-derived heterogeneities that influence origin of diagenetic fabrics, and characteristics of permeable conduits and flow-units, including variations in baffles and barriers defining reservoir architecture. Applications of this scheme is useful in building reservoir models based on textural relationships derived in feeding dynamics, including tiering and niche differentiation, as primary controls on distribution patterns in dolomites and diagenetic fabrics, intercrystalline porosity-permeability variations, and developments of permeable conduits in flow-units. Since characteristics of bioturbate textures inherently control processes in diagenesis, applications of these genetic classification schemes represent tools for modelling reservoir parameters, including quality and distribution patterns in permeable flow-units that result in compartmentalization. Mapping such textural flow-units that define fluid-pressure compartments is facilitated by using aspects of feeding behaviours as tools to understand variations in fabrics linked to developments of dolomites, and porosity-permeability relationships that resulted in tortuosity and anisotropy in conduit systems. Therefore, such a paleoecological approach to modelling reservoirs through classifications of bioturbate textural heterogeneities, associated dolomites and diagenetic fabrics provide insights on variations in the quality of flow-units, including characteristic baffles and barriers that result in fluid-pressure compartmentalization.

Accordingly, a bioturbate textural classification scheme for tiering-defined tortuosity is proposed in regard to aspects of permeable-conduits, inherently linked to burrow-fabrics produced at varying depths in deposit-feeding activities. Likewise, genetic characteristics of burrow-fabrics provide insights on such behavioural controls on diagenetic fabrics, including textural aspects of baffles and barriers, defined by amounts of fitted versus non-fitted dolomite crystals, which outline reservoir qualities ranging from non-reservoir to poor, reduced, and good to optimal levels. Furthermore, distribution patterns in such variations of reservoir quality define productive versus non-productive zones, where constituent burrow-fabrics reflect paleoecological dynamics related to availability of trophic resources that range from unlimited to limited food; and, bioturbate textures show distribution patterns varying from random to aggregated to uniform spatial relationships, respectively. These genetic linkages manifest in the characteristics of paleobiologically-influenced dolomites, highlight the usefulness of applying paleoecological concepts to gain insights on variations in diagenesis, and intrinsic controls on reservoir architecture defined by textural parameters of an ichnofacies. Therefore, applications of paleoecology-based textural classification schemes demonstrate that variations in flow-units have resulted from deep-burrowing activities in resource-rich muddy substrates, where interpenetration of burrow-fabrics has occurred without complete homogenization in coprophagy; and, these organism-sediment interactions produced extensive connectivity of spreiten-defined permeable conduit systems. Textural evolution in diagenesis, and enhanced reservoir quality are essentially controlled by widespread development of such conduit systems, which facilitated bioturbate texture-selective dolomitization; and, percolation of leaching fluids resulted in moldic voids within morphological elements of burrow-fabrics; and, improved intercrystalline porosity-permeability relationships and effectiveness of the reservoir, locally.

Acknowledgements

We are grateful to Saskatchewan Industry and Resources, Subsurface Geological Laboratory for access to the core research facilities, and we extend thanks to Erik Nickel and Andrew Nimegeers for their support. We recognize support from Don Resultay for preparing thin-sections and polishing core samples at the Department of Earth & Atmospheric Sciences. We thank Randy Pakan for help with core photography. We acknowledge financial support from the University of Alberta Ph.D. Scholarship.

References

Gingras, M.K., Pemberton, S.G., Mendoza, C.A. and Henk, F., 1999, Assessing the Anisotropic Permeability of *Glossifungites* Surfaces, Petroleum Geoscience (1999) 5 (4): 349-357.

Keswani, A.D. and Pemberton, S.G., 2007, Applications of Ichnology in Exploration and Exploitation of Mississippian Carbonate Reservoirs, Midale Beds, Weyburn Oilfield, Saskatchewan, Let It Flow - The Flow of Ideas, Hydrocarbons and Business, Canadian Society of Petroleum Geologists and Canadian Society of Exploration Geophysicists Conference, May 14-17, Calgary, Alberta, Canada, 28 p.

_____ , 1993, Sedimentology, Ichnology, and Paleoecology of the Mississippian Midale Carbonates in the Williston Basin, Radville Area, Saskatchewan: Preliminary Interpretations: *in* R. Karvonen, J. Den Haan, K. Jang, D. Robinson, G. Smith, T. Webb, J. Wittenberg, eds., Carboniferous to Jurassic Pangea, Core Workshop Guidebook, Canadian Society of Petroleum Geologists, Calgary, p. 206-228.

Nimegeers, A.R. and Qing, H., 2002, Depositional Model of the Mississippian Midale Beds, Steelman Field, Southeastern Saskatchewan, Summary of Investigations, Volume 1, Saskatchewan Geological Survey, Saskatchewan Industry and Resources, Misc. Reports 2002-4.1, p. 47-67.

Pemberton, S.G., and Gingras, M.K., 2005, Classification and Characterizations of Biogenically-Enhanced Permeability, AAPG Bulletin 89 (11): 1493-1517.

Qing, H. and Nimegeers, A.R., 2008, Lithofacies and Depositional History of Midale Carbonate-Evaporite Cycles in a Missisippian Ramp Setting, Steelman-Bienfait Area, Southeastern Saskatchewan, Canada, Bulletin of Canadian Petroleum Geology, 56 (3), p. 209-324.