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Research paper

An ichnological-assemblage approach to reservoir heterogeneity assessment in bioturbated strata: Insights from the Lower Cretaceous Viking Formation, Alberta, Canada

Andrew D. La Croix [a], [*], James A. MacEachern [b], Korhan Ayranci [c], Amy Hsieh [b], Shahin E. Dashtgard [b]

[a] Energy Initiative, University of Queensland, Brisbane, Queensland 4072, Australia
[b] Applied Research in Ichnology and Sedimentology (ARISE) Group, Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby V5A 1S6, BC, Canada
[c] Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, University of Alberta, Edmonton T6G 2E3, Alberta, Canada

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ABSTRACT

Facies-scale trends in porosity and permeability are commonly mapped for reservoir models and flow simulation; however, these trends are too broad to capture bed and bed-set heterogeneity, and there is a need to up-scale detailed, bed-scale observations, especially in low-permeability reservoir intervals. Here we utilize sedimentology and ichnology at the bed- and bedset-scale to constrain the range of porosity and permeability that can be expected within facies of the Lower Cretaceous Viking Formation of south-central, Alberta, Canada.

Three main facies were recognized, representing deposition from the middle shoreface to the upper offshore. Amalgamated, hummocky cross-stratified sandstone facies (Facies S_{HCS}) consist of alternations between intensely bioturbated beds and sparsely bioturbated/laminated beds. Trace fossil assemblages in bioturbated beds of Facies S_{HCS} are attributable to the archetypal *Skolithos* Ichnofacies, and are morphologically characterized by vertical, sand-filled shafts (VSS). Bioturbated beds show poor reservoir properties (max: 10% porosity, mean: 85.1 mD) compared to laminated beds (max 20% porosity, mean: 186 mD). Bioturbated muddy sandstone facies (Facies S_B) represent trace fossil assemblages primarily attributable to the proximal expression of the *Cruziana* Ichnofacies. Four ichnological assemblages occur in varying proportions, namely sediment-churning assemblages (SC), horizontal sand-filled tube assemblages (HSF), VSS assemblages, and mud-filled, lined, or with spreiten (MLS) assemblages. Ichnological assemblages containing horizontal (max: 30% porosity, mean: 1.28 mD) or vertical sand-filled burrows (max: 10% porosity, mean: 2.2 mD) generally have better reservoir properties than laminated beds (max: 20% porosity, mean: 0.98 mD). Conversely, ichnological assemblages that consist of muddy trace fossils have lower porosity and permeability (max 10% porosity, mean: 0.89 mD). Highly bioturbated, sediment churned fabrics have only slightly higher porosity and permeability overall (max: 15% porosity, mean: 1.29 mD). Bioturbated sandy mudstone facies (Facies M_B) contain ichnofossils representing an archetypal expression of the *Cruziana* Ichnofacies. Four ichnological assemblages occur throughout Facies M_B that are similar to Facies S_B; SC, HSF, VSS, and MLS assemblages. The SC (max: 15% porosity, mean: 21.67 mD), HSF (max: 20% porosity, mean: 3.79 mD), and VSS (max: 25% porosity, mean: 7.35 mD) ichnological assemblages have similar or slightly lower values than the laminated beds (max: 20% porosity, mean: 10.7 mD). However, MLS assemblages have substantially lower reservoir quality (max: 10% porosity, mean: 0.66 mD).

Our results indicate that the most likely occurrence of good reservoir characteristics in bioturbated strata exists in sand-filled ichnological assemblages. This is especially true within the muddy upper offshore to lower shoreface, where vertically-oriented trace fossils can interconnect otherwise hydraulically isolated laminated sandstone beds; this improves vertical fluid transmission. The results of this work largely corroborate previous findings about ichnological impacts on reservoir properties. Unlike previous studies, however, we demonstrate that the characteristics of the ichnological assemblage, such as burrow form and the nature of burrow fill, also play an important role in determining reservoir

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[*] Corresponding author.
E-mail address: a.lacroix@uq.edu.au (A.D. La Croix).

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characteristics. It follows that not all bioturbated intervals (attributed to the same facies) should be treated equally. When upscaling bed-scale observations to the reservoir, a range of possible permeability-porosity values can be tested for model sensitivity and to help determine an appropriate representative elementary volume.

1. Introduction

Porosity and permeability are dominant controls on the storage capacity, production rate, and recovery of hydrocarbons from subsurface reservoirs. Fractures, lithology, compaction, cementation, and diagenesis have been well studied with respect to their relationship(s) to porosity and permeability (e.g., Weber, 1982; Long and Witherspoon, 1985; Houseknecht, 1987; McKinley et al., 2004; Ehrenberg and Nadeau, 2005). In the field of applied ichnology, the last few decades have seen many studies examining the effects of bioturbation on reservoir properties (e.g., Qi, 1998; Gingras et al., 1999; Pemberton and Gingras, 2005; Cunningham et al., 2009; Tonkin et al., 2010; Gingras et al., 2012; La Croix et al., 2012; La Croix et al., 2013; Baniak et al., 2014b; Knaust, 2014; Bednarz and McIlroy, 2015; Hsieh et al., 2015). This is due to the increasing importance of unconventional reservoir types.

In low-permeability reservoirs (i.e., <0.1 mD; Spencer, 1989), horizontal drilling and hydraulic fracture stimulation are used to induce economic production rates and larger recovery volumes from mature fields. The halos — hydrocarbon-charged reservoir on the peripheries of mature fields — cannot be economically produced using conventional drilling methods. Hydraulic fracturing is one method of producing from halo plays, but the effectiveness of “fracking” depends on the character of the original porosity and permeability (Britt et al., 2004), which are typically assessed based on lithologic properties. In the Cretaceous Viking Formation, and in other similar reservoirs in southern and central Alberta, such as the Cardium Formation (e.g., Clarkson and Pedersen, 2011; Friesen et al., 2017), variably bioturbated intervals abound, and the permeability more closely correlates with sedimentary facies than it does with lithology alone (Hsieh et al., 2015).

In this study, we undertake a combined sedimentological-ichnological assessment of three subsurface cores to analyze the distribution of porosity and permeability in the Lower Cretaceous Viking Formation in the Western Canada Sedimentary Basin. We examine reservoir properties at the bed-scale to compare them to the porosity and permeability that occurs within facies-scale packages of rock. This study elucidates a strategy for assessing and characterizing bed- and bedset-scale assessments of bioturbation (i.e., ichnological assemblages) for predicting ichnological effects on porosity and permeability away from the wellbore.

2. Background

Bioturbation can improve petrophysical properties or be detrimental to them, depending on the characteristics of the sedimentary facies. Porosity improvement occurs where burrow fills are coarser grained than the surrounding media (Gingras et al., 2004a; Pemberton and Gingras, 2005; Tonkin et al., 2010; Lemiski et al., 2011; La Croix et al., 2013; Baniak et al., 2015; Friesen et al., 2017). Permeability enhancement under these conditions is related to the degree of interconnectivity between burrows, as well as the permeability contrast between the burrows and matrix (Cunningham et al., 2009; Gingras et al., 2012; La Croix et al., 2012; Bednarz and McIlroy, 2015). By contrast, porosity and permeability can be largely obliterated due to increased sediment compaction, biogenically-driven disruptive grain sorting, and the introduction of mud linings or muddy burrow fills (Qi, 1998; Tonkin et al., 2010; Gingras et al., 2012). Burrow-associated diagenesis is also a factor that commonly results in improved porosity and permeability (Gingras et al., 2004b; Zorn et al., 2007; Baniak et al., 2013), and is particularly applicable to carbonate reservoirs due to the reactivity of carbonate minerals.

Trace fossils generally increase heterogeneity and anisotropy in flow media, and complex flow networks in two or three dimensions are common (Gingras et al., 2004a, 2012). Such burrow networks can cross cut bedding plane boundaries, and interconnect otherwise hydraulically isolated layers (La Croix et al., 2013). In some exceptional instances, the anisotropic bioturbation is a primary contributor to reservoir production, such as in the Arab-D interval within the Ghawar Field, Saudi Arabia (Pemberton and Gingras, 2005). The tortuous flow pathways that result from bioturbation promote matrix-into-burrow diffusion as well as increased dispersivity (Gingras et al., 2004a).

Bioturbation-related porosity and permeability effects have been characterized in various frameworks (Pemberton and Gingras, 2005; Knaust, 2014), each focusing on different facets of ichnofabrics and their relationship(s) to the stratigraphy and sedimentology of the reservoir interval. Pemberton and Gingras (2005) recognized five categories of bioturbation-mediated porosity and permeability based on the final appearance of the bioturbate heterogeneity. These categories were later amended in Gingras et al. (2012) and comprise surface constrained, non-surface constrained, weakly-defined, cryptic, and diagenetic textural heterogeneity. Such bioturbate fabrics can arise from combination of sedimentological, ichnological, and diagenetic factors. This scheme has proven useful for characterizing the types of heterogeneity and their relationship(s) to fluid flow, but is less predictive in nature, because it is only passively tied to the paleoenvironmental interpretation of the sedimentary successions.

Another method of systematically characterizing the effects of ichnofabric on fluid flow was developed by Knaust (2014). His system consists of three categories: microbioturbation, meiobioturbation, and macrobioturbation. Macrobioturbation is further subdivided into three groups: bioturbate texture, burrows, borings, and root traces. The focus of Knaust's scheme is to understand the types of fabrics that result at or near the time of deposition. Knaust (2014), however, used a case study of carbonate rocks from the Permo-Triassic Khuff Formation from the Pars Field, offshore Iran to propose his scheme. It is unclear, at present, how these categories relate to siliciclastic strata. Further, it is not clear that the same classification scheme can be applied to other depositional environments. Both schemes leave room for additional case studies to refine their frameworks, particularly those of a predictive nature that can be applied to hydrocarbon or water resource exploitation in the subsurface.

3. Geological setting

The Viking Formation is a Lower Cretaceous (Late Albian)