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Impact of Bioturbation on Reservoir Quality and Production – A Review

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ABSTRACT

Bioturbation is a typically small scale yet potentially significant geological process altering rock properties by reworking. For many years, bioturbation studies found application in exploration geology to estimate paleobathymetry, interpreting depositional environment and identifying key stratigraphic surfaces. These act as vital inputs to the geological models, for determination of source rock potential, reservoir quality and modeling of petroleum systems. Recently geologists extended the application of bioturbation studies to address production related challenges. Recognizing the bioturbation effects and incorporating them in reservoir simulation models can improve production predictions and enhanced oil recovery operations. This paper discusses bioturbation and its effects on reservoir quality, its performance and production.

INTRODUCTION

Sediments undergo several modifications to become source rocks, reservoirs and seals to form a petroleum system. Diagenesis includes the processes of compaction, cementation, dissolution and recrystallization. But before any of these occur, another process may significantly affect rock properties – bioturbation. Bioturbation is simply the disruption of sediments and soil by living organisms. It can take several forms, including displacement of soil by roots, burrows/bores and even footprints of dinosaurs (Gingras et al., 2011). Oil and gas industry is mostly interested in understanding the changes brought about by organisms, active near the sediment-water interface in shallow marine and marine settings. Such activities are generally vertically restricted to a meter but laterally these can cover an area of tens to hundreds of square kilometers. Understanding the behaviors of these organisms helps to characterize the-then depositional environment when sediments were deposited but still were soft enough to be deformed by bioturbation.

The process of bioturbation, or the organism/sediment interaction, has a crucial impact on reservoir quality and its flow behavior. Thus in bioturbated reservoir facies, ichnology is integral to reservoir characterization (Ali et al., 2010), bioturbation is capable either to enhance or diminish the reservoir porosity as well as permeability. Ichnological analysis of a reservoir facies and subsequent classification into ichnofabrics or ichnofacies allows for characterization of reservoir properties. Bioturbation can redistribute grains and cause sorting or mixing, this physical modification of the primary sedimentary fabric causes changes in porosity, and permeability of reservoir facies. In highly bioturbated reservoir facies, bioturbation can be the first order control on petrophysical properties (Al-Hajeri et al., 2009).

LIFE JUST UNDER THE SURFACE

Organisms living near the sediment-water interface often leave evidences of their life styles. For example, surface expressions of sub-surface bioturbation can be discerned in the intertidal zone of a beach (Fig.1). Infaunal organisms living in the sediments (like crabs, shrimp, tubeworms etc.) can disrupt sediments in many ways. They may create tube like tunnels and shafts of varying inclination. These burrows may remain open for a period of time (Fig.2), collapse or be filled immediately with similar or contrasting sediments (Fig.3 and 4). While burrows made on a consolidated substrate have better potential to stay open for a longer span of time, those made on soft substrates are prone to be filled. Some infaunal activity can cause complete mixing of a volume of sediment but leave no detectable trace (Fig.5). For example, animals foraging in layered sediments may disrupt the substrate so completely that the layering can no longer be visible. Epifaunal organisms may not burrow or modify the sediments to a great degree, but they can also leave traces of their activities in form of furrows or other tracks (Fig.6).

In the rock record, bioturbation manifests itself mainly as fossilized traces of animal activities. The study of these traces is called Ichnology. Ichnologists interpret these traces to indicate animal activities as escaping, dwelling, crawling, feeding, farming and grazing, among others. Traces may be variations or combinations of these (Buatois and Mangano, 2004; Hickey and Henk, 2007). Ichnologists use the evidence of these behaviors to characterize the paleoenvironment of a rock layer. A variety of species can produce similar structures if their activities are similar. Even a single species can produce different kinds of traces while performing different activities and traces may vary depending on the substrates (Gingras et al., 2009).

Thus a basic way to interpret sedimentary rocks is to divide them into three main types of lithified sediments as unburrowed, burrowed and massive (Fig.7) (Gingras et al., 2009). This serves as the starting point for interpreting depositional conditions under which such sediments formed.

Unburrowed

Relatively undisturbed sediments, i.e. those with original layering intact and with little or no evidence of bioturbation, are usually ascribed to one or more following depositional environments:

- Freshwater, with few deeply burrowing organisms (Loucks and Ruppel, 2007)
- Anoxic settings (poorly oxygenated) (Taylor and Goldring, 1993)
- Constantly shifting sediments on seafloor (Pemberton et al., 2008)
- High sedimentation rates (Gingras et al., 2009)
- Arid or frozen areas (Gingras et al., 2009)

Unburrowed sandy sediments usually indicate freshwater deposition or shifting sedimentation. However many continental environments do exhibit trace fossils. Unburrowed fine grained sediments (silty or clay dominated) are typically interpreted as product of sedimentation in fresh water or anoxic conditions, although high sedimentation rates might yield similar result. Many organic rich source rocks (some are targets of tight oil and shale gas plays) are examples of fine grained sediments deposited in environments with low oxygen supply, as such environments are not appreciable to many

Fig.1. Grazing trails of Hermit crabs, Chandipur intertidal flat, east coast India

organisms and hence layering are preserved in the sediments (little or no bioturbation).

Burrowed

Burrowed media is categorized based on the distribution of ichnofossils and their characteristics (size, diversity etc.). Ichnologists have developed a bioturbation index (BI) to describe the degree to which sediments are affected by bioturbation (Table 1) (Taylor and Goldring, 1993). The index, on a scale of zero to six, grades trace abundance and overlap and resultant loss of primary sedimentary fabric. BI is related to the duration of colonization events and through them, to the rates of sedimentation (Taylor and Goldring, 1993; Pemberton et al., 2008), which is discussed in detail under the heading 'Bioturbation'.

Massive

Sediments that appear to be mottled or massive, i.e. homogenous in texture, can result from any of the following:

- Lack of sufficient grain size variation to define sedimentary lamination
- High enough sedimentation rate to present any grain size segregation
- Mechanical mixing from soft-sediment deformation during gravity flows
- High degree of biogenic churning

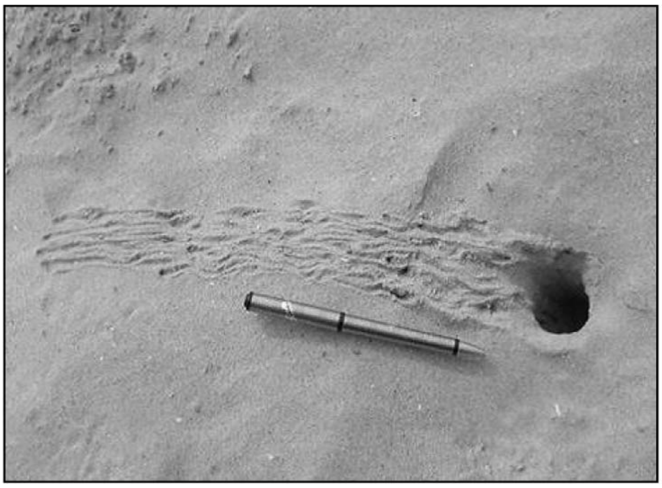

Fig.2. Open burrow and grazing trail marks made by crabs, sandy backshore area of Chandipur beach, east coast India

Table 1. Bioturbation Index (BI) – a scheme for quantifying the degree of sediment bioturbation. The index grades trace abundance and overlap and the resultant effect on primary sedimentary fabric. Adapted from Taylor and Goldring, 1993

Bioturbation Index (BI)	% Bio-turbated	Classification
0	0	No bioturbation
1	1-4	Sparse bioturbation, distinct bedding and few discrete traces or escape structures
2	5-30	Low bioturbation, distinct bedding, low trace density and escape structures often common
3	31-60	Moderate bioturbation, sharp bedding boundaries, discrete traces and rare overlap
4	61-90	High bioturbation, indistinct bedding boundaries and high trace density with common overlap
5	91-99	Intense bioturbation, completely disturbed bedding (just visible), limited reworking and later burrows discrete
6	100	Complete bioturbation and sediment reworking because of repeated overprinting

Though the last one is caused by bioturbation, but it may be difficult to recognize them as the rock may appear homogenous. This is also known as cryptic bioturbation. The homogenous appearance is resulted from the rapid reworking of sediments by organisms in search of nutrients. Complete obliteration of layering is the highest degree of cryptic bioturbation. Cryptobioturbation in sand usually indicates a marine depositional environment, but in fine grained sediment it may be produced in marine or fresh water environments (Gingras et al., 2009).

BIOTURBATION AND CONTROLLING FACTORS

Trace fossils are biogenic sedimentary structures, tracks, trails and borings produced by animals on or within the sediment or rock (Hantzschel, 1975; Bertling etal., 2006). Trace fossils record fossil behavior, effectively the response of organisms to the physical, biological, and chemical environments in which they lived. Integrating sedimentology and ichnology results in more comprehensive paleoenvironmental reconstructions, including physico-chemical parameters, and aids in the identification of key stratigraphic surfaces (Taylor et al., 2003; Gingras et al., 2011). Ichnological analysis provides insights into some important aspects of ancient environments (e.g. salinity and relative oxygenation) that cannot be gleaned from the study of physical sedimentary structures alone (Ekdale and Mason, 1988; Savrda and Bottjer, 1991). Studying the effects of bioturbation is important in understanding the dynamic processes associated with sedimentation in shallow marine settings.

Paleoenvironmental Controls on Bioturbation

The main paleoenvironmental controls on bioturbation are sedimentation rate, salinity, turbidity, oxygenation, substrate consistency, hydro dynamic energy, and event bed deposition (see reviews in Taylor et al., 2003; Mcllroy 2004a; Gingras et al., 2011).Physico-chemical parameters that affect bioturbation include grain size, turbidity, light, temperature and sediment supply, while biological constraints include salinity tolerance of the trace maker, food supply and burrow morphology.

Hydrodynamic Energy and Bioturbation

The distribution of trace fossils is linked to hydrodynamic energy in all depositional settings. The dominant hydrodynamic processes

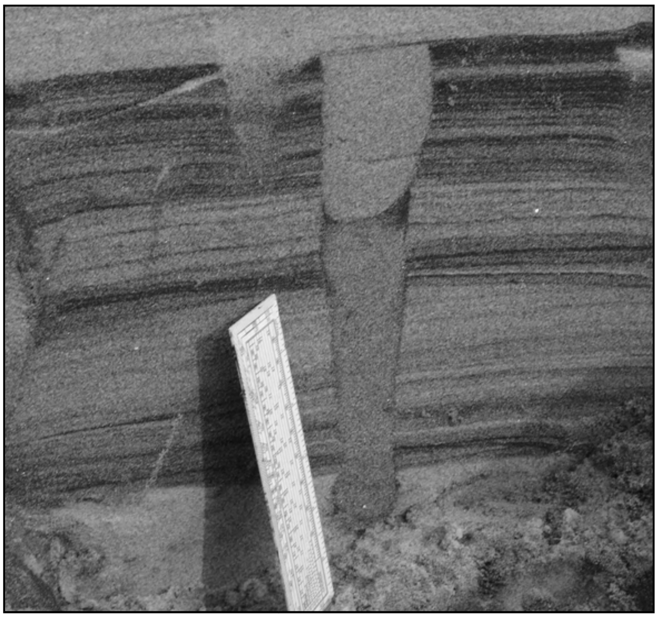

Fig.3. Filled vertical burrow, backshore area of Chandipur beach, east coast India

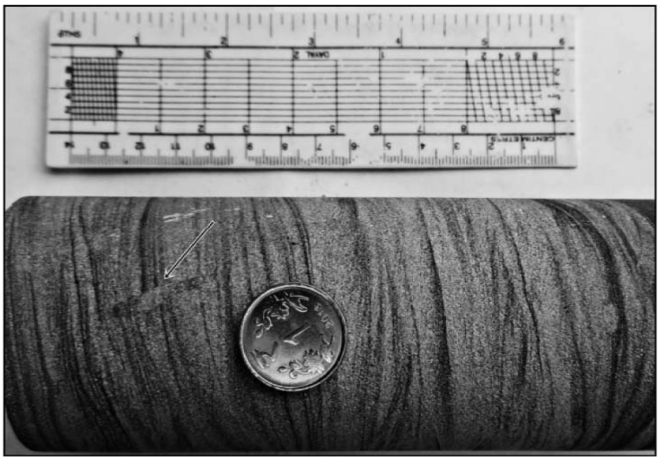

Fig.4. Subvertical burrow in core (pointed by arrow), core top towards right, facies interpreted as levee deposit, Raniganj formation (Permian), EOL CBM block, adapted from Sen et al. (2015)

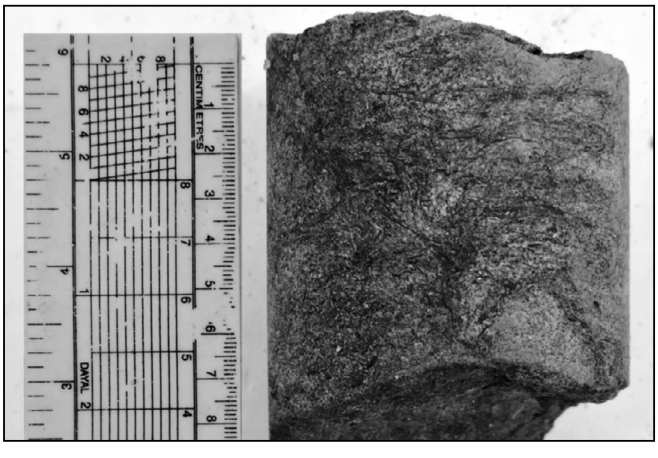

Fig.5. Reworking of sediments by bioturbation leaving no detectable trace in core, core top aligned with photograph top, facies interpreted as levee deposit, Raniganj formation (Permian), EOL CBM block, adapted from Sen et al. (2015).

Fig.6. Trails of gastropod *Natica tigrina*, Chandipur intertidal flat, east coast India

that actively erode, transport or deposit sediment are fluvial currents, hyperpycnal flows, tidal currents, longshore wind-generated currents, wave- and storm-induced gravity flows, and turbidity currents (Nittrouer and Wright, 1994). The shore face and proximal delta front are high hydrodynamic energy settings with rapid sedimentation rates. Shallow marine facies arc typically well sorted and sand-rich (Reading and Collinson, 1996) and are associated with enhanced porosity and permeability.Consequently, the distribution of reservoir properties with regard to geometry and architecture is of particular interest in hydrocarbon reservoir characterization (Brandsaeter et al., 2005; Howell et al., 2008; Ainsworth et al.,2011). Upper shore face and proximal delta front facies arc typically characterized by low bioturbation intensities and low ichnological diversities. Typical trace fossils that can be found in the high-energy environments such as the upper shore face and proximal delta front deposits are vertical burrows including *Diplocraterion, Ophiomorpha*, *Skolitho*,and *Arenicolites* (Gingrasetal., 1998; Mcllroy et al., 2005). As such, the deposits have an ichnological assemblage comparable to the *Skolitho*ichnofacies (Seilacher, 1964; 1967a; Bromley and Asgaard, 1991; MacEachern et al., 2007). Figure 8 shows an extensive *Ophiomorpha* abundance on the huge tidal flat region (coverage of nearly 10 square kilometers) of Chandipur beach, east coast India.

Trace fossil diversity and intensity of bioturbation generally increase both offshore and laterally away from sources of high sedimentation input such as distributary channel mouths(Gingras et al., 1998, 2011; Mcllroy et al., 2005). Facies with low sedimentation rates or event-bed type sedimentation patterns (e.g., lower shore face, distal delta front to prodelta and shelf settings) are typically characterized by moderate to high bioturbation intensity and trace fossil diversity. Overprinting of ichnocoenoses (i.e. palimpsesting) is common where the sedimentation rate is slow (Gingras et al., 2011).

In the moderate energy facies of the delta front, lower shoreface and the inner shelf, deposits are dominated by a mix of vertical and horizontal trace fossils including *Teichichnus, Asterosoma, Ophiomorpha , Thalassinoides* and *Planolites* (broadly equivalent to the *Cruziana* ichnofacies; Gingras et al., 1998; Cumming et al., 2006; Buatois et al., 2008). In low to variable energy facies including prodelta, offshore transition zone below storm-wave base, and in the outer shelf, deposits typically contain *Phycosipholl, Cholldriles, Zoophycos, and Scolicia* (equivalent to the *Cruziana* and *Zoophycos* ichnofacies; Pemberton et al., 2008; Wetzel and Uchman, 2001).

Salinity tolerance of trace-making organisms

The salinity characteristics of depositional systems can be broadly

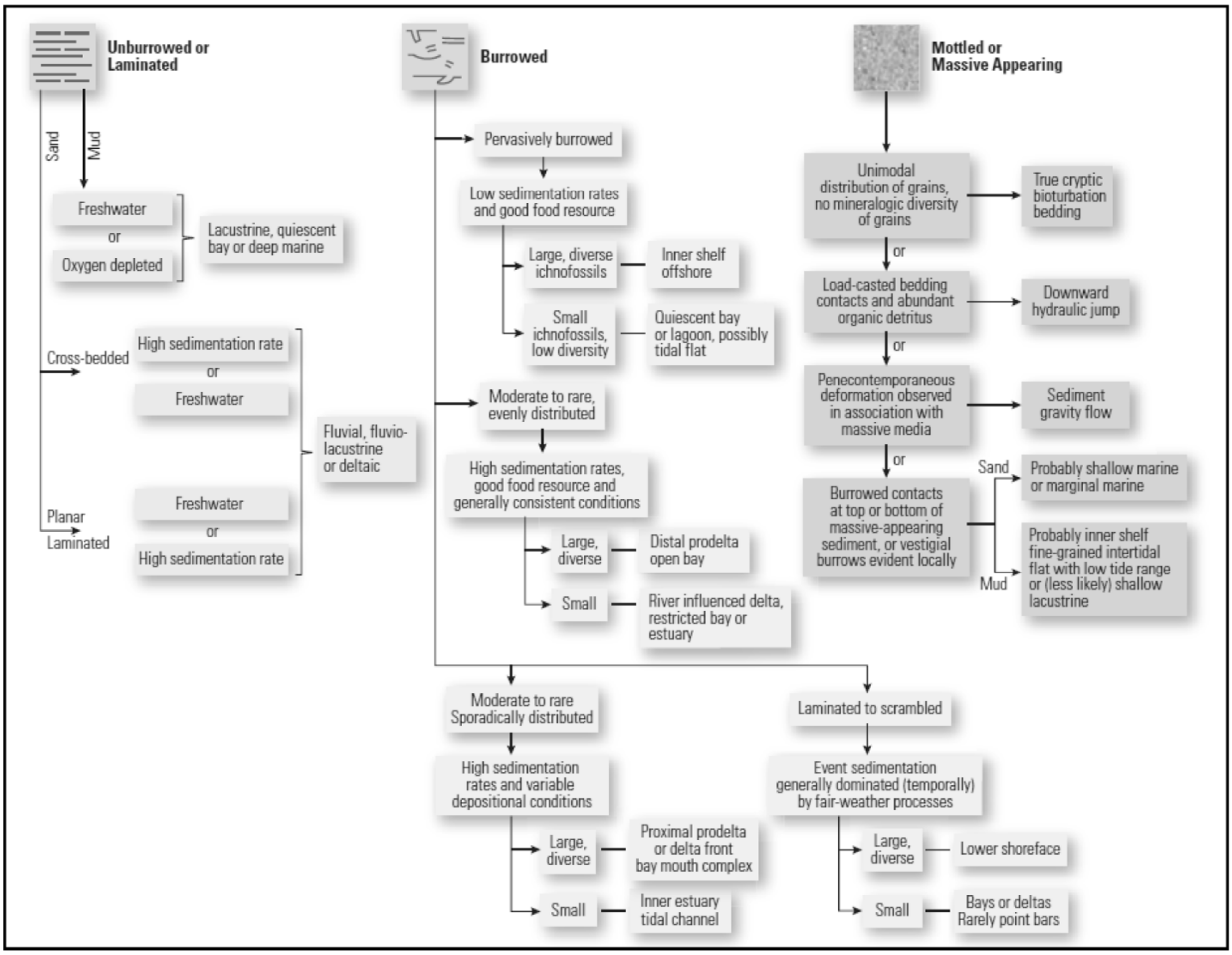

Fig.7. Interpreting depositional conditions from bioturbation texture dividing it in three main types – unburrowed, burrowed and massive appearing, adapted from Gingras et al., 2009

grouped into: normal marine, brackish and fresh-water environments. Biological diversity and organism size are thought to co-vary with salinity (Pickerill and Brenchley, 1991;Pembertonet al., 1992; Gingras et al., 2011). Rapid salinity fluctuations are somewhat buffered in pore-water systems due to slow rates of diffusion (see discussion in Mcllroy, 2004a). Infaunal biomineralized organisms have behavioral adaptations to protect against short term osmotic stress caused by rapid salinity change (Buatois et al., 1997; Mcllroy, 2004a; Gingras et al., 2011). Ichnological assemblages of fresh-water environments are usually devoid of complex feeding burrows (e.g. *Mermiaichno* facies; Mangano and Buatois, 2004). Brackish water or marginal marine assemblages are characterized by simple horizontal and vertical burrows including *Planolites, Diplocraterion, Skolithos, Palaeophycus, Lockeia*and *Thalassilloides* (Buatois et al., 2005).In these ichnological assemblages, salinity is seldom demonstrably the first order control on ecology (temperature, sedimentation rate, substrate consistency and turbidity are generally all involved ; Mcllroy et al., 2004b; Buatois et al., 2005).

Fluvial, brackish, and marine assemblages have distinct ichnological assemblages. Some ichnotaxa are seemingly ubiquitous such as *Planolites* which is considered to have been made by euryhaline organisms (Mangano and Buatois, 2004). Low diversity assemblages interpreted as being made by euryhaline organisms are commonly considered to be indicative of brackish water settings (Mangano and Buatois, 2004). An integrated approach incorporating careful sedimentary facies and ichnological analysis is required. Persistently brackish palaeoenvironments are only really expected in distributary channels, near-channel palaeoenvironments and potentially in restricted seas, lagoons, estuaries and fjords (Martinius et al., 2001; Mcllroy et al.,2004a; Dalrymple, 2010).

Sedimentation Rate and Colonization Window

The deceleration of fluvial or marine currents can cause rapid deposition of the suspended sediment load, as can flocculation in the mixing zone of estuaries (Pryor, 1975, Mcllroy, 2004b; Boyd et al., 2006). Sedimentation rate is variable, from instantaneous and permanent deposition to erosion and redistribution by waves and tides, sometimes in a multi-cyclic fashion (Einsele et al., 1991). Rates of sediment deposition and reworking are to a large degree controlled by depositional setting (particularly water depth), hydrodynamics of the receiving basin (Orton and Reading, 1993) and destruction/generation of accommodation space by both autocyclic and allocyclic processes (Van Wagoner et al., 1988; Einsele et al., 1991).

In order to assess the paleoenvironmental significance of a highly bioturbated bed or bedset it is important to be able to compare the intensely bioturbated unit with its “normal” counterpart. In shallow marine successions, some facies are persistently highly bioturbated indicating persistently low rates of sedimentation relative to the rate of bioturbation. Preservation of physical sedimentary structures within a bed is a function of sedimentation rate, bioturbation rate, and bed thickness (Wheatcroft, 1990; Bentley and Sheremet, 2003). This window of opportunity on the seafloor for bioturbation of the substrate (and potential obscuring or destruction of primary sedimentary fabric) is known as the colonization window (Pollard et al., 1993). Environmental stability can be reflected in the length of time that the colonization window is open (Taylor et al., 2003).

Fig.8. *Ophiomorpha* abundance on tidal flat, Chandipur beach, east coast India. Photo courtesy: Jayanta Saha, Jadavpur University

Shallow marine facies have highly variable sedimentation rates (Walker and James, 1992). Successions characterized by rapid continuous sedimentation are commonly devoid of trace fossils or are sparsely bioturbated, with optimal preservation of primary sedimentary fabrics. In areas of slow continuous sedimentation, bioturbation intensity and ichnodiversity are commonly high. This is due to the colonization window being open long enough for biogenic reworking of sediments. Facies with such low net accumulation rates, and repeated overprinting may be characterized by intense bioturbation, which obscures/destroys most of the primary sedimentary structures (Taylor and Goldring, 1993).

Fluvial input to the marine basin, and generation of sediment gravity flows can be seasonally variable. The inter-bedding of fair-weather and event-bed deposits may produce “lam-scram” fabrics of alternating low (“lam” or laminated) to high (“scram” or scrambled) intensities of bioturbation (Howard, 1972). The thickness of an event bed is an important limiting factor on benthic ecology, as it may restrict existing infaunal communities, effectively causing macrofaunal defaunation if the endobenthos are unable to escape to the new sediment-water interface (Pollard et al., 1993; Wheatcroft and Drake, 2003). If colonization from below is not possible, post-depositional re-colonization by juveniles or adult organisms is possible (Mcllroy, 2004a), though the new seafloor substrate may not be initially entirely hospitable to deposit feeding organisms due to a lack of deposited organic matter (Herringshaw et al., 2010).

Oxygenation

The oxygenation of interstitial pore-waters at the sediment-water interface is a relatively common first order control on trace fossil distribution in subaqueous environments (Savrda and Bottjer, 1991). Well-oxygenated seafloors will typically exhibit high degrees of bioturbation, and burrowing to depth below the ancient sea floor. The maximum depth of burrowing and infaunal colonization of shallow, mid-, and deep-tiers (i.e., the vertical partitioning of substrate; Berger et al., 1979; Ausich and Bottjer, 1982) or mixed and transition layers (Goldring, 1995; Bromley, 1996) can be used as an indicator of well-oxygenated bottom waters and pore waters (Bromley and Ekdale, 1984; Bromley, 1996).

Some marginal marine and delta plain environments may be rich in sedimentary organic matter (e.g., swamps, tidal flats, marshes, lagoons and bay fills; Reading and Collinson, 1996). Increased accumulation of organic carbon-bearing sediment at or near the sediment-water interface can result in higher microbial productivity that uses free oxygen and leads to locally oxygen-poor, pore-water environments (Jorgensen and Postgate, 1982; Konhauser and Gingras, 2007). Endobenthic activity in such organic-rich sediments is seldom limited by the absence of pore-water oxygen. Oxygenated waters can be introduced to the sediment by bio-irrigation, which also stimulates microbial growth in the near-burrow environment (Gust and Harrison, 1981; Herringshaw et al., 2010) or simply by maintaining a connection to the sediment-water interface while feeding on sediments below the redox boundary (Bromley, 1996). Tidal flat facies containing solely *Ophiomorpha* or *Thalassinoides* traces may be indicative of a periodically oxygen stressed paleoenvironment where pore-water oxygenation fluctuate through the tidal cycle (Swinbanks and Lutternauer, 1987).Shoreface, deltaic and shelf facies are areas of dynamic coastal processes and are characterized by strong bottom currents (Reading and Collinson, 1996). These currents are commonly a combination of fluvial, wave and tidal processes, which keep the water column mixed, and the bottom water oxygenated, making it suitable for endobenthic/trace-making organisms. Consequently, bottom-water oxygenation in shallow marine settings is not generally a controlling factor in the occurrence and distribution of shallow marine trace fossils.

Substrate Consistency and Bioturbation

Shallow marine substrates are commonly found to be softgrounds, with occasional soupground, firmground and woodground substrates (Seilacher, 1978; Ekdale, 1985; Goldring, 1995). Bioturbated soft ground substrates are typical of depositional settings with continuous deposition, or hiatuses. Bioturbated firm ground substrates can also be interpreted as a hiatal surfaces (e.g., *“Glossifimgites* surfaces”; Gingras et al., 1999, 2007). Firmground surfaces in shallow marine settings may typically be colonized by *Thalassinoides* andhave autocyclic (e.g., change in sediment delivery) or allocyclic (e.g., eustatic sea level fluctuations) causative mechanisms. Soup grounds are generally found in association with rapid deposition, especially where rapid flocculation in the mixing zone, or remobilization of partly settled mud by waves and tidal currents produces hyperpycnal flows, and fluid mud deposition (Bentley and Nittrouer, 2003; Bhattacharya and MacEachern, 2009; Macquaker et al., 2010a, 2010b).

Nutrients and Feeding Mode of the Tracemaker

Organic nutrients are not typically a limiting resource in shallow marine depositional environments. This is evident by the presence of particulate organic matter in most shallow marine sandstones and mudstones (Macquaker et al., 2010b).

Organic matter availability is not considered to be a limiting factor in the ecology of most benthic marine systems. Organic particulates from terrestrial and marginal marine vegetation are commonly rich in refractory organic compounds (Gooday et al., 1990). Many shallow marine trace fossils (e.g. *Arenicolites*) are thought to culture micro-organisms on buried detrital organic matter, processing the microbial biomass for food (Bromley, 1996; Herringshaw et al., 2010). Bioavailable organic matter is commonly present both in suspension and buried in sediments. The trace fossil assemblages found in shallow marine facies are likewise inferred to represent a mixture of suspension, gardening, scavenging and deposit feeding behaviors (Nickell and Atkinson, 1995; Mcllroy, 2004b; MacEachern et al., 2007b; Herringshaw et al., 2010).

While trace fossil morphology does reflect behavior of the trace-maker, the feeding strategy of the trace maker is commonly more complex. Recent research has demonstrated that number of modern benthic burrowing organisms display significant behavioral plasticity, with a single burrow serving multiple purposes (e.g. Thalassinid shrimps, Suchanek, 1985; Nickell and Atkinson, 1995; Herringshaw el al., 2010).

ICHNOLOGICAL ANALYSIS

Ichnological analysis of sedimentary rocks is a powerful tool in facies characterization. Infaunal and epifaunal trace-producing organisms adjust their behavior to suit changes in environmental parameters. Sedimentological and ichnological data are combined and assessed using the concepts of ichnofabric analysis and application of the ichnofacies paradigm (Buatois and Mangano, 2004; Mcllroy, 2008). Ichnological analysis when integrated with detailed sedimentological studies is readily applicable to siliciclastic sedimentation, and highlights ichnological response to changes in environmental conditions (Taylor and Goldring, 1993; Mcllroy, 2004c, 2008). This method allows direct comparison of different ichnofabrics from different geographic or stratigraphic successions. The focus on cross-cutting relationships can provide insights into community development and to determine ichnocoenoses.

Ichnofabric Analysis

Ichnofabric is defined as "all aspects of the texture and internal structure of sediment that result from bioturbation at all scales" (Bromley, 1990). Ichnofabric analysis is a description of the ichnology, diversity, bioturbation level and colonization order of bioturbated beds (Taylor et al., 2003; Mcllroy, 2004a). Bioturbated sedimentary fabrics are studied on a bed-by-bed basis, and involve quantification of bioturbation intensity, documentation of diversity and cross-cutting relationships.

The ichnofabric analysis method is used to: identify key stratigraphic surfaces (Bromley and Ekdale, 1986; Taylor and Gawthorpe, 1993; Goldring, 1995; Droser et al., 2002) and formulate depositional models (Droser and Bottjer, 1989; Bottjer and Droser, 1991; Ekdale and Bromley, 1991; Pollard et al., 1993; Martin and Pollard,1996; Gowland, 1996; Mcllroy, 2004a, b), and create fully integrated reservoir characterizations (Bromley and Ekdale, 1986; Bockelie, 1991; Taylor and Gawthorpe, 1993; Mcllroy, 2007; Tonkin et al., 2010).

Ichnofacies Analysis

Bioturbated rocks can also be categorized using Seilacherian ichnofacies (MacEachern et al., 2007). The archetypal ichnofacies concept (Seilacher, 1964, 1967a, b) is widely used to describe trace fossil associations and facies successions in terrestrial and marine environment. Originally, ichnofacies were considered to be bathymetrically controlled (Seilacher, 1964).

The current definition of an ichnofacies is a recurring ichnological assemblage that has paleoenvironmental implications (Bromley and Asgaard, 1991; Buatois and Mangano, 2004). Ichnofacies are not restricted to specified salinity or bathymetric conditions and can occur in a range of marine and non-marine environments (Frey et al., 1990; Bromley and Asgaard, 1991; Buatois and Mangano, 2004). This broadening of ichnofacies concept, defines ichnofacies as being paleoenvironmentally controlled, rather than a simple paleobathymetric proxy (Frey et. al, 1990).

SEQUENCE STRATIGRAPHIC INTERPRETATION

Through sequence stratigraphy, geologists and basin modelers identify sequences bounded by unconformities (non-deposition or erosional surfaces bounding the sequences) and system tracts. Identifying key bounding surfaces and correlating them from well logs and/or seismic dataset is the basis of sequence stratigraphic interpretation (Sen et al., 2015). For an integrated interpretation, geologists use trace fossils along with the sedimentological analysis, core analysis and well logs to characterize sediments within each sequence and identify the depositional surfaces and discontinuities that separate system tracts and sequences (Pemberton and Gingras 2005; Al-Hajeri et al., 2009). The distribution of the organisms on the surfaces they inhibit is an important factor. Ichnology characterizes sedimentary surfaces according to the consistency of the ground (Gingras et al., 1998), as below:

- Soupground – water saturated mudrocks
- Softground – muddy sediment with some dewatering
- Looseground – sandy
- Stiffground – stabilized
- Firmground – dewatered and compacted
- Hardground – lithified

Without adequate stiffness, these media cannot support traces which can be preserved as trace fossils (Bentley and Nittrouer, 2003; Macquaker et al., 2010a). Therefore, ichnofossils are usually discernable only in stiffground and firmground. Hardground surfaces are too hard for most of the organisms to penetrate (except few boring organisms). Firmgrounds in marine settings may be attractive to animal colonization (Al-Hajeri et al., 2009). Their firmness offers protection to the animals, apart from that firm substrates does not require continuous burrow maintenance (Bhattacharya and MacEachern, 2009). A surface has to be deposited, dewatered and compacted to be used as habitat. In clastic settings, these requirements are often met by the erosionally exhumed substrates and resulting surfaces correspond to erosional discontinuities (Pemberton et al., 2004; Al-Hajeri et al., 2009); these are important as they form the bounding surfaces of sequences.

Geologists and basin modelers have incorporated ichnological information in sequence stratigraphic studies in a wide range of environments, including Jurassic marine sequences of North Sea, Permian fluvio-lacustrine facies of Argentina, Jurassic carbonates of Saudi Arabia, Cretaceous marine sequences of Canada etc. (Taylor and Gawthorpe, 1993). Most such studies make use of ichnofossils in outcrops and cores; as well as from image logs. While identification of the ichnofossils did not drive the interpretation of depositional sequences, it improved the analysis of the lithostratigraphic, biostratigraphic, sedimentological and petrophysical properties derived from cores and log data, yielding an integrated interpretation (MacEachern et al., 2007; Al-Hajeri et al., 2009). Geologists were able to identify maximum flooding surfaces and correlate them between wells in the field and were also able to extend this interpretation to neighboring fields.

RESERVOIR QUALITY PREDICTION IN BIOTURBATED SUCCESSIONS

Reservoir quality is one of the key controls on prospectivity during petroleum exploration. It is important to have a detailed understanding of what controls reservoir quality to assist with the appraisal of the economic viability of petroleum discoveries. When a petroleum discovery has been made in a basin, it is essential to gain as much understanding of reservoir quality to help focus further exploration and appraisal efforts (Selley, 1997).

Petroleum geologists are primarily concerned with the effect that bioturbation has on the petrophysical properties of a reservoir facies, rather than the details of ichnotaxonomic identification. Sediment packing and sediment mixing styles commonly reduce porosity/permeability, while sediment cleaning bioturbation style enhances porosity/permeability (Bentley and Nittrouer, 2003; Worden and Burley, 2003). Pipe-work building and combination bioturbation styles are highly dependent on the lithological contrast between burrow fill, and enclosing substrate (Macquaker et al., 2010a). The use of bioturbation style categories, and the classification of trace fossils into these categories may be more user-friendly for reservoir geologists than existing paleoenvironmentally-driven ichnofacies or ichnofabric analysis (Cunningham et al., 2009).

The majority of studies discussing the relationship of bioturbation to porosity and permeability in carbonate and siliciclastic reservoirs have focused on burrow enhanced porosity/permeability trends (McAlpine, 1990; Cannon and Gowland, 1996; Gingras et al., 1999, 2002, 2004; Smith et al., 2003; Pemberton and Gingras 2005; Spila et al., 2007; Florea et al., 2009; Cunningham et al., 2009). The literature on the effects of bioturbation on petroleum reservoirs is biased towards permeability-enhancing trace fossils of Ophiomorpha. *Phycosiphon*, *Macaronichnus*, *Thalassinoides*, *Zoophycos* and *Glossifungites* surfaces (Gingras et al., 1999, 2002, 2004, 2007, 2010; Cunningham et al., 2009; Knaust, 2009; Gordon et al., 2010; Tonkin et al., 2010).

While categorization of bioturbation style is a useful tool in reservoir characterization, lateral variations in reservoir quality and heterogeneity of ichnofacies or ichnofabric must be incorporated into geological models in order to predict fluid flow in bioturbated facies at the inter-well scale (Pemberton and Gingras, 2005). Ichnological analysis allows insight into variations in sedimentation rate, hydrodynamic energy (erosive currents), substrate consistency, length of colonization window, and community succession (Al-Awadi et al., 2009). This ichnological dataset means that inferences regarding both physical and chemical processes acting at the time of bioturbation can be made (Smith et al., 2003). There is inherent ichnological variability within most bioturbated beds. Instead, the most critical factor appears to be the sediment accumulation style. Slow continuous deposition was found to produce complex and highly patchy ichnofabrics, whereas rapid, episodic, event bed deposition was found to be associated with the most uniform development of ichnofabric (Baniak et al., 2013).

EFFECT OF BIOTURBATION ON RESERVOIR PERFORMANCE AND PRODUCTION–EXAMPLES FROM VARIOUS RESERVOIRS WORLDWIDE

Tonkin et al. (2010) classified the action of bioturbators into sediment mixing, sediment cleaning, sediment packing, pipework building and sediment packing or combination of these. They further suggested that sediment packing and sediment mixing styles commonly reduce porosity/ permeability while sediment cleaning bioturbation mechanism enhances porosity/permeability. The general notion is that bioturbation reduces permeability of sedimentary strata because biogenic churning of laminated sediment that lowers the sorting of the sediment preserved within the laminae (Gingras et al., 2012), however, several examples of enhanced permeability as a result of bioturbation have also been reported (Dawson, 1978~ Gingras et al., 2004~ Pemberton and Gingras, 2005~ Gordon et al., 2010~Tonkin et al., 2010). Bioturbation is commonly overlooked in intensely bioturbated media because of a lack of lithological definition and complex fabrics that are sometimes present (Gingras et al., 2011).

The storage capacity and productivity of a reservoir are determined by its porosity and permeability. Permeability is also an important aspect that controls reservoir response during enhanced recovery. Correspondingly, understanding and projecting variations in porosity and permeability within a reservoir are vital to maximizing the acquisition of the resource. Recently, there has been considerable enthusiasm in recovering hydrocarbons from marginal (generally lower-quality) reservoirs using horizontal drilling techniques and fracturing, particularly in areas prone to light oil. Researchers at the University of Alberta in Edmonton, Canada, have studied the porosity and permeability effects of bioturbation (Pemberton and Gingras, 2005). They have seen the greatest effects when burrows in dewatered firmground are filled with coarse grained sediments. The effects on permeability depend on burrow connectivity, depth of penetration and permeability contrast between matrix and burrow fill.

Ghawar oil field in Saudi Arabia, the world's largest, is a great example of bioturbation effects. Carbonates of Jurassic Arab-D formation is the reservoir zone. Production logging has detected thin, super-permeability zone, called super-K, which contributes to majority of the total flow (Al-Awadi et al., 2009). Geologists of the University of Alberta examined cores from super-K layer and reported the presence of a geologic surface with burrow enhanced permeability. This is interpreted as a result of regional erosion of firmground (low porosity micritic calcite layer). It resulted in abandoned burrows, which were filled with sucrosic dolomite, which is porous and permeable than the micrite matrix (Al-Awadi et al., 2009). Although this high permeability zone is great for oil production, yet it can be a source of problem, if water is drawn into it from underlying aquifer.

Within calcareous sediment, chemical and physical alteration of the substrate by burrowing organisms can result in fabric-selective dolomitization. In many examples, these dolomitized burrows have been identified as having significantly higher permeabilities relative to the surrounding lime mud matrix (e.g. Ordovician Yeoman/Red Rivers Formations, Williston Basin, Gingras et al., 2004; Upper Jurassic Ula Formation, Norwegian North Sea, Baniak et al., 2011).

Baniak et al. (2012) performed a reservoir characterization study of burrow mottled dolomites from Devonian Wabamun group, west-central Alberta, Canada. Historically many of the Wabamun limestones throughout Alberta have been considered very poor reservoir rock because of low porosities and permeabilities, ranging below 1% and 1mD respectively (Saller and Yaremko, 1994). But these limestones often are chaotically distributed which shows higher effective porosity (as high as 5-6%) and very high permeabilities, up to 500mD (Gingras, 2002, 2004). These zones are burrow mottled wackestones-mudstones with preferentially dolomitized burrows (Baniak et al, 2012). The dolomitized burrows, although difficult to discriminate within core, are most comparable to examples of *Thalassinoides* and *Palaeophycus* based on morphology and orientation (Baniak et al, 2012). Analysis of bioturbated facies through Micro-CT and spot-permeametry suggests high burrow connectivity, potentially yielding a continuous flow network between the burrow systems. Horizontal burrow connectivity was found more than vertical burrow connectivity. The burrows, therefore, act as biogenic fracture systems. Unlike natural fracture systems, however, interconnected burrow networks have considerably higher surface areas and, therefore, greater amounts of flow conduits within the lower permeability matrix. Consequently, natural gas movement becomes concentrated within the burrow networks during the production phase of the reservoir.

In another study of core samples (approximately 32 feet length) and thin sections from the Miocene interval of Agbada Formation in south-eastern offshore Niger delta, Odelugo et al. (2016) found dominance of bioturbated lithofacies with the spread of the Skolithos ichnofacies. They found the bioturbated zones are having higher porosity and permeability when compared to less or non-bioturbated zones and concluded that bioturbation influenced porosity and permeability positively, improving the reservoir quality of the well.

Gas and oil prone mudstone and shale formations, i.e. unconventional reservoirs can be benefited from bioturbation as well like conventional reservoirs. Economic production from such low-permeability reservoirs relies upon identifying regions of the reservoir that will yield the highest gas production rates. Currently available gas recovery technologies are highly dependent on the fracturability of the reservoir. Zones of enhanced brittleness and permeability within shale-gas reservoir horizons are a prerequisite for successful shale-gas recovery. Such brittle zones are directly linked with increased quartz and/or carbonate content within the mudstone. In mudstones with high clay-mineral content, quartz may be concentrated and redistributed as a result of burrowing activities of infaunal organisms

(Bednarz and Mcllroy, 2012). High quality porosity and permeability zones in shale-petroleum reservoirsmay be present in the form of silty and sandy tortuous strips of selectively concentrated grains of quartz that constitute burrow halos (Bednarz and Mcllroy, 2012). Grain-selective burrows therefore can improvereservoir capacity, permeability, and fracturability and thus control the storativity of the shale-petroleum reservoir (Bednarz and Mcllroy, 2012).

In a classic study on the effect of Phycosiphoniform burrows on shale hydrocarbon reservoir quality, Bednarz and Mcllroy (2012) presented a three dimensional reconstruction of different types of Phycosiphon like burrows and investigates the possible fluid flow paths caused by ichnofabric. The volumetric approach to the bioturbation generated by phycosiphoniform burrow-makers shows that the volume of sediment that becomes more porous and more permeable media within such bioturbated interval can range from 13 to 26% of the total volume (Bednarz and Mcllroy, 2012). The quartzose strips of sediment caused by bioturbation are highly tortuous and interconnected vertically and horizontally, thereby increasing both horizontal and vertical permeability (Bednarz and Mcllroy, 2012). Additionally, the quartz frameworks created by the burrows may locally increase fracturability within otherwise non-brittle mudstones (Bednarz and Mcllroy, 2012).

Few focused studies of the ichnology of shale gas reservoirs exist (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 andGingras,2005). Evidence of bioturbation has been documented in several low permeability fine grained rocks (Hickey and Henk, 2007; Loucks and Ruppel, 2007; Aplin and Macquaker, 2011). Ichnofossils have also been identified from Woodford Formation, Lower Marcellus shale in the US and Bakken shale, Montney shale in Canada. Extensive trace fossils zones have been identified in the Pine Creek field, which may improve gas storativity and the connectivity of porosity with induced fractures (Aplin and Macquaker, 2011). Bioturbation may also affect rock mechanical properties, potentially influencing the outcome of hydraulic fracturing, which are necessary to enable low permeable unconventional reservoirs to produce hydrocarbons.

There are cases, where burrows can fail to add effective porosity, like what happened in case of Naith Formation, Oman. It deposited in shallow marine carbonate platform setting (Smith et al., 2003; Baniak et al., 2013). Core study from this formation reveals these rocks have abundant burrows, but are not interconnected to produce significant amount of oil. Unfortunately the neutron and density porosity logs cannot distinguish between effective and ineffective porosity, resulting in inaccurate reserve calculations.

In another study on the reservoir sandstone of Baram delta, Sarawak, Malaysia, Ben-Awuah and Padmanabhan (2014) focus on the impact of bioturbation on reservoir quality. They analyzed reservoir rocks using thin sections, spot permeability, scanning electron microscopy and energy dispersive X-ray. Sediment packing has been observed in core samples. Sediment packers incorporate fine grade material (clay and organic matter) from the host sediment into burrow fills and/or linings decreasing isotropy and sorting of the sediments in the burrow; thin section analysis show poorer grain sorting within the burrow and burrow lining compared to the host sandstone (Ben-Awuah and Padmanabhan, 2014). A permeability reduction of 78% in the burrow over the host sandstone had been recorded by Ben-Awuah and Padmanabhan (2014). This study is another example of porosity and permeability reduction in bioturbated sediments.

Bioturbation can have the similar effects on fine grained layers as it has on reservoir zones (O'Brien, 1987). Shales and mudstones may lose their capability to act as seal rocks, if bioturbation results in significant increment in vertical permeability. Typical examples are Sirasun and Terang gas fields in Indonesia, where marly caprock with burrows filled with hollow foraminifera act as leaky seal (Aplin and Macquaker, 2011).

Bioturbation remains an under-appreciated mechanism by which porosity and permeability of a sedimentary facies are modified (Pemberton and Gingras, 2005). Even when considered, bioturbation is generally perceived to be detrimental to bulk permeability, through reduction of primary grain sorting, homogenization of the sediment, and introduction of mud through linings, biogenic deposits, and feces (Dewhurst et al., 1998; Qi, 1998; Dewhurst et al., 1999; Dornbos et al., 2000; Qi et al., 2000; McDowell et al., 2001; Pemberton et al., 2004; Pemberton and Gingras, 2005; Gingras et al., 2004; Pemberton and Gingras, 2005; Pemberton et al., 2008; Tonkin et al., 2010; Lemiski et al., 2011; Gingras et al., 2012; La Croix et al., 2013). Additionally, burrows are capable of increasing vertical permeability in laminated sedimentary rocks, where horizontal permeability otherwise tends to dominate (Gingras et al., 2012). Burrow fills also may undergo diagenetic changes that may lead to higher permeability than that of the surrounding matrix (Pemberton and Gingras, 2005; Tonkin et al., 2010; Gingras et al., 2012). Despite this, permeability across unfractured sedimentary reservoirs is commonly assessed solely on the basis of grain size (e.g. lithostratigraphic units).

DISCUSSION AND CONCLUSION

Bioturbation in sediments and sedimentary rocks results in a variety of trace fossils and microstructures (MacEachern et al., 2007). The organisms rework the sediments, mineral grains and organic matter to alter the primary fabric of sedimentary rock and it can destroy or enhanceformation porosity as well as permeability. Geologists generally consider bioturbation detrimental to permeability; biogenic churning tends to undo grain sorting and redistribution of fine clay grains can reduce overall permeability of layered media. However, evidences in recent soils and sediments shows that in some cases, bioturbation enhances porosity and permeability by creating new pathways for fluid movement.

Porosity and permeability increase when holes are burrowed into a firmground are filled with contrasting, usually coarser grained sediments (Pemberton and Gingras, 2005). These ichnofossils can add porosity and permeability to an otherwise low porosity, impermeable media. If the media is dominated by vertically aligned burrows, resulting reservoir permeability will be anisotropic with a better permeability in vertical direction and lesser in horizontal direction. In some cases, burrows can be filled with finer grained sediments resulting in destruction of permeability. Failing to detect or ignoring the presence of biogenically modified porosity can result in erroneous hydrocarbon reserve estimation. If the burrows filled with highly porous materials are not taken into account, it may lead to underestimated reserve estimation. Identifying and quantifying the effects of enhanced permeability in reservoir zones are critical for successful well completions and accurate production simulations.

Lastly, many anthropogenic activities also qualify as bioturbation. The wells we drill, tunnel we bore are similar to those burrows made by sea creatures. By recognizing bioturbation and appreciating its consequences, geoscientists are likely to upgrade their understanding of reservoirs and come up with integrated reservoir model, which ultimately will help in gaining greater degree of confidence about reservoir characterization.

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