Ichnological Controls on Hydrocarbon Shale Properties in the Light of Three-Dimensional Volumetric Reconstructions of Shale Ichnofabric*

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Abstract

The present study aims to evaluate the impact of ichnofabric on the shale-hydrocarbon reservoir quality in terms of porosity, permeability and fracturability. Volumetric models of reconstructed trace fossils allow for consideration of their influence on the petrophysical properties of the containing rock. Herein we present detailed three dimensional morphologies of Phycosiphon-like burrows and Chondrites isp., which are two of the most common ichnofabric forming trace fossils for shale-hydrocarbon reservoir facies. Spatial geometry and petrological nature of these two types of trace fossils have significant impact on the distribution and concentration of quartz grains within mudstones and siltstones. This fact illustrates the importance of understanding how brittle, and relatively porous, quartzose material may be distributed in low permeability rocks, influencing their porosity, permeability and fracturability. Silt- and sand-rich ichnological conduits may comprise complex geometries in low permeability organic-enriched rocks. Ichnofabrics generated by Phycosiphon-like burrows and Chondrites are here reconstructed in three dimensions in order to understand spatial geometries, density and distribution of burrows in shale-hydrocarbon facies, and allow consideration of connectivity and volumetrics of biogenic pore-networks. Examination of the reconstructed ichnofabrics illustrates that ichnofabrics may not only modify the sediment properties of large volumes (even more than 25%) of bioturbated sedimentary fabrics, but can also create vertically and horizontally interconnected frameworks of fracture-responsive quartzose strips. The highly tortuous morphology of the burrows additionally results in a large surface area of quartzose conduits that significantly reduces the distance across which diffusive transport of hydrocarbon molecules acts before contributing to connected pore volumes that can be commercially exploited.

Introduction

Unconventional gas (tight-gas, coal-bed methane and shale-gas) has become an increasingly significant source of energy. Shale-gas and other shale-hosted hydrocarbon-reservoirs are unconventional hydrocarbon resources that rely upon the connectivity of porous and permeable sediment zones and fractures - both natural and induced - in organic-rich mudstones and very fine-grained siltstones. The host sediment for such hydrocarbon plays is typically an ultra-low permeability organic-rich mudstone and/or siltstone with poor vertical permeability that is rich in biogenic and/or thermogenic gas tightly bound within the host sediment (Curtis, 2002). Shale gas and other shale petroleum targets are commonly composed of inter-bedded successions of dominantly fine-grained rocks (siltstones and mudstones) of variable but generally low permeability (e.g. Lemiski et al., 2011). Economic production from such heterogeneous, low-permeability—but volumetrically large—reservoirs relies not upon locating the organic-rich mudstone, but also upon identification of stratigraphic intervals within the reservoir that are sufficiently fracturable and permeable to allow exploitation (Jenkins and Boyer, 2008). The highest rate of gas or liquid petroleum production is required to create maximally effective fields. Currently available shale gas and oil shale recovery technologies are largely dependent on the fracturability of the reservoir to connect zones with the potential to have a high gas yield. Such high-yield zones include permeable siltstone laminae and beds that allow production of fluids from the otherwise largely impermeable mudstone (Jenkins and Boyer, 2008). Zones of enhanced brittleness and permeability within shale petroleum reservoir horizons are a prerequisite for effective development of shale-gas reservoirs, and are directly linked to the quartz content of the sediment (Narr and Currie, 1982). In mudstones and siltstones with high clay mineral content, silt-grade quartz grains may be preferentially sorted from the clay-rich host sediment and concentrated in burrow fills and burrow linings during the grain-selective deposit feeding activities of infaunal organisms (Bednarz and McIlroy, 2009). We therefore predict that zones of intense bioturbation in shale-gas reservoir facies have the potential to significantly influence the rheological and petrophysical properties of the reservoir, by enhancing fracturability and primary porosity (Bednarz and McIlroy, 2012). Burrow-related zones of enhanced porosity and permeability in shale-gas reservoirs are typically in the form of tortuous burrows that have hitherto received little attention in terms of their three-dimensional geometries (Bednarz and McIlroy, 2009, 2012).

There has been little consideration of how burrows orientated oblique-to-bedding in shale petroleum reservoirs might influence the efficiency of gas or liquid recovery. There are few focused studies of the ichnology of shale-gas reservoirs (Pemberton and Gingras, 2005; Hovikoski et al., 2008; Lemiski et al., 2011). Within some mudstones, siltstones and sandstones with low net-permeability, fluid flow is considered to be possible through conduits, formed by induced fracturing, that connect isolated high porosity trace fossils such as Phycosiphon, Zoophycos and Chondrites (Pemberton and Gingras, 2005, Spila et al., 2007; Lemiski et al., 2011). Such burrows, when present in shale-gas reservoirs, can constitute a significant volume of the reservoir, enough to sustain an economically significant flow (Pemberton and Gingras, 2005). Zoophycos, Chondrites and Phycosiphon are extremely efficient sediment processors. The sediment-processing capacity of Phycosiphon-like burrows and Chondrites are assessed in this study. The analysis is built around deterministic, three-dimensional, volumetric reconstructions of the investigated burrows.

Procedures

Hand size samples containing Chondrites and Phycosiphon-like burrows were collected to encapsulate the same sort of deposit feeding/sediment cleaning behavior in rocks of different ages, but from facies similar to shale-gas reservoir facies. Three samples of Phycosiphon-like burrows and two samples of Chondrites were examined: 1. Sample Ph1 (form The Upper Cretaceous Rosario Formation, Baja California, Mexico); 2. Sample Ph3 (from The Lower Jurassic Staithes Sandstone Formation, the Yorkshire coast, UK); 3. Sample Ph7 (from the Mississippian Yoredale Sandstone Formation, Craster, Northumberland UK); 4. Sample Ch3 (from The Lower Jurassic Staithes Sandstone Formation, the Yorkshire coast, UK); 5. Sample Ch2 (from the Upper Cretaceous Ferron Sandstone Member of Mancos Shale, Muddy Creek, Utah, USA).

All samples were accurately ground with precise computer-controlled machinery and photographed in order to examine mineralogy and grain distribution. The photographs of strict spacing (ranging between 0.2 and 0.5 mm dependently on burrow size/diameter) are the basis of three-dimensional reconstructions modeled with volume-visualizing computer software.

In case of phycosiphoniform ichnofabrics, both burrow cores and burrow halos of Phycosiphon-like burrows were reconstructed separately. This approach allowed for detailed 3D reconstruction of the volume and geometry of each of the two main parts of phycosiphoniform burrows. Burrows halo is composed of the coarser-grained material and provide potential fluid flow paths within the bioturbated mudstones, enhancing the sediment's potential as a shale gas reservoir.

Digital 3D models of reconstructed ichnofabric of Phycosiphon-like burrows and Chondrites were subject of quantitative ichnological methods in order to describe spatial geometry and analyze ichnofabric volumes and surface area (Platt et al., 2010; Bednarz and McIlroy, 2012).

Results

Three-dimensional digital models of reconstructed ichnofabrics allowed for realistic assessment of burrow geometries and further for volumetric approach. Examination of the models reveals that the similar types of trace fossils can generate different patterns of spatial ichnofabric characterized by specific morphological and volumetric attributes.

The three studied types of phycosiphoniform ichnofabric display three different but regular relations between burrow core and quartzose halo. This relations impact the volume of coarser-grained material that is present in each sample. The study indicates that the volume of quartzose material concentrated in burrow halo is essentially constant for a single burrow representing a given type of Phycosiphon-like burrow and is greater than the volume of muddy core ~ 6, 4.5 and 8 times for Ph1, Ph3 and Ph7 respectively. Spatial density of ichnofabric is partly dependent on different nature of tortuosity characterizing each type of physosiphoniform burrows and influences the net volume of quartzose material within a sample. Studied samples bioturbated in 20% up to 65% (bioturbation index III to IV) contain from around 13% up to 26% of quartzose material concentrated in continuous and interconnected strips generated as phycosiphoniform burrow halos (Figure 1). Surface area of the halo component of the phycosiphoniform ichnofabric is more than one up to twice than the surface area of the enclosing prism-shaped sample.

In case of Chondrites, the volume of biogenically concentrated quartzose material enclosed in the sample is lesser even with higher bioturbation index (IV) and does not exceed 10%. Important characteristic of Chondrites ichnofabric is that the thin branches of each burrow (0.5 - 2 mm in diameter) propagate in all directions infiltrating vast spatial volume of surrounding matrix and generating horizontally and vertically connected network of densely packed slim quartzose stripes (Figure 2). Thus, the surface area of the Chondrites ichnofabric is significantly large as for volume it is enclosed in and it is more than twice larger than the surface area of containing prism-shaped sample.

Conclusion

Ichnofabric may greatly increase the porosity and permeability of reservoir facies. Frameworks created by biogenically concentrated quartzose material within clay-rich shale provides or/and improves zones that are susceptible for natural or induced fractures. Even low intensity Phycosiphon and Chondrites ichnofabrics, demonstrate that quartzose strips can be connected throughout the sample in both vertical and horizontal planes, thereby potentially both enhancing horizontal permeability, and breaching the typical lithologic barriers resulting from horizontal lamination within shale hydrocarbon facies.

Enhanced porosity and inherent natural fracture responsiveness of quartzose material within significant volume of burrow framework provide additional space for hydrocarbon molecules increasing reservoir capacity and storativity. Considerable surface area of the interface between organic-rich host sediment and permeable ichnofabric material enhance fluid migration from matrix into the fracturable framework increasing deliverability of the reservoir. Thus, comprehensive understanding of density, structure and distribution of ichnofabric in three dimensions is a prerequisite for accurate reservoir assessment in bioturbated shale-hydrocarbon facies.

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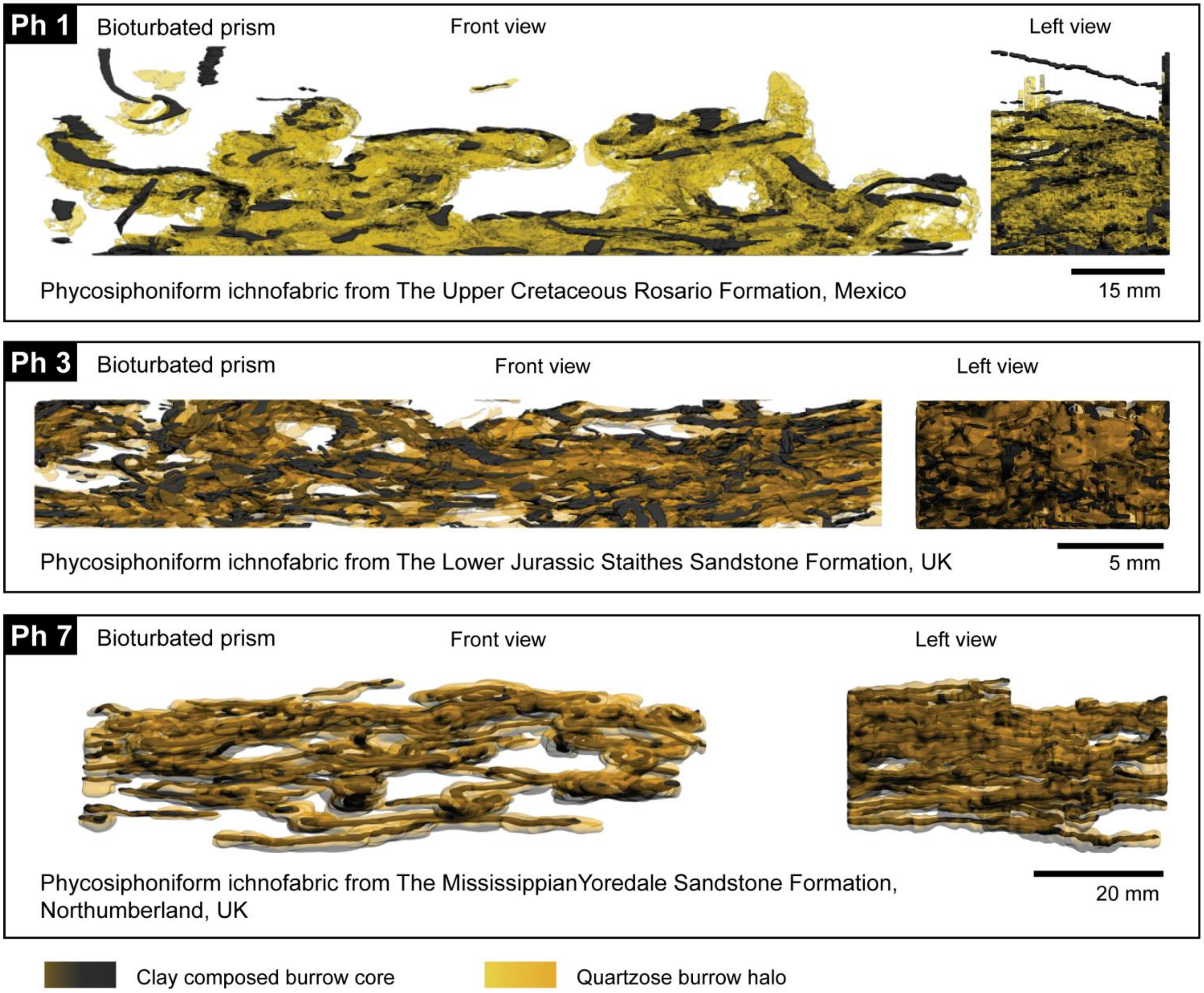
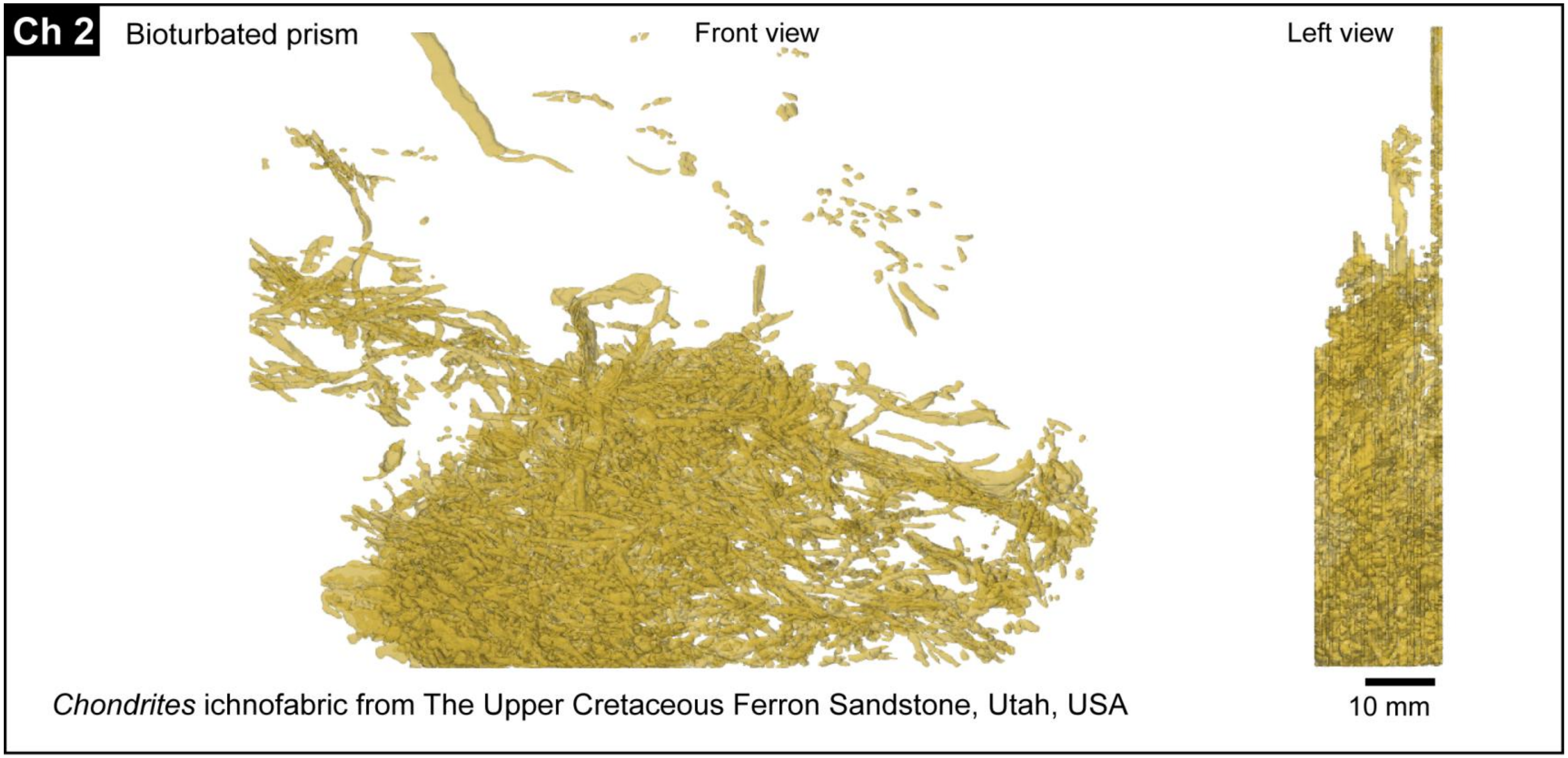
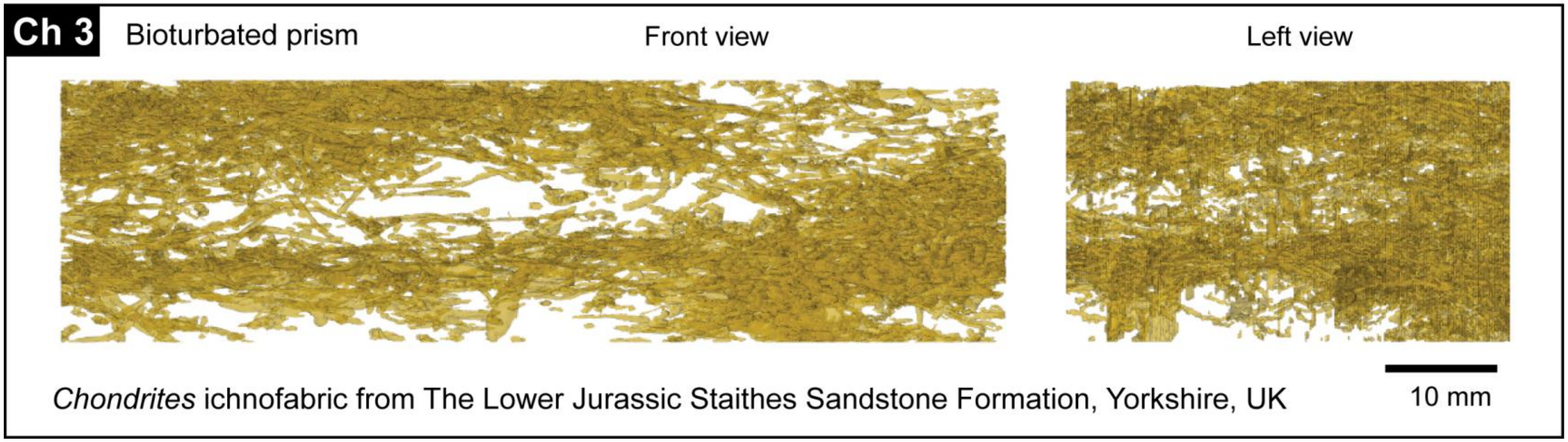


Figure 1. Location map of the Kaiparowits Plateau with outcrops of the Straight Cliffs Formation shown in green. Field areas including previous work are highlighted with dots. Cross Section from A-A' shown in Figure 2.



Chondrites ichnofabric from The Upper Cretaceous Ferron Sandstone, Utah, USA



Chondrites ichnofabric from The Lower Jurassic Staithes Sandstone Formation, Yorkshire, UK

Figure 2. Stratigraphy of the Straight Cliffs Formation, top right after Shanley and McCabe (1993); bottom right from this study.