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Part VI

Ichnology in Hydrocarbon-Reservoir and Aquifer Characterization

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Chapter 27

C0135
Porosity and Permeability in Bioturbated Sediments

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s0005 1. INTRODUCTION TS1

p0005 It is generally believed that bioturbation reduces the permeability of sedimentary strata. This is because biogenic churning of laminated sediment lowers the sorting of the sediment preserved within laminae. Also, bioturbation is commonly overlooked in intensely bioturbated media because of a lack of lithological definition and because of the complex fabrics that are sometimes present. However, several examples of bioturbation-enhanced bulk permeability have been reported in the literature (e.g., Cunningham et al., 2009, 2012; Dawson, 1978; Gingras et al., 1999, 2004a,b; Gordon et al., 2010; Gunatilaka et al., 1987; La Croix, 2010; Lemiski et al., 2011; McKinley et al., 2004; Mehrtens and Selleck, 2002; Sutton et al., 2004; Tonkin et al., 2010; Zenger, 1992). These range from biogenic modifications of the primary depositional fabric to diagenetic alterations (typically recrystallization) of the sedimentary matrix.

p0010 Permeability fabrics and the distribution of porosity result from physical heterogeneities in sedimentary rocks. Physical heterogeneity may result from the presence of laminae, the arrangement of grains or fossils, fabric-retentive and fabric-destructive diagenesis, and structural deformation. Bioturbation alters local grain distributions in the hosting sedimentary media, and trace fossils commonly possess geochemical characteristics that differ from the surrounding sedimentary rock (e.g., Konhauser and Gingras, 2011; McIlroy et al., 2003; Over, 1990; Petrash et al., 2011). Thus, trace fossils can influence the distribution of porosity and permeability in sedimentary rocks by physically

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changing the pore-throat distribution and by acting as loci of cementation and dissolution processes during early and late stages of diagenesis. These processes commonly act together, and the range of permeability fabrics generated by biogenic modification is broad.

p0015 Factors such as the morphology of the original burrow(s), the impact of bioturbation on grain-size distributions, the distribution of organics within incipient trace fossils, the mineralogy of fossils and grains, and a host of postdepositional chemical processes determine the distributions of porosity and permeability (summarized in Lemiski et al., 2011; Pemberton and Gingras, 2005; Tonkin et al., 2010). Burrowed fabrics are commonly three dimensional in their geometry and burrow shapes and sizes are variable. Thus, bioturbated media are more spatially complex than bedded media, and flow through bioturbated media is difficult to model (see Knaust, 2012). Even very simple fabrics contain a range of burrow forms, and it is difficult to statistically characterize that range (cf. McIlroy, 2007). An important outcome of burrow-associated permeability is that burrows tend to improve the vertical permeability (k_v) over the horizontal permeability (k_h). In unfractured laminated media, k_h is almost always larger than k_v.

p0020 Many oil and gas reservoirs contain zones that are bioturbated, or are entirely composed of burrowed strata. In such cases, ichnological permeability and porosity likely contribute to storativity and deliverability of resource, and important relationships, such as k_v versus k_h are altered. The analysis of bioturbated strata in hydrocarbon reservoirs should constitute part of reservoir analyses. However, due to the aforementioned complexities, this seldom occurs.

p0025 This chapter provides a summary of the concepts associated with the applications of ichnology to reservoir fluid flow. We focus on the nature of permeability and porosity and scrutinize the ways in which burrows might influence those parameters. Physical and chemical modifications resulting from bioturbation are discussed and their relationships to a classification system for burrow-related permeability are considered.

s0010 2. THE NATURE OF ICHNOLOGICAL PERMEABILITY

p0030 Trace-fossil permeability is broadly comparable to fracture permeability in that trace fossils are discrete entities displaying predictable permeabilities that, due to their large surface areas, have significant flow interactions with the surrounding matrix. There are differences: trace fossils are tubular, trace-fossil permeabilities are lower than (open) fracture permeabilities (Gingras et al., 1999), and the volume comprising the biogenic fabric is commonly much higher than the volumes of fracture systems (10–100% vs. 1–3%). Flow interactions between burrow fabrics and matrix are therefore more extensive than those between fractures and their hosting matrix. The burrow distribution can also be much extensive, whereas fractures present localized permeability streaks.

p0035 The permeability/porosity modification associated with burrow fabrics ranges between severe reductions of the bulk permeability and notable Au4 bulk-permeability enhancement. The nature of permeability enhancement can be described as either dual-porosity flow media or as dual-permeability flow media. Dual-porosity flow media include burrowed sediment wherein the matrix permeability is within two orders of magnitude of the burrow permeabilities (Fig. 1). In examples where the matrix permeability and the burrow permeability differ by three orders of magnitude or more, a dual-permeability flow network is established (Fig. 2).

p0040 In dual-porosity flow media, most of the rock volume is used to conduct flow. Although a larger fluid flux occurs through the higher permeability zones, flow interactions between burrows and the matrix are extensive (Fig. 1). This has several implications regarding reservoir behavior: (1) more pore volume contributes to fluid or gas production; (2) due to capillarity, multiphase fluid transport may lead to segregation of the different fluid phases (e.g., oil may be isolated in finer-grained parts of the reservoir); and (3) advection will be dominant over diffusion (in other words: resource flows through the stratum in response to a hydraulic gradient). Broadly speaking, fluids transported within

f0005 **FIGURE 1** Fluid-flow behavior in dual-porosity biogenic fabrics. (A) Slabbed core image of sand-filled burrows encased in a sandstone matrix (*Ophiomorpha* and vague *Thalassinoides* are discernible). (B) Schematic sedimentary medium with bioturbation shown as darker gray. (C) Within dual-porosity flow media, fluid is advected through both the matrix and the trace-fossil fill. Where Au1 the trace-fossil permeability is higher, a larger exists in the burrows.

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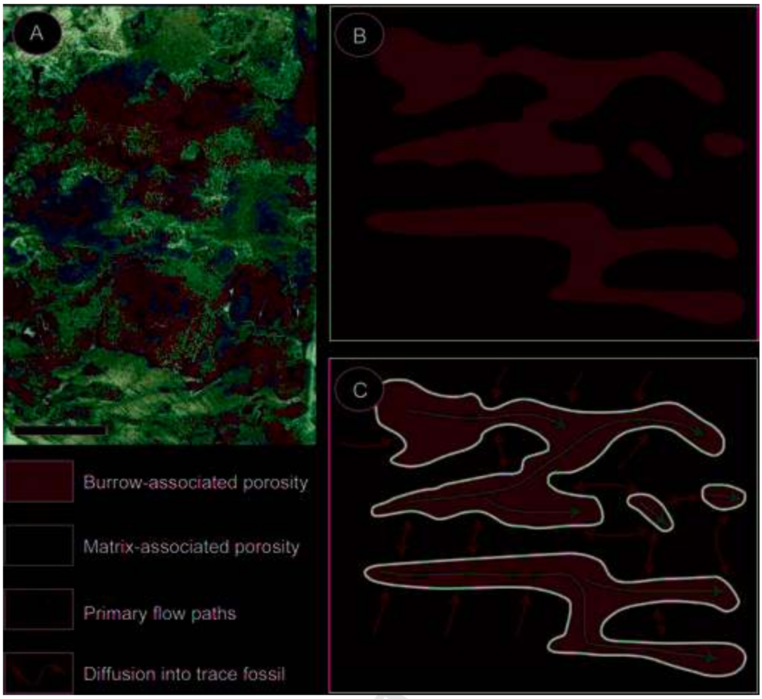
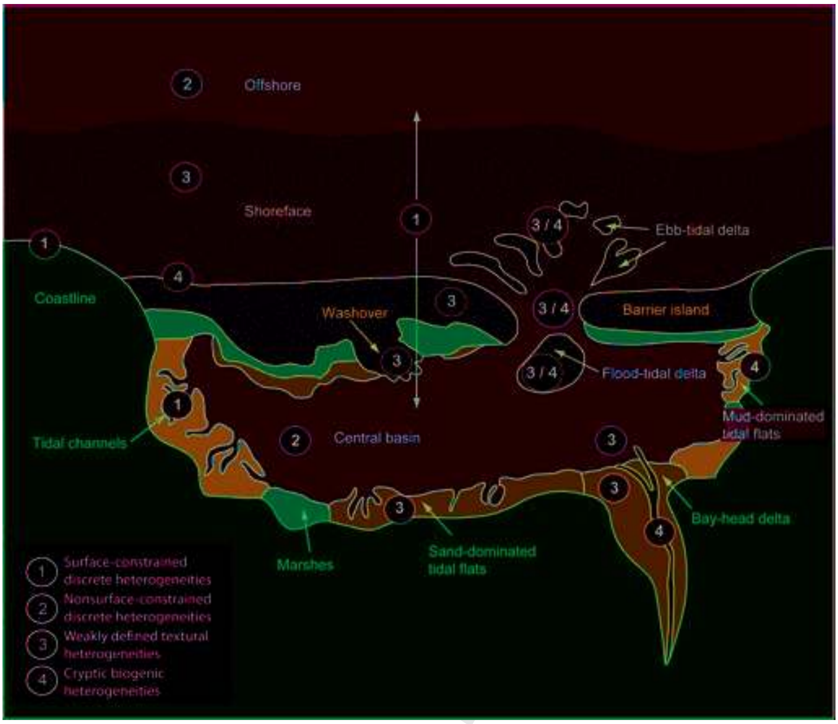


f0010 **FIGURE 2** Fluid-flow behavior in dual-permeability biogenic fabrics. (A) Slabbed core image showing trace-fossil-associated dolomite in a limestone matrix. (B) Schematic sedimentary medium with bioturbation shown as darker gray. (C) Within dual-permeability flow media, fluid is advected through both the trace fossils and the matrix (dominantly by advection). The lower permeability matrix contributes to flow only via diffusion.

dual-porosity media are not likely to move uniformly. The flow follows preferentially higher permeability beds in which the flow paths are variably tortuous, depending on to the burrow morphology. Notably, flow within the lower permeability rock may move 10–100 times more slowly than in the higher permeability burrowed zones. With regard to cryptically bioturbated intervals, where the trace-making organism is <1 mm in size, reduction of heterogeneities commonly occurs and k_v typically becomes equal to k_h.

p0045 In general, (bioturbate) dual porosity is either created by animals moving through the sediment, or is the result of sand-dwelling animals that selectively ingest and rework the sediment. Therefore, dual porosity is most commonly associated with cryptic bioturbation, the presence of *Macaronichnus*, and in bioturbated sandstone that contains *Thalassinoides*, *Ophiomorpha*, *Skolithos,* or *Arenicolites* (discussed below). Depositional settings that are associated with biogenic dual-porosity flow media thus include foreshore, sand-dominated intertidal flat, tidal bars, and lower shoreface deposits (Fig. 3).



f0015 **FIGURE 3** Biogenic flow medium characteristics are strongly influenced by the environment of deposition. Biogenic dual-permeability flow media are associated with (1) surface-constrained discrete heterogeneities and (2) nonconstrained discrete heterogeneities. Dual porosity is strongly associated with (3) weakly defined textural heterogeneities and (4) cryptic biogenic heterogeneities. Lagoonal and offshore settings are dominated by dual permeability and shoreface associations tend toward dual porosity.

p0050 For conventional oil production, dual-permeability flow media have comparably poorer resource characteristics (although they may provide good gas reservoirs). The impacts of dual-permeability systems in reservoirs and aquifers include: (1) only the higher permeability parts of the rock contribute to flow, (2) the matrix dominantly interacts with the flow conduits via diffusion, and, (3) the highly contrasting permeability fields may lead to “watering out” of the reservoir and also mitigates the effectiveness of secondary recovery techniques (e.g., water flooding). On the other hand, gas production may not be impacted by the presence of dual-permeability flow media. This is because gas flows more readily through tortuous networks than liquids, and gas may be stored in the matrix and delivered by the permeability streaks.

p0055 Dual permeability is the result of open burrows passively filled in with coarser grains, burrows being actively backfilled with coarse material or burrow-associated diagenesis in carbonate strata. Therefore, dual permeability is associated with elements of the *Cruziana*, *Zoophycos,* and *Glossifungites*

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ichnofacies, but dominantly *Zoophycos*, *Thalassinoides,* and *Planolites* (discussed below). Sedimentary environments associated with biogenic dual porosity are offshore to lower shoreface, heterolithic tidal bars and at the base of transgressive successions (Fig. 3). In the case of carbonate successions, burrow-associated diagenesis has been associated with carbonate accumulation in restricted platform and low-energy ramp settings (Beales, 1953; Corlett and Jones, 2012; Gingras et al., 2004b; Knaust, 2009).

p0060 Burrow-induced heterogeneity normally results in the presence of complex, two- or three-dimensional flow networks. Where the burrow permeability is markedly higher than the matrix, complex ichnofabrics are prone to flow-conduit cut-off and a volume of the transmissive rock is rendered ineffective. In these cases, the assessment of the ineffective flow volume is. Other major problems Au5 include fabric upscaling and determination of the three-dimensional fabric. The latter issue is solved in part through imaging techniques, such as computed tomography (CT) and magnetic resonance imaging (MRI) (discussed below). Regarding the former, pervasive fabrics, including cryptic bioturbation and general biogenic mixing, are amenable to upscaling. However, the upscaling of biogenic fabrics composed of discrete trace fossils still remains a leap of faith.

p0065 Increased complexity of flow paths results in higher tortuosity, which leads to higher dispersivity, which is the rock property related to hydrodynamic spreading of a solute or phase. Low dispersivity means that a fluid can pass through the porous media with minimal (primarily mechanical) mixing of fluids and gasses, and is a characteristic of homogeneous flow media. High dispersivity indicates more flow mixing, which is related to increased rock heterogeneity.

p0070 The impact of bioturbation on dispersivity was demonstrated by Gingras et al. (2004a). Using laboratory experiments and a burrowed (dual porosity) limestone medium, they showed that gas was transported rapidly through the higher permeability burrows whereas the matrix contributed minimally to bulk flux. The dispersivity of the burrowed limestone was higher than other flow media tested (sandstone and fractured limestone), an outcome of the high heterogeneity of the burrowed media. This is important because dispersivity partly determines secondary recovery efficiency (Gingras et al., 1999, 2004a; Pemberton and Gingras, 2005; Fig. 4).

p0075 Simple ichnofabrics have been numerically modeled using flow-simulation software (e.g., Gingras et al., 1999), but complex ichnofabrics (i.e., more than three trace-fossil types and variably permeable burrow fills) have proven Au6 difficult to model.

s0015 3. FRAMEWORK FOR ASSESSING BURROW-ASSOCIATED PERMEABILITY

p0080 A number of factors strongly influence bulk-flow parameters. These are permeability contrast, bioturbation intensity, burrow connectivity, burrow surface area, and burrow architecture.

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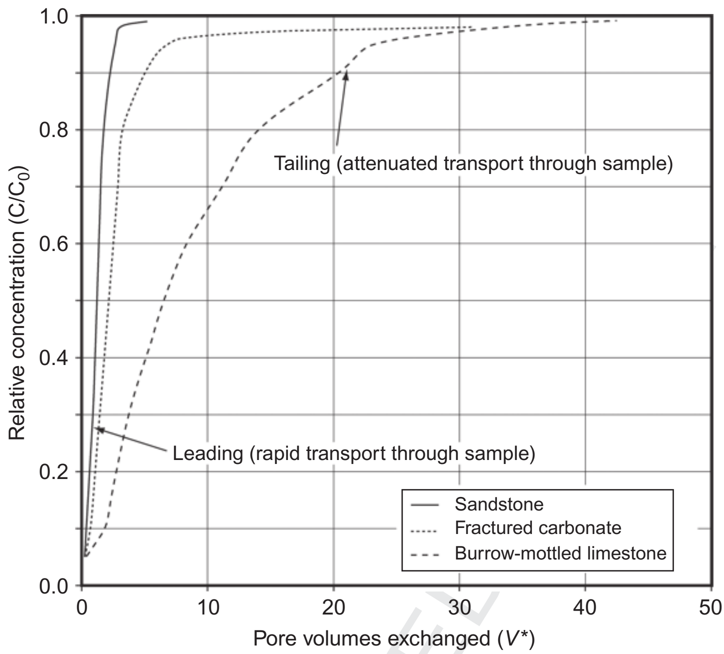

Au14

Au2 f0020 **FIGURE 4** Gingras et al. (2004a,b) determined the relative dispersivities of three types of geological media: Homogeneous sandstone, fractured limestone, and burrowed dolomitic limestone. Their results showed that the flow paths present in burrow-associated dolomite are tortuous, and that the interaction between the flow paths and the matrix is extensive. Results from their dispersivity experiments support this by indicating substantial leading of tracer gas through the sample (indicated). Leading is associated with permeability streaks in the rock, and tailing, which is associated with extensive matrix/flow path interactions.

s0020 3.1 Permeability Contrast

p0085 In stratified sedimentary media, fluid flow dominantly occurs either parallel or perpendicular to the layers. Assuming that each layer is homogeneous, the system as a whole can be characterized as a homogeneous, yet anisotropic medium (Freeze and Cherry, 1979). An estimate of the overall bulk permeability parallel to stratification is obtained from a simple volume-weighted arithmetic mean of the permeability of each layer:

$$K_{\text{arithmetic}} = \sum_{i=1}^{n} \frac{k_i d_i}{d},$$

where k_i is the permeability of each layer, d_i is the individual layer thickness, and d the total thickness.

p0090 For fluid flow occurring perpendicular to layered media, applying a volume-weighted harmonic mean provides an estimate of the bulk vertical permeability:

$$K_{\text{harmonic}} = \frac{1}{\sum_{i=1}^{n} \frac{d_i}{k_i d}}.$$

p0095 Finally, if the porous medium is not layered (i.e., it is homogeneous), the effective homogeneous permeability is isotropic and is best estimated by the volume-weighted geometric mean of the measured permeabilities (Warren et al., 1961):

$$\text{In}(k_{\text{geometric}}) = \sum_{i=1}^{n} \frac{\text{In}(K_i) d_i}{d}.$$

p0100 Gingras et al. (1999) explored the concept of applying arithmetic and harmonic means to estimate the bulk permeability of bioturbated media. By developing a set of empirical and numerically modeled solutions to bulk permeability, they showed that, under conditions of low burrow connectivity, bulk permeability could best be characterized using the harmonic mean. As burrow networks became increasingly interconnected, a modified arithmetic mean could be used, particularly for the estimation of k_v. The geometric mean is broadly applied in transitional situations where the permeable burrow structures were only locally connected (this is further explored in La Croix et al., 2012). For these studies, the above equations were modified such that the weighted volume (i.e., d_i/d) represents the proportional volume occupied by burrows, which is proportional to burrowing intensity.

s0025 3.2 Bioturbation Intensity and Connectivity

p0105 Higher intensities of bioturbation contribute to a higher effective permeability in two ways: (1) by increasing the amount of permeable flow media present and (2) by providing continuous flow paths through burrow interpenetration. Gingras et al. (1999) conducted a sensitivity analysis of flow responses in a numerical model with varying burrowing volumes (1.0%, 2.0%, 10%, 25%, and 50%). Because burrows possess at least a partial vertical component, changes in burrow abundance have an effect on both the bulk k_h and k_v. Generally, vertical permeability is semilogarithmically enhanced by increases in burrow density (Gingras et al., 1999; Weaver and Schultheiss, 1983).

p0110 As noted above, burrow interpenetrations increase in number with bioturbation intensity: exceptions to this generalization might include monospecific assemblages, such as *Skolithos* piperock, wherein, due to the burrow morphology, interpenetrations are rare. Using a range of recognized burrow morphologies and populating a three-dimensional model using various Monte Carlo simulations, La Croix et al. (2012) produced randomly generated bioturbate flow media. They observed that between levels of 20% and 30% bioturbation (by volume), continuous flow paths were formed across the modeled flow medium. Above this degree of bioturbation, the geometric and arithmetic means of permeability can be used to characterize the bulk permeability of a flow medium.

s0030 3.3 Burrow Surface Area and Trace Architecture

p0115 The presence of permeable burrows within a comparatively tight matrix increases the surface area of flow conduits within reservoirs. For instance, the surface area represented by 100 *Thalassinoides*/m^2, with 2 cm diameter tubes that descend 50 cm into the substrate, is a little over 3 m^2. This is three times more than the horizontal section and six times the vertical section. A simple fracture would possess a surface area roughly equivalent to twice the cross-sectional area of the block. It is easy to imagine extensive burrow-to-matrix interactions with higher burrow densities.

p0120 Storativity within burrow fabrics is simply related to the volumetric fraction the biogenic fabric occupies. Crustacean-generated traces, such as *Thalassinoides* and *Ophiomorpha*, can occupy more than 50% of the local sample volume. *Macaronichnus* may easily exceed 70% of the rock volume. Diagenetic fabrics around burrows (e.g., dolomitized burrows) range up to 80% of the volume before the matrix is no longer discernible. These examples illustrate that burrowed horizons not only change flow characteristics within a reservoir but also have an impact on resource production and reserve calculations as well.

p0125 In addition to its size, a burrow's overall architecture can influence the degree of connectivity and tortuosity present in biogenically modified flow media (La Croix et al., 2012). Branching burrows with vertical elements provide the highest likelihood of developing an effective, isotropic network. A common example of this is *Thalassinoides*. Many trace fossils do not exhibit branches, and thus rely on chance interpenetration to connect the biogenic flow paths (e.g., *Zoophycos*). Cryptic bioturbation is so highly interconnected that the flow medium is essentially isotropic and permeability dead zones likely are rare.

s0035 4. ANALYTICAL METHODS

p0130 The assessment of ichnological permeability revolves around measuring the permeability of matrix and trace fossils, and resolving the shape and distribution of trace fossils for upscaling. In both areas, analytical techniques have a range of limitations.

s0040 4.1 Permeability Assessment: Spot Permeametry

p0135 Permeability assessments most commonly are derived from spot permeametry, which provides small-scale measurements that are not particularly accurate. Plug, core, and bulk permeability measurements, which normally are some modification of a Darcy experiment, are time-consuming and technically problematic as summarized in Gingras et al. (1999). Darcy experiments are not further discussed here, because they are well outlined in other works (e.g., Freeze and Cherry, 1979). The strategy for most ichnological spot-permeametry studies is outlined below.

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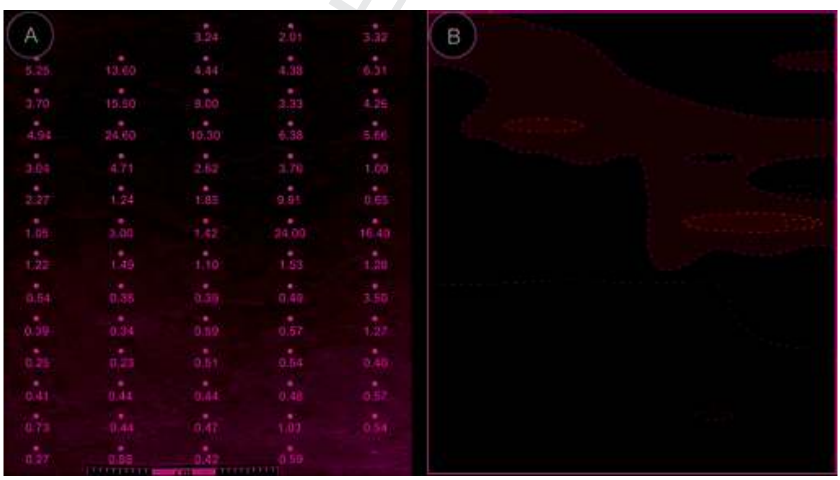
p0140 In many instances, spot-permeametry testing is undertaken using a Pressure-Decay Profile Permeameter. Lab bench devices measure the permeability of gas in the range from 0.001 mD to >30 D through a probe tip (e.g., Knaust, 2009; Lemiski et al., 2011; Pemberton and Gingras, 2005; Tonkin et al., 2010). Permeability is normally measured using a grid pattern on slabbed and cleaned cores or rock faces. Good practice is to collect five measurements from each point on the grid, with the maximum and minimum values for each spot being discarded, and the remaining three values averaged (La Croix, 2010; Lemiski et al., 2011; Fig. 5). Anomalous measurements can result from poor probe-tip seals, and should be removed from the dataset altogether. The averaged permeability values can then be plotted and contoured to produce plots of the permeability fields.

s0045 ## 4.2 Trace-Fossil Architecture and Distributions

s0050 ### *4.2.1 Outcrop and Core Data*

p0145 Spatial data is commonly interpreted from two-dimensional data sets such as core and outcrop data. Observations that can be made pertaining to the bioturbate texture are limited by the size and quality of the rock exposure or sample available. The sample size is very important, as permeability fabrics must be upscaled. Unfortunately, outcrops seldom provide a three-dimensional understanding of their structure, but the spatial distribution of burrow fabrics may be displayed. Because it commonly samples the reservoir, core is a good source of permeability data; however, the representative elemental volume is small.



f0025 **FIGURE 5** An example of contoured spot-permeameter data from the Alderson Member, Milk River Formation, Cretaceous of Alberta (Canada). This example is dominated by *Phycosiphon* and shows a range of permeability variance from <1 to >24 mD.

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s0055 4.2.2 *Nondestructive Methods of Spatial Analysis*

p0150 Nondestructive methods can be used to resolve the three-dimensional nature of sedimentary structures at the hand-sample scale. The most common of these are X-ray and X-ray CT. X-rays provide only two-dimensional data. CT scans are three dimensional. Neither X-ray nor CT scans are particularly sensitive to slight variations in density. Nevertheless, CT scans have the potential to yield high-resolution data that can be used to establish the three-dimensional nature of biogenic fabrics (Herringshaw et al., 2010; Pierret et al., 2002).

p0155 Microtomography (Micro-CT) is beginning to be used for ichnological applications (e.g., La Croix, 2010). It permits the resolution of micron- through to millimeter-scale density heterogeneities in geological media and is appropriate for the delineation of small to microscopic borings, burrows, and fecal pellets. Importantly, the technique can resolve the pore distribution in a small volume of sediment.

p0160 Unlike the aforementioned radiographic techniques, MRI does not measure the density of a rock directly. Rather, it is sensitive to fluids imbibed into the pore space of a rock. Therefore, MRI allows for three-dimensional mapping of a magnetic resonance signal, providing a tool that geologists can use to map the pore-space distribution in rocks (e.g., Gingras et al., 2002a,b). MRI can also be used to visualize the imbibition of porosity by gas or fluids, a true advantage in permeability studies (e.g., Chen et al., 2003).

s0060 4.3 Mechanisms and Styles of Burrow Permeability

p0165 In modern sediments, bioturbating animals, including earthworms, crustaceans, amphipods, polychaetes, and meiofauna, have been shown to enhance permeability and porosity primarily by creating macropores within the sediment (e.g., Aller, 1983, 1994; Katrak et al., 2003; Lavoie et al., 2000; Meadows and Tait, 1989; Pedley, 1992; Pierret et al., 2002). Although this type of flow-media enhancement can be a factor in the later developing of permeability fabrics, burrows do not remain open and unfilled in their passage to the rock record, and they are not preserved as macropores. In the rock record, the preserved patterns of permeability and porosity are strongly influenced by the character of burrow-filling sediment, the nature of burrow backfilling, compaction, and cementation. Recognizing this, Pemberton and Gingras (2005) classified biogenic flow media on the basis of their sedimentological, ichnological, diagenetic, and stratigraphical contexts. Pemberton and Gingras proposed that biogenic flow media could be separated into five classes (Fig. 6), including (1) surface-constrained discrete heterogeneities (SCD), (2) nonconstrained discrete heterogeneities (NCD), (3) weakly defined heterogeneities, (4) cryptic heterogeneities, and (5) diagenetic heterogeneities. In this context, "surface-constrained" implies that the bioturbation descends from a single surface and "nonconstrained" suggests that the burrows are distributed vertically and not associated with a

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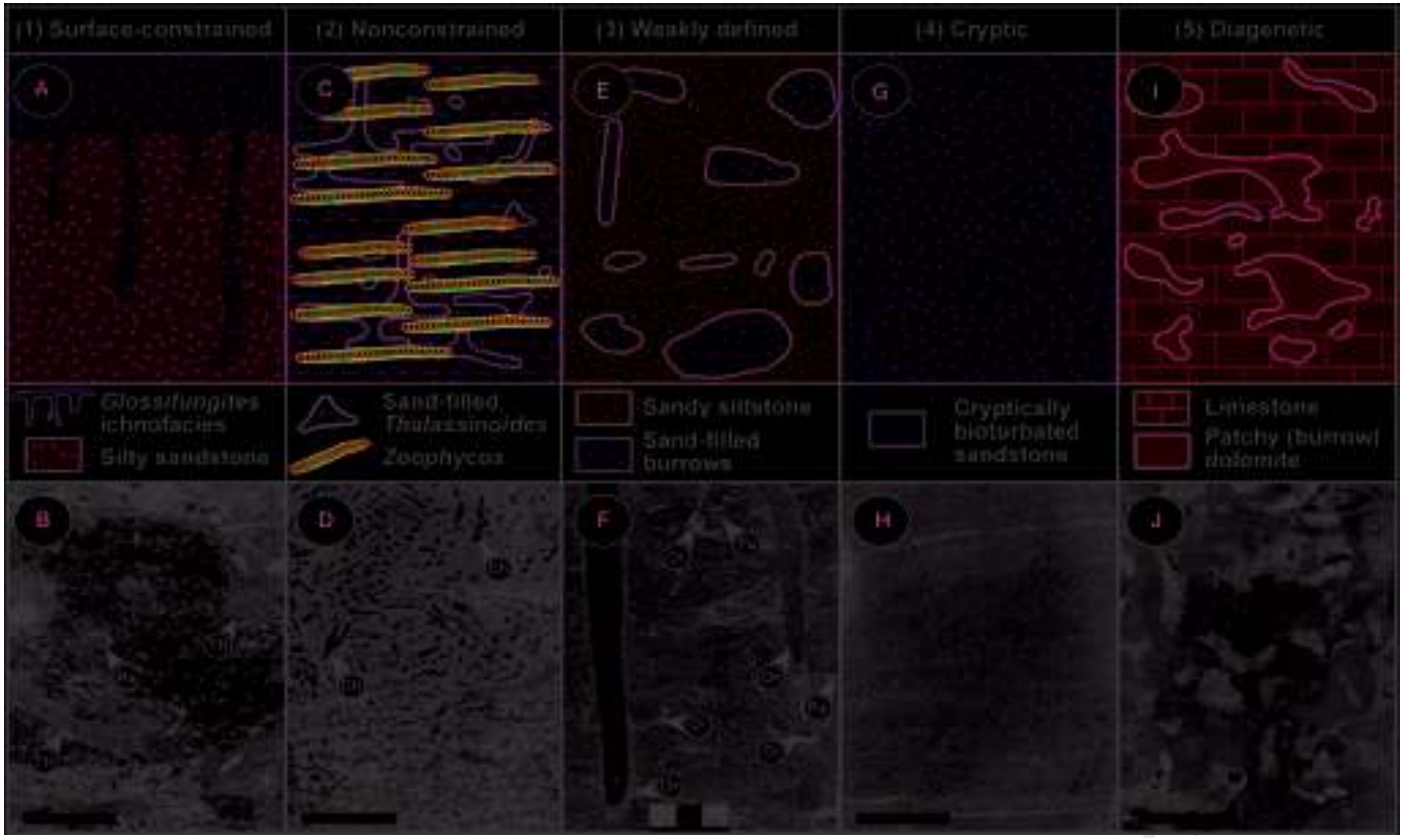

f0030 **FIGURE 6** Examples of each class of biogenic flow media from drill cores, which is 10 cm in diameter. (A) Surface-constrained discrete heterogeneities (SCD). (B) Example from Jurassic strata of Germany with *Thalassinoides* (Th) and *Paleophycus* (Pa) indicated. (C) Nonconstrained discrete heterogeneities (NCD). (D) Example, with *Chondrites* (Ch) indicated, from the Debolt Formation, Mississippian, Alberta. (E) Weakly defined textural heterogeneities (WDH). (F) Example from Jurassic strata, North Sea. *Ophiomorpha irregulare* (Oi), *Ophiomorpha nodosa* (On), and *Paleophycus* (Pa) are indicated. (G) Cryptic biogenic heterogeneities (CBH). (H) Example from Jurassic strata, North Sea. (I) Diagenetic textural heterogeneities (DTH). (J) Example from Wabamun Formation, Devonian, Alberta (Canada).

particular geological level. Discrete heterogeneities are sharply demarcated from the matrix by their texture, whereas cryptic heterogeneities are not. Diagenetic heterogeneities represent recrystallized cement accompanying burrow fabrics. Below, the permeability classifications are expanded upon case studies from the literature are summarized with each example.

s0065 *4.3.1 Surface-Constrained Discrete Heterogeneities*

p0170 This class of biogenically enhanced flow media is characteristic of trace-fossil assemblages associated with the *Glossifungites* Ichnofacies. The *Glossifungites* Ichnofacies comprises unlined burrows that descend from a single surface. The burrows commonly exceed 10 cm in diameter and show little or no evidence of postdepositional compaction. These characteristics are associated with the development of *Glossifungites* assemblages, which dominantly result from animals burrowing into firm sediment (i.e., compacted substrates). The most common expression of the *Glossifungites* Ichnofacies is sand-filled burrows within a mud matrix (e.g., Gingras et al., 2001; MacEachern et al., 1992; Pemberton and Frey, 1985).

p0175 Trace-fossil assemblages that constitute the *Glossifungites* Ichnofacies typically penetrate as little as a few centimeters and as much as approximately 70 cm below their surface of origin. Some commonly associated ichnogenera include isolated burrows such as *Skolithos*, *Diplocraterion,* and clavate bivalve burrows (e.g., Gingras et al., 2001) and burrows that potentially interpenetrate one another such as *Thalassinoides* (e.g., Pemberton and Frey, 1985) and *Zoophycos* (MacEachern and Burton, 2000). Deeply emplaced burrows that interpenetrate, such as *Thalassinoides*-dominated *Glossifungites* assemblages, can constitute flow units that are, broadly speaking, isotropic in character. Owing to the presence of sand-filled burrows within muddy matrix, SCD normally represent dual-permeability flow media (Fig. 5). The proportion of burrowing ranges from 10% to 80% of the volume. Notably, horizontal connectivity is limited until burrow volumes approach 20–30% (depending on the burrow architecture; La Croix et al., 2012).

p0180 *Glossifungites*-associated SCD are typically limited in their distribution. Due to their association with a single surface, the thickness of the permeability enhanced zone is typically <1 m (e.g., Gingras et al., 2001; MacEachern et al., 1992). Additionally, the colonization of firmgrounds depends upon a number of factors, so their stratigraphic expression is discontinuous (cf. Gingras et al., 2001; Pemberton and Gingras, 2005): SCD are generally limited in scale to some hundreds of square meters, with a maximum areal extent of about a square kilometer (Pemberton and Gingras, 2005).

p0185 Surface-constrained permeability enhancement is probably not limited to *Glossifungites* Ichnofacies-demarcated surfaces. For example, short-term colonization windows in deep-water environments (e.g., a turbidite fan) may promote the emplacement of sand-filled burrows along singular bedding planes.

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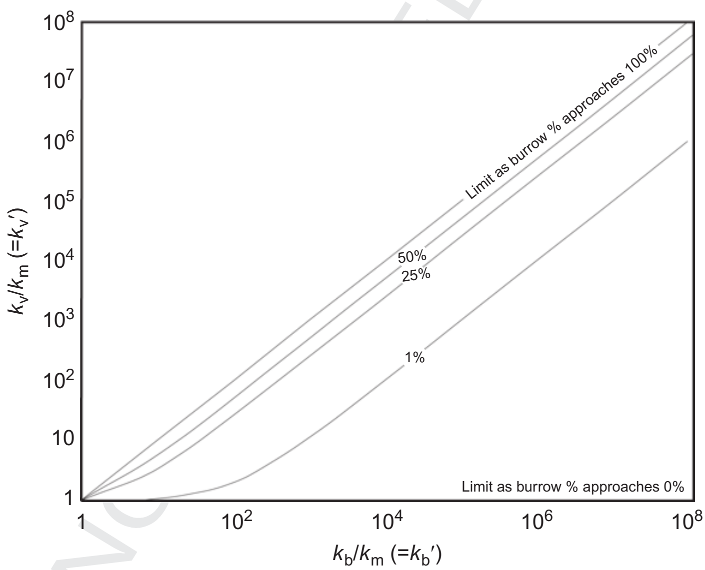
The porosity and permeability distributions in such occurrences are likely similar, but no case studies have as yet been conducted on such media.

s0070
4.3.1.1 Willapa Bay (Pleistocene), Washington, USA

p0190 The only detailed permeability study of SCD, by Gingras et al. (1999), investigated Pleistocene examples of *Glossifungites* Ichnofacies-enhanced permeability using field slug tests, laboratory Darcy tests, and numerical models. They reported that three variables determine the flow characteristics of a *Glossifungites* surface: (1) the degree of contrast between burrow permeability (K_b) and matrix permeability (K_m), (2) the amount of burrow interpenetration, and (3) the burrow density. Their computer simulations indicated that the dominant influences are the permeability contrast (K_b/K_m) and the degree of burrow connectivity. Gingras et al. (1999) further showed that empirical and analytical formulae could be derived to determine the effective (bulk) permeability (Fig. 7). This was determined from K_b, K_m, and the degree of connectivity. The general formula can be applied in any geological medium as a simple, first-run approximation:



f0035 **FIGURE 7** Curves showing the relationship: $\log K_{bulk} = \log[(1 - V_b)K_m + V_b K_b]$ for volumes of 1%, 25%, 50%, and 100% bioturbation. In this instance, enhancement of the vertical permeability is shown. The *x*-axis shows how the ratio of burrow (k_b) and matrix (k_m) permeabilities diverts the behavior from the predicted permeability. The *y*-axis indicates how much bulk permeability is enhanced of the matrix permeability (k_v/k_m), depending on (1) the burrow and matrix permeability ratio and (2) the proportion of media that is bioturbated. This relationship was derived empirically using Darcy experiments, slug tests, and numerical models. The formula is best applied to surface-constrained discrete heterogeneities and is useful for the estimation of the bulk permeability.

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$$\log K_{\text{bulk}} = \log[(1 - V_b)K_m + V_b K_b],$$

where V_b is the fractional volume of burrows within a block.

s0075 #### 4.3.1.2 Hawiyah Portion of the Ghawar Field (Jurassic), Saudi Arabia

p0195 SCD have also been reported from carbonate strata. Pemberton and Gingras (2005) presented data from the Hawiyah portion of the Ghawar Field, where a distinct interval of stacked *Glossifungites* Ichnofacies-demarcated surfaces occurs. The Ghawar example is rather extreme as it is characterized by *Thalassinoides* with 1–2 cm in burrow diameter that penetrates up to 2.1 m below the surface. The burrow-encapsulating matrix is composed of low-permeability micritic calcite. The burrow fills and the overlying strata consist of detrital sucrosic dolomite, providing a biogenic flow system for some of the Ghawar reservoirs. The permeability of the burrow fill is high enough to cause the biogenic flow medium to locally develop into high permeability (also known as "Super K") stratigraphic levels. Au7

s0080 #### 4.3.1.3 Baldonnel Formation (Triassic), British Columbia, Canada

p0200 Outcrops of the Baldonnel Formation display discontinuity surfaces, delineated by granule/pebble lags, substrate-controlled trace-fossil assemblages, and pronounced diagenetic alteration of underlying strata in the Carnian Baldonnel Formation at Williston Lake, north-eastern British Columbia. Many of these surfaces are characterized by well-developed, low- to moderate-diversity trace-fossil assemblages attributed to the *Glossifungites* Ichnofacies that locally are overprinted by sparse, low-diversity trace-fossil assemblages characteristic of the *Trypanites* Ichnofacies, together comprising a polygenetic SCD (Fig. 8). Fabric selective (interparticle, intraparticle, and biomoldic) and nonfabric selective (vuggy and burrow) porosity are best developed in them, in association with bioclastic packstone and grainstone beds immediately beneath discontinuity surfaces, particularly those characterized by *Glossifungites* assemblages. Complex depositional/diagenetic relationships occurred where substrata characterized by moderately diverse *Skolithos* or proximal *Cruziana* trace-fossil assemblages were buried, exhumed, colonized by firmground-preferring infauna, lithified, colonized by hardground-preferring infauna, and reburied. Diagenetic alteration occurred via fluid penetration through burrows during, and shortly after, hardground formation.

s0085 ### *4.3.2 Non-SCD*

p0205 Nonsurface-constrained discrete (textural) heterogeneities (NCD) comprise sharply defined burrows that are encased in a fine-grained matrix. Like surface-constrained heterogeneities, this architecture is common in clastic strata where sand-filled burrows descend into mudstone. However, NCD are laterally and vertically distributed (i.e., burrows originate from several depositional

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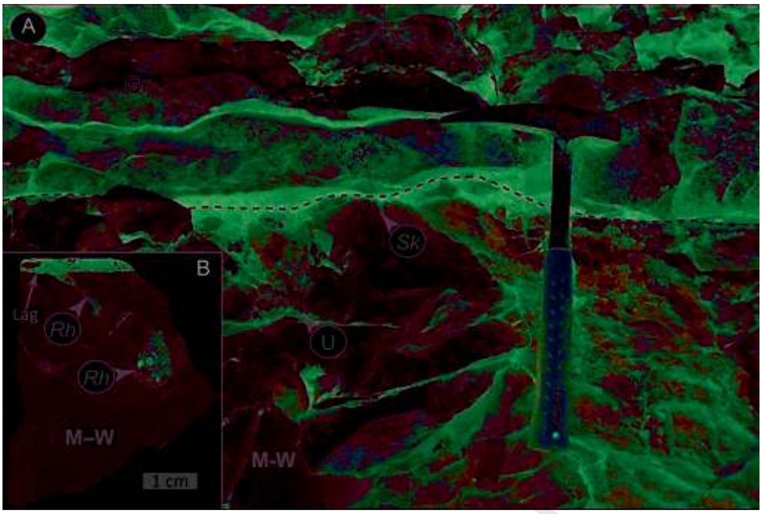

f0040 **FIGURE 8** Intraformational unconformity within the Late Triassic Baldonnel Formation. This surface is characterized by low-diversity *Glossifungites* trace-fossil assemblages that consist of *Arenicolites*, *Rhizocorallium*, *Skolithos,* and *Thalassinoides* as well as large, unnamed burrow networks. The lower lithofacies consists of a variably bioclastic fine-grained mudstone–wackestone (M–W) with low, mixed interparticle and intercrystalline porosity of ~2.5%. The upper lithofacies is a sandy bioclastic grainstone (Gr) with fine-to-medium-grained matrix and mixed interparticle, mouldic, and intercrystalline porosity of ~6–9%. These facies are separated by a discontinuous coarse-grained lag (Lag) that infills fractures and burrows that emanate downward from this surface. (A) Outcrop of the Baldonnel intraformation unconformity, East Carbon Creek, north-eastern British Columbia (Canada). Two burrows are identified including a solitary *Skolithos* (*Sk*) and a large, approximately U-shaped burrow (U) that is believed to be part of a complex arthropod domichnion. (B) Polished hand sample illustrating the sharp boundary between the mudstone–wackestone (M–W) and the coarse-grained lag that infills burrows such as the obliquely-cut *Rhizocorallium* (*Rh*) illustrated here.

surfaces) and the bioturbation intensity must be high enough to afford connectivity in three dimensions. This type of permeability enhancement is most common in strata that accumulated in offshore settings, although lagoon and bay settings, including deposits dominated by inclined heterolithic stratification cannot be discounted.

p0210 NCD flow media are dominantly dual permeable in character (Figs. 2 and 6). Au8 Owing in part to the association of NCD with offshore settings, the bioturbation intensity can be quite high with burrows occupying between 30% and 90% of the sediment volume. In offshore and shelf settings, vertical and horizontal burrow architectures are common (e.g., *Cruziana* and *Zoophycos* ichnofacies): as such NCD are likely to be highly interconnected (Fig. 9) and permeability should be isotropic. In increasingly distal settings characterized by the *Nereites* Ichnofacies, bioturbation is dominantly restricted to bedding planes and vertical permeability is not normally enhanced. The thicknesses of permeability enhanced zones range between 5 m and tens of meters (e.g., Pemberton and Au9

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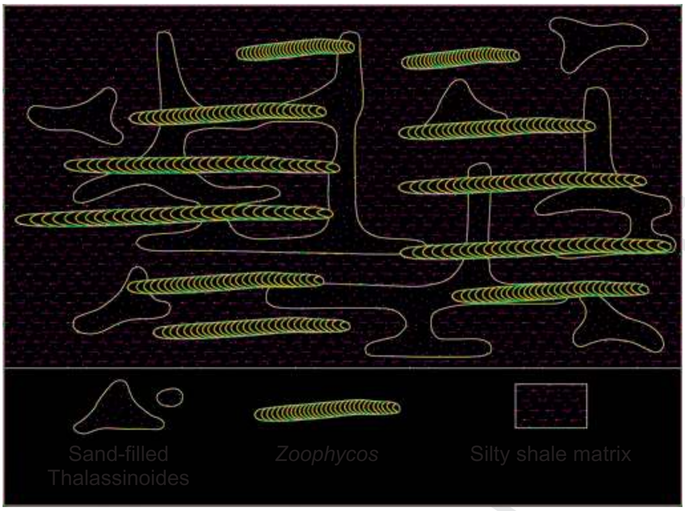

f0045 **FIGURE 9** Foram-filled *Zoophycos* (Zo), encased in a lower permeability matrix, form an important part of the Sirasun Field in Indonesia. The burrows are further connected by *Thalassinoides* and *Chondrites*: thus, the biogenic reservoir is largely isotropic and is a prodigious natural gas producer.

Gingras, 2005). Additionally, the permeability enhancement is stratigraphically continuous. Stratal units characterized by non-SCD can exceed several square kilometers in area (Pemberton and Gingras, 2005).

s0090 #### 4.3.2.1 Lysing Formation (Cretaceous), Norwegian Sea (Unpublished Case Study)

p0215 Within the Late Cretaceous Lysing Formation, biogenic fabrics appear to enhance the reservoir permeability significantly. The Lysing Formation is composed of interbedded very fine- to fine-grained sandstone, siltstone, and shale that contain a diverse trace-fossil suite. Sediment accumulation is the result of alternating fine- and coarse-grained sedimentation within a mid to outer shelf setting. The trace-fossil assemblage includes *Thalassinoides*, *Planolites*, *Scolicia*, *Chondrites*, *Paleophycus*, and *Zoophycos* (i.e., distal *Cruziana* Ichnofacies). The trace fossils commonly contain coarser sediment (fine-grained sandstone) than the shale matrix.

p0220 Spot-permeability data taken from core datasets indicate that the burrow permeability can be up to two orders of magnitude higher than the matrix, thus proffering a dual-permeability flow medium. Importantly, bulk assessments of permeability based on core-plug data indicate that the harmonic mean of matrix versus burrow permeabilities provides the most accurate estimate of bulk permeability in the Lysing example (Fig. 10). The harmonic relationship suggests that the flow is largely directed across the lower permeability matrix from

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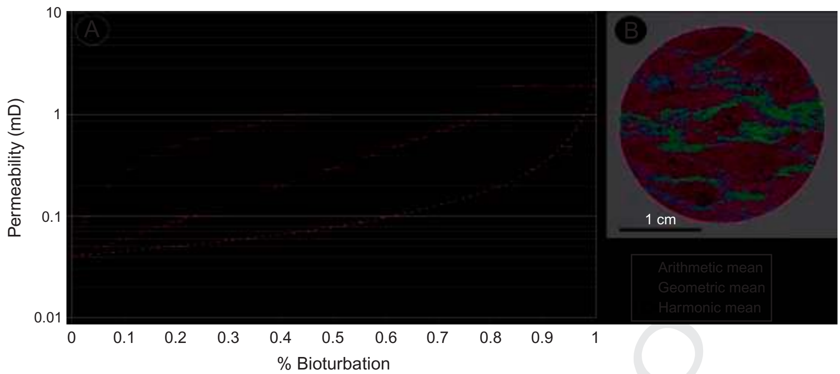

f0050 **FIGURE 10** The predictable permeability relationships that may be present in bioturbated flow media (Lysing Formation, Norway). (A) Graph showing three possible solutions to estimating the bulk permeability (geometric, arithmetic, and harmonic means). The red star indicates the actual bulk permeability of a sampled plug (B), which is plotted according to its degree of bioturbation and measured permeability. Here, it appears that the burrows are conforming most closely to the harmonic mean, suggesting that, in spite of the high levels of bioturbation, some flow complexities are present.

burrow to burrow. This is, in fact, characteristic of NCD dominated by sparse bioturbation. As with most other biogenic flow media, the resulting flow network is an overall intricate, locally interconnected horizontal and vertical burrow system. In this example, bulk permeability measurements also show that k_h is higher than k_v (Fig. 10) and that permeability distributions are anisotropic. This is likely the result of increased horizontal burrowing associated with shelfal trace-fossil assemblages or may be related to the small (2.54 cm) scale of the permeability measurement.

s0095

4.3.2.2 Terang-Sirasun (Miocene), East Java Sea

p0225 Pemberton and Gingras (2005) provided an example of non-SCD from the Terang-Sirasun gas field of the East Java Sea. Terang-Sirasun resides in the Kangean block approximately 140 km north of Bali (Matzke et al., 1992). The field comprises reserves residing in the Lower Paciran Sandstone Member (Late Miocene), the Upper Paciran Sandstone Member (Late Miocene), and the Paciran Limestone Member (Pliocene). Noble and Henk (1998) showed that the Paciran Limestone Member is a deep-marine pelagic carbonate deposit. The lower lithofacies are mainly grainstones, wackestones, and packstones, and the upper lithofacies predominately comprise marls. The upper marl lithofacies of the Paciran Limestone contains abundant, gas-charged *Zoophycos*. The *Zoophycos* are backfilled with hollow globeriginid tests (Fig. 9), and the trace-fossil permeability is substantially higher than the matrix. The ichnogenus is deeply penetrative; so, the burrows are interconnected and the permeability is isotropic.

s0100 4.3.3 *Weakly Defined Textural Heterogeneities*

p0230 Sedimentary media that exhibit less than two orders of magnitude between the trace fossils and matrix permeabilities comprise weakly defined textural heterogeneities (WDH) (i.e., dual-porosity system). This class of flow media dominantly comprises sand-filled burrows within a sandstone matrix or very fine sand in siltstone matrices (Figs. 6 and 11). In examples of WDH, the sorting of the burrow infill tends to be better than the matrix, and the grain packing is in some cases likely to be looser—especially with passively infilled burrows. Biogenic permeability modification ascribed to WDT most commonly is associated with the presence of *Planolites*, *Thalassinoides*, *Skolithos,* and some expressions of *Macaronichnus*. In the light of their branching morphology, deeply penetrative nature and passive infill, *Thalassinoides* and *Ophiomorpha* are likely the most important permeability enhancing trace fossils, although Tonkin et al. (2010) observed permeability reduction with *Ophiomorpha* as well. La Croix et al. (2012) and Lemiski et al. (2011) drew attention to another style of WDH comprising *Phycosiphon*-dominated intervals in siltstones. In these examples, the small trace fossils provided additional flow paths for natural gas to reach both the well bore and bedded reservoir units.

p0235 WDH are mostly associated with lower shoreface, sand-rich proximal offshore settings, and various bay-margin deposits (Pemberton and Gingras, 2005), with *Phycosiphon*-bearing (impoverished *Cruziana* Ichnofacies) examples largely identified within offshore siltstones. Sand-dominated intertidal flat deposits should be included in WDH, but no studies have been conducted to demonstrate this. Due to the variable sedimentary conditions present in lower shoreface and (particularly) tidal flat deposits, the thicknesses and lateral extents of associated facies are generally limited. In strata hosting these fabrics, affected beds and bedsets reach thicknesses of up to 10 m (Pemberton and Gingras, 2005). The lateral extents of subtly burrowed facies range between hundreds of meters (tidal flat settings) and several kilometers (offshore associations).

s0105 4.3.3.1 Ula Formation (Jurassic), Offshore Norway

p0240 Located in the north-eastern corner of the Norwegian Central Graben, the Late Jurassic (Kimmeridgian-Oxfordian) Ula Formation hosts significant hydrocarbon fields within the oil-rich Ula Trend (Spencer et al., 1986). Interpreted as a storm-influenced, fault-controlled shoreface deposit, hydrocarbon production from the Ula Formation occurs primarily from bioturbated units. Spot permeametry, Micro-CT, and Visual Modflow modeling of the Ula Formation demonstrated that the permeability enhancement within *Ophiomorpha*-dominated sandstone intervals represents a dual-porosity network (Fig. 11). The distal *Skolithos* Ichnofacies, that is gradational with proximal expressions of the *Cruziana* Ichnofacies, constitutes a good example of a dual-porosity rock fabric that can be categorized using the arithmetic mean. An example includes horizontal oriented networks of *Ophiomorpha* with high bioturbation intensities

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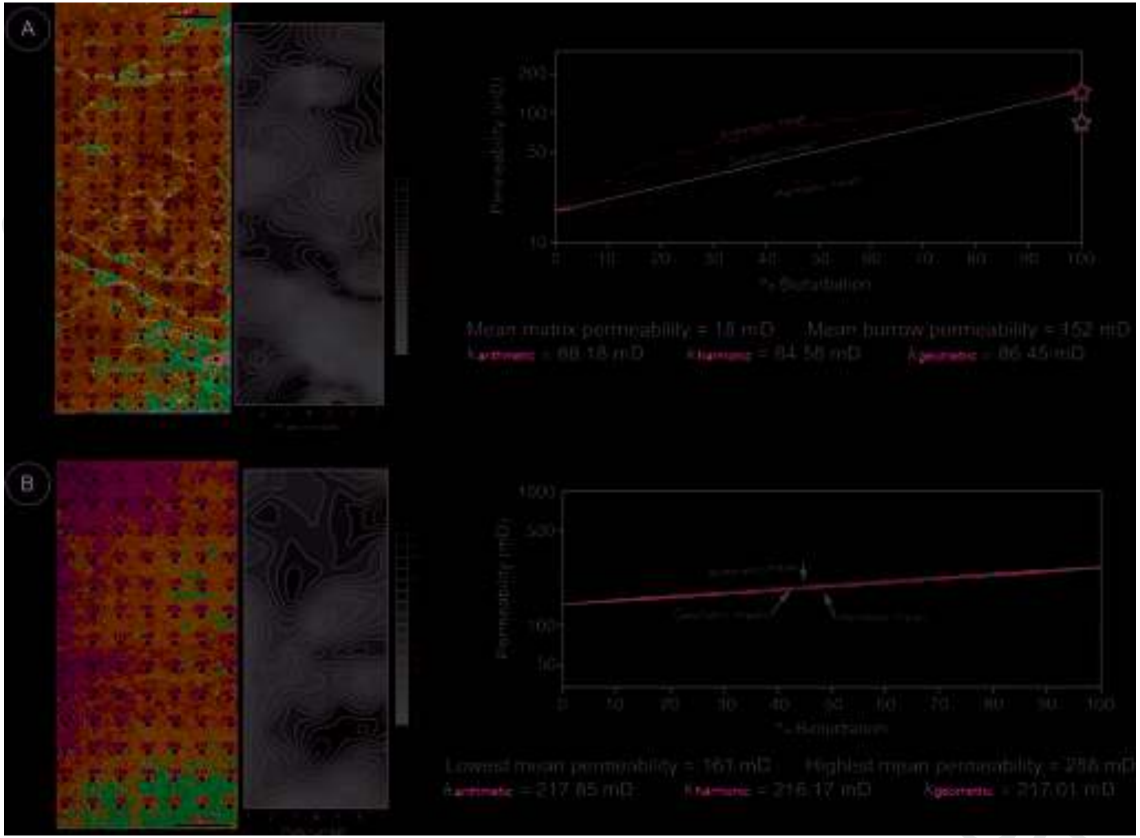

f0055 **FIGURE 11** Biogenically modified flow media from the Late Jurassic Ula Formation, Norwegian North Sea. (A) Minipermeametry of a weakly defined textural heterogeneity for well 7/12-6, depth 3439.00 m. From the contour map, it is apparent that the higher permeabilities are localized along well-defined burrow networks. This suggests that the arithmetic mean represents fluid flow along the most permeable conduits. Because of small-scale heterogeneities within the sample (i.e., burrow mud linings) the $k_{arithmetic}$ is only at 88.18 mD at 100% bioturbation (green star). This is opposed to the idealized 100% bioturbation intensity, which predicts 152 mD (red star). (B) Minipermeametry of a cryptic textural heterogeneity for well 7/12-6, depth 3503.00 m. The highest permeabilities in this section are a result of higher levels of sediment reworking by microorganisms. Therefore, utilization of the geometric mean would be the most accurate for examples of cryptic bioturbation because it represents fluid movement in an unstructured medium (i.e., $k_v = k_h$).

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(BI = 4–6). Conversely, the archetypal *Skolithos* Ichnofacies was found to be a good example of the harmonic mean in shoreface environments. Vertically orientated *Ophiomorpha* burrows with low bioturbation intensities (BI = 1–3) were found to be good examples.

s0110 4.3.3.2 Ben Nevis Formation (Cretaceous), Newfoundland, Canada

p0245 The Ben Nevis Formation largely represents a marine embayment deposit with several sand-rich levels (Pemberton et al., 2001; Spila et al., 2005). Tonkin et al. (2010) showed that *Thalassinoides* enhance the petrophysical properties in the net-pay intervals. Examples of *Ophiomorpha* also contain cleaner sediment surrounded by a muddy lining. Among Tonkin et al.'s (2010) key findings were the following: (1) the presence of *Thalassinoides* increases isotropy and enhanced porosity and permeability by up to 600%, (2) burrowing behavior (e.g., backfilling vs. passive filling; tunneling vs. sediment swimming) has a predictable effect on the permeability of sedimentary media, and (3) characteristic bioturbate texture can be used to predict broad permeability classes.

s0115 4.3.3.3 Cusiana/Cupiagua Field (Eocene), Columbia

p0250 The Columbian Cusiana/Cupiagua Field is located in the Llanos Foothills of the Eastern Cordillera of the Andes. The field comprises three main sandstone units: quartz arenites of the Eocene Mirador Formation, quartz arenites of the Paleocene Barco Formation, and phosphatic litharenites and quartz arenites of the Early Cretaceous Guadalupe Group (Warren and Pulham, 2001). A suite of the *Glossifungites* Ichnofacies, associated with a basin-wide unconformity, occurs at the base of the Mirador Sandstone. The assemblage is characterized by *Thalassinoides*, which have a substantially higher porosity than the surrounding matrix (Fig. 12). In the case of the Mirador Sandstone, the highest rates of production are commonly associated with the *Thalassinoides*-dominated zone.

s0120 4.3.3.4 Medicine Hat Member, Niobrara Formation (Cretaceous), Alberta, Canada

p0255 The Santonian Medicine Hat Member was deposited in the broad, shallow Western Interior Seaway and is variably interpreted as offshore or delta-influenced offshore (La Croix, 2010; Pedersen and Nielsen, 2006). The Medicine Hat Member produces gas prolifically in the Medicine Hat Gas Field. La Croix et al. (2012) used spot-minipermeametry and Micro-CT to assess the effects of bioturbation on porosity and permeability within the Medicine Hat field (Fig. 13). The authors showed that the sandy burrows are two orders of magnitude more permeable than the mudstone matrix, resulting in a dual-porosity flow system. The authors further suggested that the bioturbate fabrics contribute to gas production within the field.

p0260 La Croix et al. (2012) modeled the permeability distributions and were able to establish that the permeability of the bioturbated intervals within the

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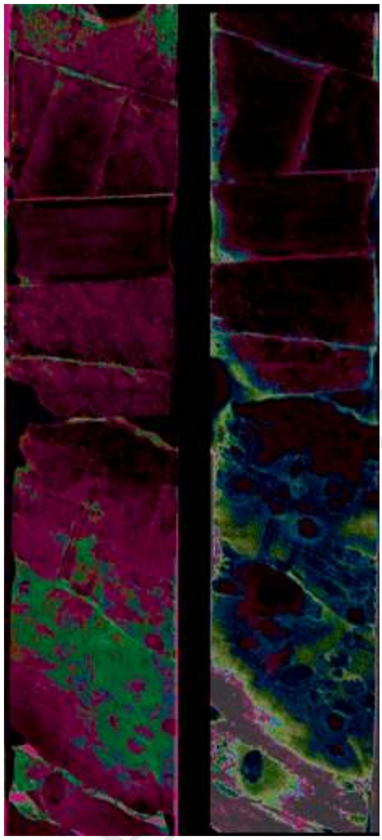


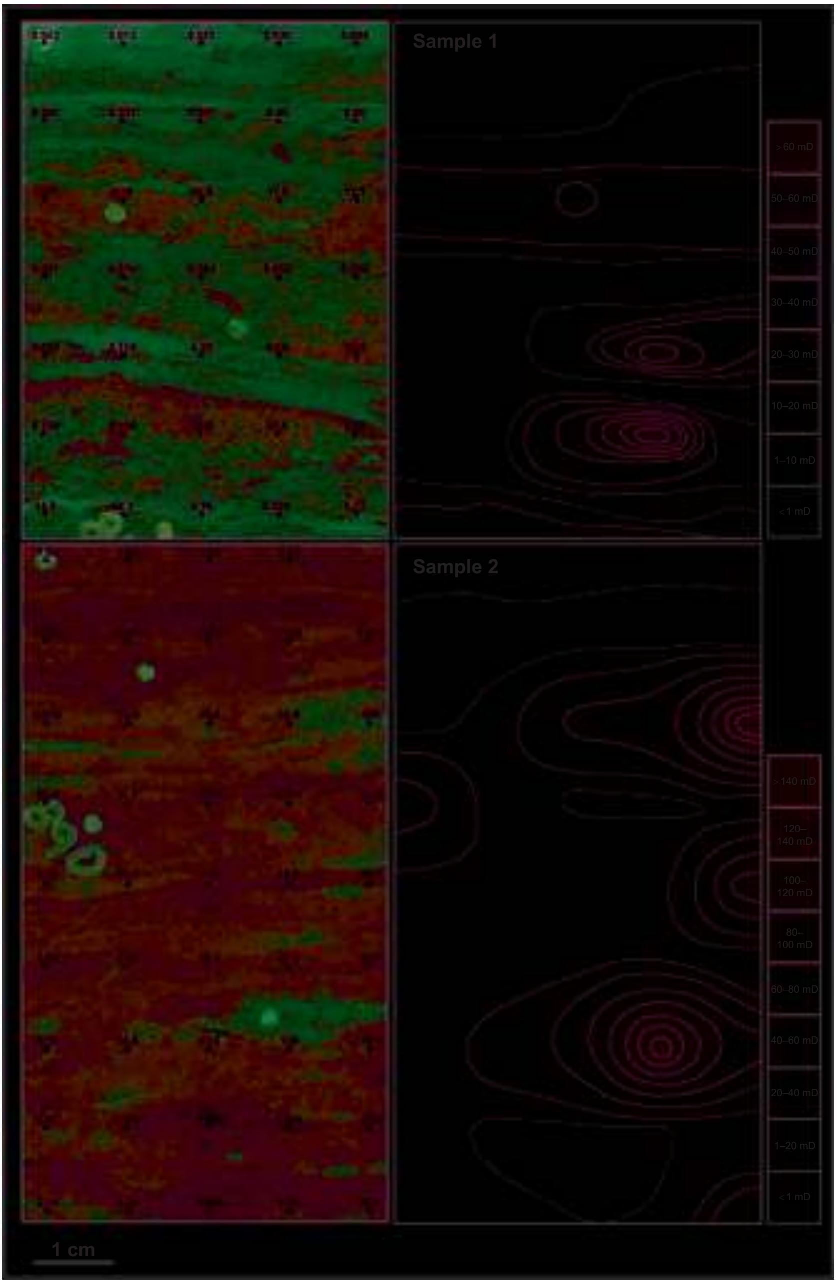
f0060 **FIGURE 12** Burrow-enhanced permeability in surface-constrained textural heterogeneities, Cusiana-Cupiaugua Field, Llanos Basin (Colombia). Core width is 8.9 cm (3.5 in.). (A) Core of the *Glossifungites* Ichnofacies at the base of the reservoir sandstone, Eocene Mirador Formation. (B) The same as (A) but under ultraviolet light, showing that the burrow systems are filled with hydrocarbons and constitute the primary pathway for the migration of the oil (photos courtesy of A. Pulham).

Medicine Hat Member can be estimated using the arithmetic mean of the trace-fossil and matrix permeabilities. This led the authors to suggest that the burrows are intensely interpenetrating and, at the reservoir scale, fluid flow through the burrowed intervals is analogous to bedded sandstone.

s0125

4.3.3.5 Alderson Member, Lea Park Formation (Cretaceous), Alberta, Canada

p0265 The Alderson Member comprises bioturbated shale, mudstone, siltstone, and fine-grained sandstone. The gas fields contained within the Alderson Member produce from continuous and laterally extensive, thin bedded, fine-grained sandstone within muddy units at depths <600 m (Hovikoski et al., 2008; Lemiski et al., 2011).

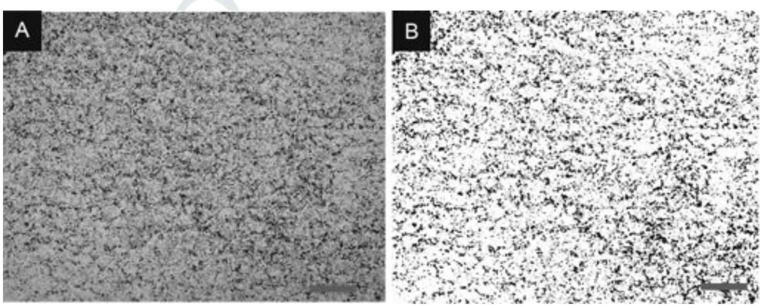


f0065 **FIGURE 13** The results of the spot-minipermeametry testing on two examples (Sample 1 location Alberta, 06-31-14-01W4, 507.65 m depth; and Sample 2 location Alberta, 0606-31-14-01W4, 509.00 m depth). On the left, the core photographs are annotated with test locations and their corresponding permeability measurements in millidarcy (mD). On the right, contour plots highlight the distribution of permeability. The data points are arranged using 1-cm grid spacing. Gaps in the data set represent discarded measurements resulting from a poor probe-tip seal.

p0270 Lemiski et al. (2011) conducted spot-minipermeametry analyses of the Alderson Member. They demonstrated that, of the reservoir units, bioturbated heterolithic intervals make the most significant contribution to the overall storage and producibility of gas from the Alderson Member. The permeability is particularly enhanced in the *Phycosiphon*-dominated sandy mudstones (Fig. 5). Lemiski et al. (2011) further suggested that the vertical transmissivity of gas is substantially increased in the bioturbated levels. Their study concluded: "bioturbated zones may represent an important means of delivering gas from the tighter, encapsulating matrix. In other words, the burrows can act as biogenic 'fractures' (but) with higher surface area."

s0130 *4.3.4 Cryptic Biogenic Heterogeneities*

p0275 Cryptic biogenic heterogeneities (CBH) result from one of three processes: (1) meiofauna disrupting sedimentary lamination, which is referred to as cryptobioturbation; (2) some *Macaronichnus* behaviors, which preserve the vestigial sedimentary texture by implementing grain-selective deposit-feeding behaviors; and (3) eradication of sedimentary lamination by burrowing animals that churn the sediment. The effects of cryptobioturbation and *Macaronichnus*-like burrows on reservoir properties can be important (Gingras et al., 2002b; Gordon et al., 2010; Pemberton and Gingras, 2005; Tonkin et al., 2010). Although cryptobioturbated fabrics appear homogeneous (Fig. 14), Gingras et al. (2002b) and Gordon et al. (2010) demonstrate that the burrow fills relative to the unburrowed matrix commonly proffer a dual-porosity flow medium. Therefore, fluid production out of cryptobioturbated media presents challenges in terms of the presence of tortuous fluid flow pathways, permeability streaks, diffusion in and out of the burrowed zones, and complex relationships between bulk porosity and bulk permeability (Gingras et al., 1999; Pemberton and Gingras, 2005). On the other hand, cryptically bioturbated and *Macaronichnus*-dominated sands have been shown to produce comparably isotropic flow units that may be amenable to



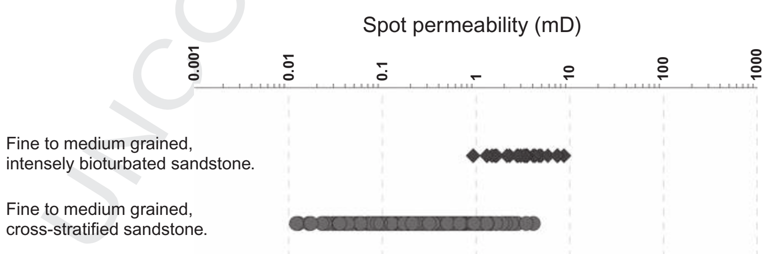
f0070 **FIGURE 14** (A) *Macaronichnus*-burrowed sand. (B) The same field of view showing image-enhanced burrow structures. The burrow halo is defined by dark grains, and the white area is the burrow fill (scale bar 0.5 cm).

hydrocarbon production (Gordon et al., 2010; Pemberton and Gingras, 2005; Tonkin et al., 2010). It is therefore important to interpret massive sandy beds in deep-water successions accurately, in order to create reliable depositional or reservoir models and to better anticipate a more complex porosity and permeability network in seemingly homogenous media.

p0280 Cryptic bioturbation (in sandstone) is common in clastic estuarine and distributary channels, as well as in upper shoreface deposits. More recently, Greene et al. (2012) identified cryptic bioturbation as a common feature of Neogene turbidite channels. The aforementioned depositional environments are dynamic, thus their thicknesses and lateral extents are limited. In general, this facies is 10 cm and 10 m thick. Amalgamated parasequences may generate stacked successions that are almost 100 m thick. Au10

s0135 4.3.4.1 Bluesky Formation (Cretaceous), Alberta, Canada

p0285 Gordon et al. (2010) studied in detail the petrophysics of *Macaronichnus* and cryptically bioturbated sandstone. Their study focused on shoreface deposits of the Early Cretaceous Bluesky Formation in western Alberta, Canada. The studied reservoir comprises lithic sandstone and several levels that were heavily bioturbated with *Macaronichnus segregatus*. Petrographic techniques were used to assess the effects of *M. segregatus* on reservoir quality. Thin-section analysis and Scanning Electron Microscopy have shown that the trace maker of *M. segregatus* avoided iron-rich detrital fragments while exploiting the sediment for food (Fig. 14). Grain avoidance led to a re-sorting of the sand such that the dark-colored grains outline the burrows, and light-colored competent grains were dominant within the burrow fill. Notably, the light-colored burrow fills contain a higher chert/quartz ratio. Owing to the fact that pore-occluding quartz overgrowths do not form on chert fragments, the primary porosity and permeability were preferentially preserved within the burrow fills (Fig. 15). Gordon et al.'s (2010) study further showed that spot permeability in the *Macaronichnus*-burrowed zones was as much as four times higher than in laminated sandstone of similar grain size (Fig. 15).



f0075 FIGURE 15 Gordon et al. (2010) showed that permeability was slightly enhanced in *Macaronichnus*-burrowed sand (Ma) compared to laminated sand, and that the burrowed media had less variance. The above data are derived from a single-cored interval of the Bluesky Formation, Cretaceous, Alberta (Canada).

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s0140 4.3.4.2 Ula Formation (Jurassic), Offshore Norway

p0290 Within the aforementioned Ula Formation, the influence of cryptically bioturbated sandstones on reservoir quality can be demonstrated. The studied reservoir units comprise upper fine to lower medium-grained sandstone that contains rare sedimentary and biogenic structures. The massive appearance of the intervals is attributed to cryptobioturbation. A petrographic thin-section study showed that the porosity is enhanced slightly (by 5–10%) within the highly bioturbated sections. Spot permeametry revealed uniform permeability distributions (Fig. 14), which explain the correspondence of permeability to the geometric mean (Fig. 11).

s0145 *4.3.5 Diagenetic Textural Heterogeneities*

p0295 Diagenetic textural heterogeneities (DTH) occur typically as bioturbated, dolomite-mottled limestones or as nodular sandstones/siltstones. With carbonates, the dolomitic mottles result from dolomitization of calcareous sediment adjacent to body fossils, sedimentary lamination, and trace fossils (Fig. 6E) (Abdel-Fattah et al., 2011; Corlett and Jones, 2012; Gingras et al., 2002a, 2004a,b; Kendall, 1977; Zenger, 1992, 1996). Another important diagenetic process is fabric-selective carbonate dissolution, which is discussed in detail by Cunningham et al. (2012).

p0300 The presence of fabric-selective dolomite in association with trace fossils is attributed to chemical and physical alteration of the substrate by burrowing organisms. Physical alteration of the substrate includes modification of the grain size, redistribution of grains, compaction, and sorting. Compositional heterogeneity is due to the incorporation of localized, concentrated organic material in the form of mucous or fecal material. It is most likely that physical and chemical factors together determine the resulting fabric in burrow-mottled limestones (Gingras et al., 2004b).

p0305 Burrow-associated cement precipitation and nodule formation have four main modes of occurrence: (1) cementation of a finer-grained burrow wall, such that siderite, dolomite, calcite, or pyrite occur as very fine-grained crystals in the burrow-wall material (preferred tube cementation); (2) cement precipitation or cement dissolution within a coarser-grained burrow fill, in which mosaic calcite is distributed heterogeneously throughout the burrowed media (preferred burrow cementation); (3) cement—usually dolomite or calcite—precipitation or cement dissolution adjacent to a trace fossil, forming a diagenetic halo around discrete trace fossils (fabric-mimicking hypoburrow cementation); and (4) concretion formation, usually calcite and rarely dolomite, with a trace fossil as the nucleation point (nodular hypoburrow cementation). This range of diagenetic–ichnological associations shows that the impacts of diagenesis are extremely variable.

p0310 In most cases, burrow-induced diagenesis profoundly alters the rock's petrophysical characteristics. The permeabilities and porosities of burrow-affected and unburrowed zones are commonly different (e.g., Knaust, 2009), and

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diagenesis most commonly occurs in and around generations of interpenetrating trace fossils. Consequently, the heterogeneity in burrow-mottled carbonates is high. Although a dual-permeability network is generally produced, dual-porosity systems are also present.

p0315 Burrow-associated dolomite is commonly present in Paleozoic carbonates. Diagenetic heterogeneities are exemplified by the Ordovician Chazy Group (Mehrtens and Selleck, 2002), Devonian strata in western Canada (Beales, 1953; Corlett and Jones, 2012; Gingras et al., 2004b), the Late Ordovician Bighorn Dolomite in Wyoming (Zenger, 1992, 1996), and the Ordovician Yeoman Formation in the Williston Basin (Kendall, 1977; Pak, 2003) of North America. Younger examples are provided in Pedley (1992). The depositional environments range from platformal offshore (Palliser Formation) to restrict offshore. The successions result in significant volumes of altered/affected strata. Thicknesses typically approach 10 m, however, more or less continuous zones may be more than 100 m thick. Likewise, the areal extents of these ramp- and platform-associated strata are potentially extensive, generally falling between one and hundreds of square kilometers.

s0150 4.3.5.1 Red River Formation (Ordovician), Saskatchewan and Manitoba, Canada

p0320 The best-characterized example of burrow-associated diagenesis in North America is the Tyndall Stone, a dolomitic-mottled limestone quarried in Manitoba, Canada. The Tyndall Stone is assigned to the Ordovician Selkirk Member of the Red River Formation (Kendall, 1977). Similarly, mottled limestones comprise the subsurface equivalent Yeoman Formation in south-eastern Saskatchewan (Kendall, 1975). The Selkirk Member and the Yeoman Formation accumulated as an epicontinental carbonate platform in the Williston Basin. The most distinctive feature of the Tyndall Stone is the presence of pervasively distributed, dolomitized branching trace fossils (Gingras et al., 2004b; Kendall, 1977). Spot-permeametry data from the Tyndall Stone show that the average permeability of the matrix is 1.65 mD, and the average burrow permeability is 19.2 mD (i.e., a dual-porosity system) (Gingras et al., 2004b; Fig. 4, inset). Oil production from the Yeoman Fm. in Saskatchewan is primarily from the dolomitic phases that occur in layers between 1 and approximately 10 m thick.

s0155 4.3.5.2 Lonely Bay Formation (Devonian), Northwest Territories, Canada

p0325 Corlett and Jones (2012) show that the Lonely Bay Formation contains an intensely bioturbated facies, characterized by dolomite- and calcite-cemented burrows. The calcite-cemented burrows were formed proximal to the shoreline and the dolomite-cemented burrows in distal units. Within the calcite-cemented burrows, the primary sedimentary and ichnological fabric was preserved. The sedimentary fabric associated with the dolomite-cemented burrows appears massive. Recrystallization associated with dolomite formation generated intracrystalline porosity.

s0160 ### 4.3.5.3 Palliser Formation (Devonian), Alberta, Canada

p0330 Another excellent example of burrow-selective dolomitization concerns the Devonian Palliser Formation (Wabamum Group in the subsurface) of the Western Canada Sedimentary Basin (Fig. 6). These rocks are composed of a series of highly bioturbated carbonate fabrics interpreted to represent a series of shallow-water ramp deposits. Spot permeametry of samples indicated that the burrows are preferentially higher in permeability than the matrix. In general, the samples have a low-permeability limestone matrix with negligible effective porosities. In turn, the limestone encompasses chaotically distributed, fabric-selective dolomite with an effective porosity as high as 5–6% (Gingras et al., 2004b). Analysis of SEM (scanning electron microscope) micrographs has indicated that preferential dissolution and precipitation of planar dolomite crystals within and adjacent to burrow fabrics and physical sedimentary structures occurred. This implies that bioturbation influenced the pore-water geochemistry, and in so doing encouraged dolomitization.

s0165 ## 5. CONCLUSIONS

p0335 Biogenic fabrics in sedimentary rocks can strongly influence the permeability fabric and therefore fluid flow in sedimentary strata. Bioturbation may impose well-defined, highly contrasting permeability fields, referred to as dual permeability, or subtly contrasting permeability fields, referred to as dual porosity. Both types of flow media influence the reservoir quality of fluid-bearing rock. Dual porosity leads to (1) the entire rock contributing to fluid or gas production; (2) in the presence of more than one fluid phase, flow is focused in higher porosity/permeability zones; and (3) moving of the fluid in the lower permeability portions of the rock into higher permeability media through diffusion and advection (mechanical movement).

p0340 Dual-permeability flow media have poorer resource characteristics, resulting in (1) burrows comprising the effective flow media present, (2) fluid resources being more slowly produced by diffusion from the tighter rock, and (3) secondary recovery techniques possibly isolating large parts of the flow network. Other factors that influence the overall behavior of the flow-media class are the burrow density, burrow connectivity, burrow/matrix permeability contrast, burrow surface area, and burrow architecture. For the most part, these parameters can be assessed and their impact estimated.

p0345 Dual porosity and permeability fabrics are a component of the burrow-media classification presented in Pemberton and Gingras (2005): (1) SCD, (2) NCD, (3) nonconstrained subtle heterogeneities, (4) CBH, and (5) diagenetic heterogeneities.

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REFERENCES

Abdel-Fattah, Z.A., Gingras, M.K., Pemberton, S.G., 2011. Significance of hypoburrow nodule formation associated with large biogenic sedimentary structures in open-marine bay siliciclastics of the upper Eocene Birket Qarun Formation, Wadi El-Hitan, Fayum, Egypt. Sed. Geol. 233, 111–128.

Aller, R.C., 1983. The importance of the diffusive permeability of animal burrow linings in determining marine sediment chemistry. J. Mar. Res. 41, 299–322.

Aller, R.C., 1994. Bioturbation and remineralization of sedimentary organic matter: effects of redox oscillation: controls on carbon preservation. Chem. Geol. 114, 331–345.

Beales, F.W., 1953. Dolomitic mottling in Palliser (Devonian) limestone, Banff and Jasper National Parks, Alberta. AAPG Bull. 37, 2281–2293.

Chen, Q., Gingras, M.K., Balcom, B.J., 2003. A magnetic resonance study of pore filling processes during spontaneous imbibition in Berea sandstone. J. Chem. Phys. 119, 9609–9616.

Corlett, H.J., Jones, B.J., 2012. Petrographic and geochemical contrasts between calcite- and dolomite-filled burrows in the Middle Devonian Lonely Bay Formation, Northwest Territories, Canada. J. Sed. Res. Au11

Cunningham, K.J., Sukop, M.C., Huang, H., Alvarez, P.F., Curran, H.A., Renken, R.A., Dixon, J.F., 2009. Prominence of ichnologically influenced macroporosity in the karst Biscayne aquifer: stratiform "super-K" zones. GSA Bull. 121, 164–186.

Cunningham, K.J., Sukop, M.C., Curran, H.A., 2012. Carbonate aquifers. In: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology, vol. 64. Elsevier, Amsterdam. TS2

Dawson, W.C., 1978. Improvement of sandstone porosity during bioturbation. AAPG Bull. 62, 508–509.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice Hall, Englewood Cliffs, NJ, 604 pp.

Gingras, M.K., Pemberton, S.G., Mendoza, C.A., Henk, F., 1999. Assessing the anisotropic permeability of *Glossifungites* surfaces. Petrol. Geosci. 5, 349–357.

Gingras, M.K., Pemberton, S.G., Saunders, T., 2001. Bathymetry, sediment texture, and substrate cohesiveness; their impact on modern *Glossifungites* trace assemblages at Willapa Bay, Washington. Palaeogeogr. Palaeoclimatol. Palaeoecol. 169, 1–21.

Gingras, M.K., MacMillan, B., Balcom, B.J., 2002a. Visualizing the internal physical characteristics of carbonate sediments with magnetic resonance imaging and petrography. Bull. Can. Petrol. Geol. 50, 363–369.

Gingras, M.K., MacMillan, B., Balcom, B.J., Saunders, T., Pemberton, S.G., 2002b. Using magnetic resonance imaging and petrographic techniques to understand the textural attributes and porosity distribution in *Macaronichnus*-burrowed sandstone. J. Sed. Res. 72, 552–558.

Gingras, M.K., Mendoza, C.A., Pemberton, S.G., 2004a. Fossilized worm burrows influence the resource quality of porous media. AAPG Bull. 88, 875–883.

B978-0-444-53813-0.00027-7, 00027

Gingras, M.K., Pemberton, S.G., Muehlenbachs, K., Machel, H., 2004b. Conceptual models for burrow-related, selective dolomitization with textural and isotopic evidence from the Tyndall Stone, Canada. Geobiology 2, 21–30.

Gordon, J.B., Pemberton, S.G., Gingras, M.K., Konhauser, K.O., 2010. Biogenically enhanced permeability; a petrographic analysis of *Macaronichnus segregatus* in the Lower Cretaceous Bluesky Formation, Alberta, Canada. AAPG Bull. 94, 1779–1795.

Greene, T.J., Gingras, M.K., Gordon, G.S., McKeel, D.R., 2012. The significance of deep-water cryptic bioturbation in slope-channel massive sand deposits of the lower Rio Dell Formation, Eel River basin, California. Mar. Petrol. Geol. 29, 152–174.

Gunatilaka, A., Al-Zamel, A., Shearman, D.J., Reda, A., 1987. A spherulitic fabric in selectively dolomitized siliciclastic crustacean burrows, northern Kuwait. J. Sed. Petrol. 57, 922–927.

Herringshaw, L.G., Sherwood, O.A., McIlroy, D., 2010. Ecosystem engineering by bioturbating polychaetes in event bed microcosms. Palaios 25, 46–58.

Hovikoski, J., Lemiski, R., Gingras, M., Pemberton, G., MacEachern, J.A., 2008. Ichnology and sedimentology of a mud-dominated deltaic coast: Upper Cretaceous Alderson Member (Lea Park Fm), Western Canada. J. Sed. Res. 78, 803–824.

Katrak, G., Bird, F., Worthington, D., 2003. Comparative effects of the large bioturbators, *Trypaea australiensis* and *Heloecius cordiformis*, on intertidal sediments of Western Port, Victoria, Australia. Mar. Freshwat. Res. 54, 701–708.

Kendall, A.C., 1975. Anhydrite replacements of gypsum (satin-spar) veins in the Mississippian caprocks of southeastern Saskatchewan. Can. J. Earth Sci. 12, 1190–1195.

Kendall, A.C., 1977. Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba. Bull. Can. Petrol. Geol. 25, 480–504.

Knaust, D., 2009. Ichnology as a tool in carbonate reservoir characterization: a case study from the Permian—Triassic Khuff Formation in the Middle East. GeoArabia 14, 17–38.

Knaust, D., 2012. Methodology and techniques. In: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology, vol. 64. Elsevier, Amsterdam. TS2

Konhauser, K.O., Gingras, M.K., 2011. Are animal burrows a major sedimentary sink for metals? Ichnos 18, 1–3.

La Croix, A.D., 2010. Ichnology, sedimentology, stratigraphy and trace-fossil permeability relationships in the Upper Cretaceous Medicine Hat Member, Medicine Hat Gas Field, Southeast Alberta, Canada. Unpublished. M.Sc. Thesis, University of Alberta, 166 pp.

La Croix, A.D., Gingras, M.K., Dashtgard, S.E., Pemberton, S.G., 2012. Computer modeling bioturbation: the creation of porous and permeable fluid-flow pathways. AAPG Bull. 96, 545–556.

Lavoie, D.L., Vaughan, W.C., Easley, D.H., 2000. Quantitative effects of bioturbation on permeability determined using a whole-tank permeameter. Eos 81, F650.

Lemiski, R.T., Hovikoski, J., Pemberton, S.G., Gingras, M., 2011. Sedimentological ichnological and reservoir characteristics of the low-permeability, gas-charged Alderson Member (Hatton gas field, southwest Saskatchewan): implications for resource development. Bull. Can. Petrol. Geol. 59, 27–53.

MacEachern, J.A., Burton, J.A., 2000. Firmground *Zoophycos* in the Lower Cretaceous Viking Formation, Alberta: a distal expression of the *Glossifungites* Ichnofacies. Palaios 15, 387–398.

MacEachern, J.A., Raychaudhuri, I., Pemberton, S.G., 1992. Stratigraphic applications of the *Glossifungites* Ichnofacies: delineating discontinuities in the rock record. In: Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration: A Core Workshop. SEPM Core Workshop 17, pp. 169–198. Au12

Comp. by: SNijam Stage: Proof Chapter No.: 27 Title Name: DS
Date:27/7/12 Time:20:19:12 Page Number: 888

Matzke, R.H., Smith, J.G., Foo, W.K., 1992. Iagifu/Hedinia field: first oil from the Papuan fold and thrust belt. In: Giant Oil and Gas Fields of the Decade 1978–1988. AAPG Mem. 54, pp. 471–482. Au13

McIlroy, D., 2007. Lateral variability in shallow marine ichnofabrics: implications for the ichnofabric analysis method. J. Geol. Soc. Lond. 164, 359–369.

McIlroy, D., Worden, R.H., Needham, S.J., 2003. Faeces, clay minerals and reservoir potential. J. Geol. Soc. Lond. 160, 489–493.

McKinley, J.M., Lloyd, C.D., Ruffell, A.H., 2004. Use of variography in permeability characterization of visually homogeneous sandstone reservoirs with examples from outcrop studies. Math. Geol. 36, 761–779.

Meadows, P., Tait, J., 1989. Modification of sediment permeability and shear strength by two burrowing invertebrates. Mar. Biol. 101, 75–82.

Mehrtens, C., Selleck, B., 2002. Middle Ordovician section at Crown Point Peninsula. In: McLelland, J., Karabinos, P. (Eds.), Guidebook for Fieldtrips in New York and Vermont. University of Maine, Orono, ME.

Noble, R.A., Henk Jr., F.H., 1998. Hydrocarbon charge of a bacterial gas field by prolonged methanogenesis: an example from the East Java Sea, Indonesia. In: Advances in Organic Geochemistry 1997. Proceedings of the 18th International Meeting on Organic Geochemistry, Part 1, Petroleum GeochemistryOrganic Geochemistry, vol. 29. pp. 301–314.

Over, D.J., 1990. Trace metals in burrow walls and sediments, Georgia Bight, USA. Ichnos 1, 31–41.

Pak, R., 2003. Implications on source rock accumulation from ichnology in the Ordovician Yeoman Formation, southeastern Saskatchewan. Reservoir 30, 17.

Pedersen, P., Nielsen, K., 2006. Cretaceous successions in the foothills of Alberta. Reservoir 33, 13.

Pedley, M., 1992. Bio-retexturing: early diagenetic fabric modifications in outer-ramp settings—a case study from the Oligo-Miocene of the Central Mediterranean. In: Sellwood, B.W. (Ed.), Ramps and Reefs, Sed. Geol., vol. 79. pp. 173–188. Au12

Pemberton, S.G., Frey, R.W., 1985. The *Glossifungites* ichnofacies: modern examples from the Georgia Coast, U.S.A. In: Curran, H.A. (Ed.), Biogenic Structures: Their Use in Interpreting Depositional Environments. SEPM Spec. Publ. 35, pp. 237–259.

Pemberton, S.G., Gingras, M.K., 2005. Classification and characterizations of biogenically enhanced permeability. AAPG Bull. 89, 1493–1517.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001. Ichnology & Sedimentology of Shallow to Marginal Marine Systems: Ben Nevis & Avalon Reservoirs, Jeanne d'Arc Basin. Geol. Ass. Can., Short Course Notes 15, 343 pp.

Petrash, D.A., Lalonde, S.V., Gingras, M.K., Konhauser, K.O., 2011. A surrogate approach to studying the chemical reactivity of burrow mucous linings in marine sediments. Palaios 26, 594–600.

Pierret, A., Capowiez, Y., Belzunces, L., Moran, C.J., 2002. 3D reconstruction and quantification of macropores using X-ray computed tomography and image analysis. Geoderma 106, 247–271.

Spencer, A.M., Home, P.C., Wiik, V., 1986. Habitat of hydrocarbons in the Jurassic Ula Trend, Central Graben, Norway. In: Spencer, A.M., Campbell, C.J., Hanslien, S.H., Nelson, P.H., Nysæther, E., Ormaasen, E.G. (Eds.), Habitat of Hydrocarbons on the Norwegian Continental Shelf. NPF/Graham and Trotman, London, pp. 111–127.

Spila, M.V., Pemberton, G., Sinclair, I.K., Hiscott, R., Pulham, A., 2005. Comparison of marine and brackish/stressed ichnological signatures in the Ben Nevis and Avalon Formations, Jeanne d'Arc Basin. In: Hiscott, R.N., Pulham, A.J. (Eds.), Petroleum Resources and Reservoirs of the Grand Banks, Eastern Canadian Margin. Geol. Ass. Can. Spec. Pap. 43, pp. 73–94. Au12

Sutton, S.J., Ethridge, F.G., Almon, W.R., Dawson, W.C., Edwards, K.K., 2004. Textural and sequence-stratigraphic controls on sealing capacity of Lower and Upper Cretaceous shales, Denver Basin, Colorado. AAPG Bull. 88, 1185–1206.

B978-0-444-53813-0.00027-7, 00027

Tonkin, N.S., McIlroy, D., Meyer, R., Moore-Turpin, A., 2010. Bioturbation influence on reservoir quality: a case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada. AAPG Bull. 94, 1059–1078.

Warren, E.A., Pulham, A.J., 2001. Anomalous porosity and permeability preservation in deeply buried Tertiary and Mesozoic sandstones in the Cusiana Field, Llanos Foothills, Colombia. J. Sed. Res. 71, 2–14.

Warren, J.E., Skiba, F.F., Price, H.S., 1961. An evaluation of the significance of permeability measurements. J. Petrol. Technol. 13, 739–744.

Weaver, P.P.E., Schultheiss, P.J., 1983. Vertical open burrows in deep-sea sediments 2 m in length. Nature 301, 329–331.

Zenger, D.H., 1992. Burrowing and dolomitization patterns in the Steamboat Point Member, Bighorn Dolomite (Upper Ordovician), Northwest Wyoming. Contr. Geol. 29, 133–142.

Zenger, D.H., 1996. Dolomitization patterns in widespread "Bighorn Facies" (Upper Ordovician), Western Craton, USA. Carb. Evap. 11, 219–225.

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