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Organism–sediment interactions in shale-hydrocarbon reservoir facies — Three-dimensional reconstruction of complex ichnofabric geometries and pore-networks

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ABSTRACT

The lithological and mineralogical characteristics of mudstones and siltstones—and their stress–strain behavior at the meter to nanometer scale—can play a critical role in the exploitation of unconventional shale reservoirs. Shale fabrics that result from bioturbation can produce extensive interconnected networks of biologically redistributed sediment grains within reservoir mudstone facies. The presence of biologically generated heterogeneities may substantially affect reservoir stimulation and thus production from shale facies. This study presents volumetric evaluation of ichnofabrics dominated by *Phycosiphon*-like and aff. *Chondrites*, and provides insights into the impact of trace fossils on the rheological and petrophysical characteristics of mudstones. It is calculated that, in addition to creating significant volumes of silty (clay-poor) zones of enhanced porosity and permeability, trace fossils create interpenetrating frameworks of brittle material that reduce communication distances from the low-permeability matrix to the higher permeability silt-rich burrows. Reducing communication distances to less than 1 cm increases the potential for diffusive transport of hydrocarbon molecules from the "tight" matrix to the wellbore-connected volumes. This is because shale ichnofabrics create abundant fracture-prone planes of weakness, and increase the surface area of the interface between the hydrocarbon-rich matrix and porous burrow fills, thereby promoting fluid exchange. Understanding of the three-dimensional characteristics of ichnofabrics may form the basis of future modeling of fracture spacing and complexity that is critical to shale gas reservoir characterization.

1. Introduction

Gas- and oil-bearing shales are lithologically diverse, including interbedded very fine grained sediments e.g., mudstones, siltstones and limestones. Because of the lack of a universal classification system for these lithologically heterogeneous deposits, the word 'shale' is used in this study according to current convention in the hydrocarbon industry rather than the strict lithological usage (e.g., Bustin, 2012). The lithological and mineralogical characteristics of shales and their stress–strain behavior at the meter to nanometer scale play a critical role in the exploitation of unconventional shale reservoirs (e.g., Bustin et al., 2008a,b; Ross and Bustin, 2009; Bustin and Bustin, 2012; Chalmers et al., 2012; Ding et al., 2012; Josh et al., 2012; Spaw, 2013a,b).

The macroscopic and microscopic sedimentary fabrics (including ichnofabrics) determine the distribution of mineral grains and organic matter particles in mudstones that control the porosity, permeability and brittleness of mudstones (e.g. Josh et al., 2012). Individual burrows within an ichnofabric can redistribute sediment grains, thereby influencing both the bulk and small-scale petrophysical properties of the host sediment (e.g., Pemberton and Gingras, 2005; Spila et al., 2007; Tonkin et al., 2010; Lemiski et al., 2011; Bednarz and McIlroy, 2012; Gingras et al., 2012, 2013). Ichnofabric in mudstones or siltstones can also create permeability isotropy by local destruction of sediment laminae (e.g., Schieber, 2003; Pemberton and Gingras, 2005; Lemiski et al., 2011; Bednarz and McIlroy, 2012; Gingras et al., 2012).

The spatial geometry of ichnofabrics reflects the cumulative effects of organism–sediment interactions after deposition (McIlroy, 2004, 2007, 2008) including bioturbation spatial re-distribution of fine-grained minerals and changes in bulk mineralogy (McIlroy et al., 2003; Harazim, 2013). The tortuosity, connectivity, surface area, volume and spatial distribution of the burrows in an ichnofabric are among the most significant factors determining response of the bioturbated mudstone or siltstone to reservoir stimulation techniques (e.g., Pemberton and Gingras, 2005; Gingras et al., 2007, 2012; Bednarz and McIlroy, 2012).

In this study, the potential influence of trace fossils on the petrophysical and rheological properties of hydrocarbon-bearing shale

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facies is presented. In contrast to our earlier work, we here consider the complete ichnofabric present in each studied sample rather than focusing on the reconstruction and quantification of isolated burrows (Bednarz and McIlroy, 2009, 2012). The term "aff. *Chondrites*" is used herein to encompass all *Chondrites* sensu stricto (s.s.) and other trace fossils closely resembling *Chondrites* isp. (cf. Bromley and Ekdale, 1984; Wetzel and Wijayananda, 1990; Fu and Werner, 1994). The interchangeable terms "aff. *Phycosiphon*", and "phycosiphoniform burrows" relate to an informal grouping of ichnofossils similar to *Phycosiphon* isp. (including *Nereites*) that are not identified to the generic level in ichnofabrics due to unresolved taxonomic issues. All phycosiphoniform burrows are considered to have similar effects on sediment fabric and reservoir quality in shale-hydrocarbon facies (cf. Bednarz and McIlroy, 2012).

Ichnofabrics rich in aff. *Phycosiphon* and aff. *Chondrites* are here reconstructed in three dimensions in order to understand the spatial geometry and distribution of biologically redistributed mineral grains and reservoir properties of shale-hydrocarbon facies. In this study, we do not attempt to remove compaction of the sediment and its impact on the geometry of the burrows. Compaction affects the geometric relationships within ichnofabrics of gas-shales in a heterogeneous manner, but is beyond the scope of this study. The rock volumes reconstructed are not from producing hydrocarbon fields, as the analyses that we perform are destructive of large volumes of rock. As such we have chosen ichnofabrics comparable to those in producing fields as model examples for analogue study.

The computer-modeled deterministic three-dimensional reconstructions allow volumetric consideration of the biogenic pore networks in the studied ichnofabric. The potential impact of aff. *Chondrites* ichnofabrics is addressed herein for the first time, and involves the same principles as used in our recent consideration of phycosiphoniform burrow volumetrics and morphometrics (see Bednarz and McIlroy, 2012). The surface area, density and distribution of three-dimensional architecture of aff. *Phycosiphon* and aff. *Chondrites* ichnofabrics is also assessed herein through the generation of three-dimensional deterministic models of aff. *Chondrites*, and aff. *Phycosiphon* burrows in highly bioturbated sediments.

2. Main ichnofabric-forming trace fossils in hydrocarbon shale facies

The productive lithologies within shale-gas reservoirs commonly have inter-bedded layers of dark organic-rich very fine-grained sediments typically marine mudstones, inter-bedded with siltstones. It has been often considered that the black organic rich mudstones that form the basis of shale hydrocarbon plays were deposited in association with anoxia or severe dysoxia (e.g., Tyson, 1995; Bohacs, 1998; Katz, 2005). The necessity for anoxia for black shale deposition has however been challenged (e.g., Schieber, 1994b, 2003, 2011; Wetzel and Uchman, 1998b; Macquaker et al., 1999; Macquaker and Bohacs, 2007; Schieber et al., 2007; Rodríguez-Tovar and Uchman, 2010; Ghadeer and Macquaker, 2012). A number of recent petrographic studies have demonstrated the presence of bioturbation in shale-hydrocarbon reservoir facies that previously seemed to be devoid of ichnofabric (e.g., Schieber, 2003; Ghadeer and Macquaker, 2012; Egenhoff and Fishman, 2013). It may commonly be the case that bioturbation is present at the microscopic scale, and that both core and outcrop studies lack the resolution to determine such small structures (cf. Wetzel and Uchman, 1998a; Schieber, 2003; Egenhoff and Fishman, 2013).

While dysoxic basins are generally considered to be hostile to macrobenthic organisms, the organic-rich sediments that are deposited host abundant small endobenthic organisms that are tolerant of dysoxic to anoxic pore waters (e.g., Bromley and Ekdale, 1984; Savrda and Bottjer, 1991; Middelburg and Levin, 2009). Such organisms with extreme tolerance to low-oxygen content (e.g., foraminifera) and/or small benthic organisms tolerant even to episodic total anoxia (e.g., nematodes, polychaetes, pogonophores, sipunculid worms and bivalves) are responsible for bioturbation of organic-rich muds (e.g., Seilacher, 1990; Savrda and Bottjer, 1991; Dufour and Felbeck, 2003; Stewart et al., 2005; Arndt-Sullivan et al., 2008; Dando et al., 2008; Dubilier et al., 2008; Middelburg and Levin, 2009). The resulting trace fossil assemblages are typical of stressed ecosystems, in having low diversity, but commonly high abundance (e.g., Goldring et al., 1991; Bottjer and Savrda, 1993; Angulo and Buatois, 2012a,b). The chemosymbiotic organisms (i.e. organisms having microbial symbionts capable of anaerobic respiration) from among the abovementioned phyla are the most likely to be candidate producers of *Chondrites* and *Trichichnus* (e.g., Swinbanks and Shirayama, 1984; Seilacher, 1990, 2007; Fu, 1991; Zuschin et al., 2001). Both *Chondrites* and *Trichichnus* are deep tier trace fossils, most commonly recorded from anoxic mudstones, where they are often present in monospecific assemblages (e.g., Romero-Wetzel, 1987; McBride and Picard, 1991; Fu and Werner, 1994; Rodríguez-Tovar and Uchman, 2010). Of these two, only *Chondrites* is a common ichnofabric-forming trace fossil (Callow and McIlroy, 2011). The producer of *Chondrites* is usually inferred to be a chemosymbiotic organism and is used as an indicator of anoxic or dysoxic settings (e.g., Bromley and Ekdale, 1984; Seilacher, 1990, 2007; Fu, 1991).

Phycosiphoniform trace fossils and *Chondrites*-like burrows that are the focus of this study, are among the most frequent ichnofabric-forming trace fossils observed in organic- and clay-rich siliciclastic marine deposits including both conventional and unconventional reservoir facies (e.g., Cluff, 1980; Wetzel and Bromley, 1994; Pemberton and Gingras, 2005; Callow and McIlroy, 2011; Lemiski et al., 2011; Bednarz and McIlroy, 2012; La Croix et al., 2013; Table 1). Other prominent trace fossils in organic-rich shale intervals are *Planolites*, *Zoophycos*, *Trichichnus*, *Helminthopsis*, *Palaeophycus* and *Teichichnus* (e.g., Cluff, 1980; Wetzel and Werner, 1980; Callow and McIlroy, 2011).

2.1. *Chondrites* ichnofabrics

Chondrites burrows are complex root-like systems of branching tunnels penetrating down with more or less vertical tunnel(s) from an opening at the sediment–water interface (e.g., Osgood, 1970; Wetzel, 1983; Wetzel et al., 2011; Löwemark, et al. 2006; Wetzel and Reisdorf, 2007; Pemberton et al., 2009). *Chondrites* s.s. and aff. *Chondrites* are common in very fine-grained sediments, such as organic-rich dark mudstones. In vertical cross section, the tunnels of *Chondrites* range from a fraction of a millimeter up to several millimeters in diameter, forming abundant circular spots. In organic-matter rich shale-hydrocarbon facies *Chondrites* burrows are generally filled by coarser-grained silty or very fine sandy material, depending on the lithology of the sediment overlaying the burrowed deposit. Where the infill is clay-rich, there is usually some color contrast (e.g., Schieber, 2003). Since the *Chondrites* producer was probably chemosymbiotic (thiotrophic and/or methanotrophic), it would likely have been able to survive and prosper in sediment with sulfidic pore waters, but would have had to have been connected to the sediment–water interface where at least some oxygen was available (cf. Bromley and Ekdale, 1984; Seilacher, 1990; Fu, 1991; Stewart et al., 2005; Dando et al., 2008). *Chondrites* is commonly the only macroscopic trace fossil found in black mudstones (e.g., Bromley and Ekdale, 1984; Bottjer and Savrda, 1993; cf. Schieber, 2003).

2.2. Phycosiphoniform ichnofabrics

Phycosiphon-like burrows are produced by grain-selective deposit feeders and are most common in comparatively less organic-rich siltstones and silty mudstones than those with monotypic assemblages of *Chondrites* (e.g., Goldring et al., 1991; Wetzel and Bromley, 1994, Bromley, 1996; Wetzel, 2002; Wetzel et al., 2011; Bednarz and McIlroy, 2009, 2012; cf. Egenhoff and Fishman, 2013). These phycosiphoniform trace fossils have a mudstone-rich fecal core surrounded by a silt-grade light-colored quartzose halo (e.g., Bromley, 1996; Wetzel and Bromley,