

APPLICATIONS OF ICHNOLOGY TO FLUID AND GAS PRODUCTION IN HYDROCARBON RESERVOIRS

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Biogenically modified sedimentary flow media can occur as well-defined, highly contrasting permeability fields (i.e., dual-permeability networks), or slightly contrasting permeability fields (i.e., dual-porosity networks). Dual porosity reduces the resource quality of a sedimentary rock, in that although the entire rock contributes to fluid flow, the presence of more than one fluid phase can induce preferential flow along tortuous permeability pathways. Additionally, fluid moves via diffusion and advection, making the pathways difficult to model. Dual-permeability flow media have even poorer resource characteristics because the higher permeability portions of the rock provide the only transmissive conduits, and fluid resources may be absent in the tighter (unburrowed) rock. Secondary recovery attempts in dual permeability media can isolate large parts of the active flow network, which may contain resource fluids or gasses.

The presence of a dual porosity versus a dual permeability network, and the stratigraphic configuration of burrow-enhanced permeability are the primary considerations when classifying the type of biogenic flow media encountered. These parameters define the five flow-media types: 1) surface-constrained textural heterogeneities; 2) non-constrained, discretely packaged textural heterogeneities; 3) selectively sorted, weakly defined textural heterogeneities; 4) cryptically bioturbated sandstone; and 5) diagenetic heterogeneities. Other factors that influence the quality and behavior of the flow media are burrow density, burrow connectivity and burrow/matrix permeability contrast, burrow surface area, and burrow architecture.

With respect to permeability fabrics, 3-D imaging techniques are an essential component of burrow-fabric analysis. Computer Tomography (CT) scans, Micro-CTscans, and MRI techniques have the most potential in burrow-reservoir analysis. These techniques can be used collaboratively to fully assess the nature of burrow-modified flow media.

INTRODUCTION

Permeability fabrics and the distribution of porosity in flow media solely reflect the physical heterogeneities of sedimentary rocks. Physical heterogeneity may result from lamination, the arrangement of clasts or fossils, and fabric-retentive and fabric-destructive diagenesis. Subtle heterogeneities, which may result from random pore-throat distributions or from various physical and biological processes, are present in massive-appearing rocks and in thickly bedded sandstones.

Bioturbation also alters local grain distributions in the sedimentary media. Trace fossils may also possess chemical characteristics that differ from the surrounding sedimentary rock. Thus, ichnofossils can influence the distribution of porosity and permeability in permeable media in two ways: (1) by physically changing the pore-throat distribution, and (2) by acting as loci of cementation- and dissolution-processes during early and late stages of diagenesis. These two processes commonly act in concert, and the variety of permeability fabrics generated by biogenic modification is vast.

In fact, there are no general rules that dictate the degree of permeability enhancement—or diminishment—that can result from a characteristic style of bioturbation. Rather, the impact of bioturbation on the overall permeability is greatly influenced by grain-size distributions, the presence of organics within incipient trace fossils, the mineralogy of fossils and grains, and a host of post-depositional chemical processes. It is fair to say, however, that bioturbation always influences the permeability and porosity of sedimentary rocks.

Burrow-associated permeability is different from laminated media in that burrows tend to improve vertical permeability over horizontal permeability. Burrowed fabrics are also significantly more difficult to model than laminated media, because they are truly 3-dimensional, and they tend to comprise a range of burrow shapes and sizes. Even very simple fabrics contain a range of

burrow dimensions, and it is difficult to statistically establish that range. Trace-fossil permeability is awkwardly comparable to fracture permeability. The comparison is conceptually correct because ichnofossils are discrete entities displaying predictable permeabilities that, due to the extensive surface areas associated with biogenic structures, have significant flow interactions with the surrounding sedimentary rock. Trace-fossil permeabilities differ from those of fractures in that the contrast between the burrows and their surrounding media is less than that observed in fractures (3 orders of magnitude *versus* 6 or more; Gingras et al. 1999), and the volume comprising the biogenic fabric is commonly more than an order of magnitude higher than the volumes associated with fracture systems (10-80% *versus* 1-3%). Thus, flow interactions between burrow fabrics and the matrix rock are far higher than those observed between the fractures and their hosting matrix.

Although permeability studies are commonly conducted on reservoir rocks, they are more likely to be directed towards assessments of laminated- or fractured-media. There are various reasons for this, but first and foremost is the conceptual simplicity of such media. In fact, it is a little surprising how little attention bioturbation-related permeability studies have actually received. Assuredly, this is not because bioturbation does not influence reservoir parameters. It is more accurate to say that biogenic fabrics are not well recognized by many sedimentary workers. Also, the range of burrow fabrics that can be observed and the lack of a preexisting burrow-permeability classification system, have hampered attempts to simplify and generalize the impact that bioturbation has on permeability distributions.

This paper provides a summary of the main concepts associated with the applications of ichnology to reservoir fluid flow. We focus on the nature of permeability, porosity, and capillary pressure, and scrutinize the various ways that burrows might influence those parameters. Physical and chemical modifications resulting from bioturbation are discussed, and their relationships to a

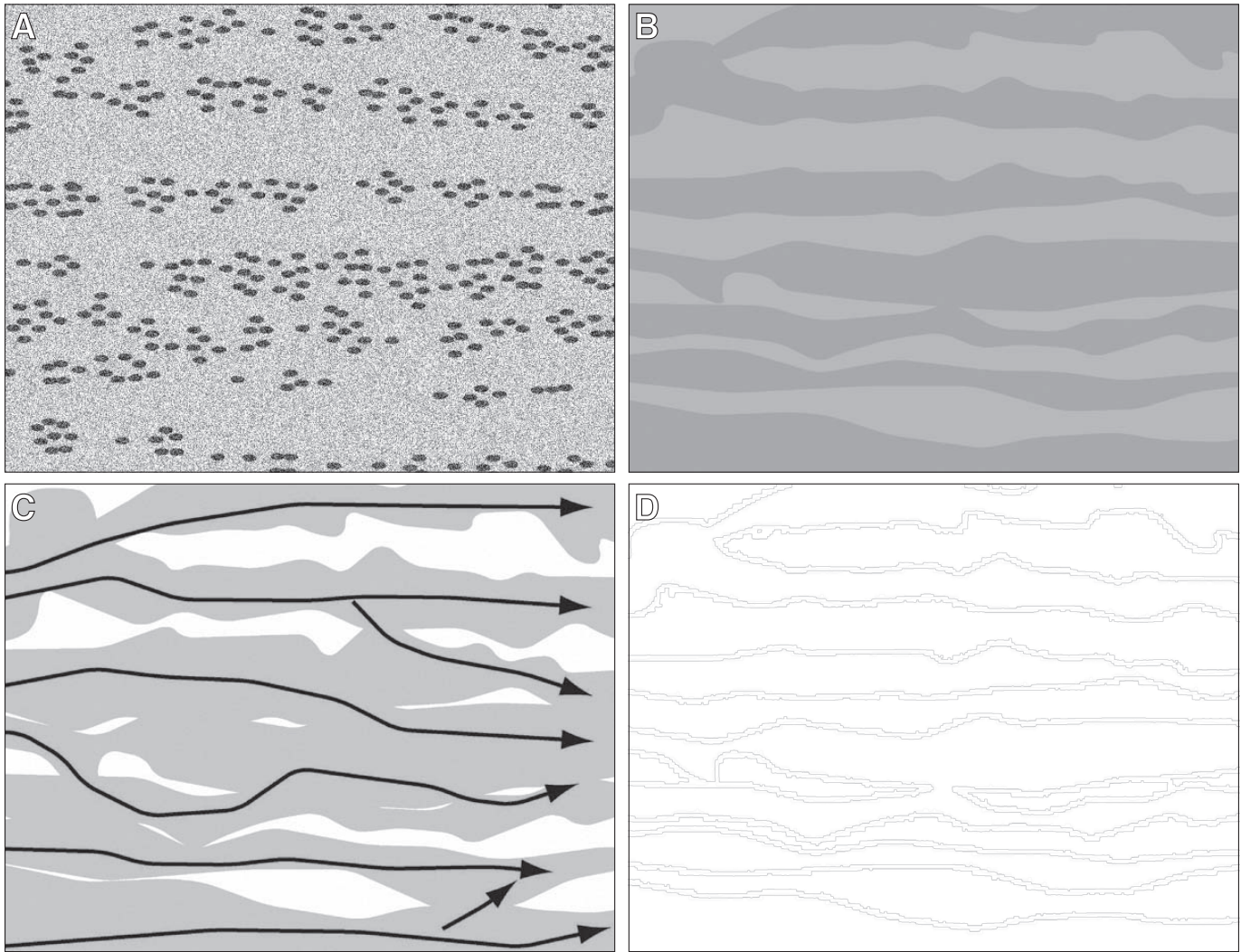


Fig. 1 – Flow behavior in dual porosity fabrics. A. Schematic sedimentary media with bioturbation shown as ovoid burrow sections. B. Fluid saturation of the rock is shown as higher along burrowed zones (dark grey) and lower away from burrowed laminae (lighter grey). Saturation only roughly follows bioturbated zones. C. When a hydraulic gradient is present, fluid moves preferentially through the more porous/permeable rock. D. Produced fluid (shown as widely spaced nondimensional contours) is primarily derived from more permeable zones, but can also be derived from the adjacent areas.

proposed classification system for burrow-related permeability are considered.

PERMEABILITY, POROSITY AND TRACE FOSSILS

The range of permeability / porosity modification associated with burrow fabrics is wide and spans the continuum from reduction to enhancement with respect to the matrix. Biogenic flow networks, wherein the matrix permeability is within two orders of magnitude relative to the burrow permeability, represent dual porosity systems. More simply stated, dual-porosity systems occur where matrix- and burrow-permeabilities are similar (Fig. 1). If the matrix permeability and the burrow permeability differ by more than two orders of magnitude or more, a dual-permeability flow network is present instead (Fig. 2; Gingras et al. 2004a)

In dual-porosity flow media, much of the rock volume is used to conduct fluids. Flow is focused through the higher permeability zones, but flow interactions between burrows and the matrix

are extensive (Fig. 1). This has several implications regarding reservoir- and aquifer-behavior: (1) with single-phase flow, the entire rock contributes to fluid or gas production; (2) the presence of more than one fluid phase—which is typical—will encourage flow to be focused in higher porosity / permeability zones; and (3) fluid in the lower-permeability portions of the rock will move into higher permeability media through diffusion and advection (mechanical movement). It is self-evident that dual-porosity flow media is detrimental to the overall resource quality of a sedimentary rock. Fluids within such media cannot be conducted as a uniform front. Instead, flow follows chaotic paths dictated by burrow morphologies. More importantly, advective fronts (the leading-edge of moving fluids or solutes) in the lower-permeability rock may advance 10 to 100 times more slowly than in the higher-permeability rock (calculable using Darcy's Law). This is a disconcerting fact, because the volume of the low-permeability rock generally exceeds 30% and commonly approaches 65%.

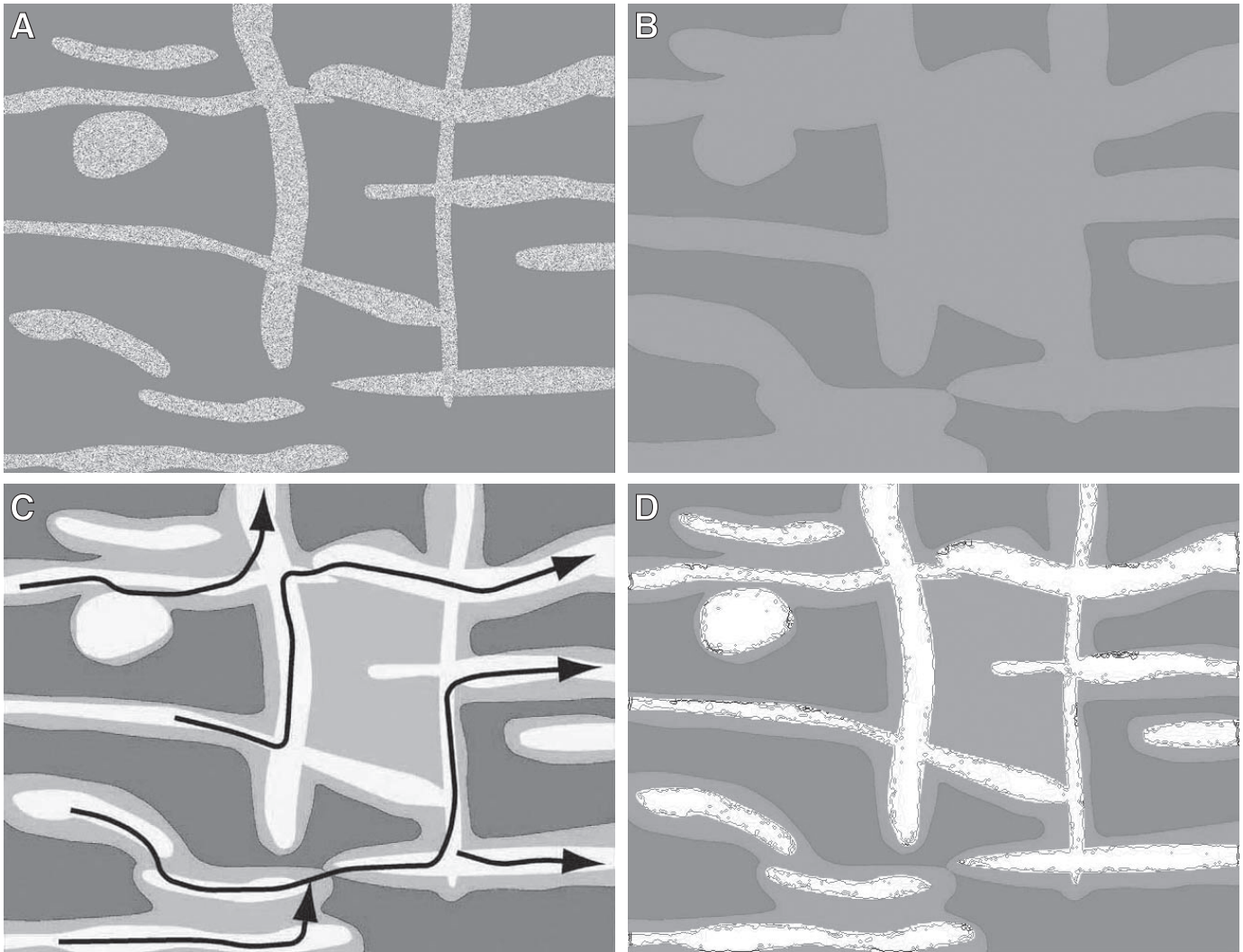


Fig. 2 – Flow behavior in dual permeability fabrics. A. Schematic sedimentary media with bioturbation shown as discrete, tubular, sand-filled *Thalassinoides*. B. Fluid saturation of the rock is shown as higher along burrowed zones (light grey) and lower away from the burrows (dark grey). Saturation mimics bioturbated zones. C. When a hydraulic gradient is present, fluid moves preferentially through the burrows. D. Produced fluid (shown as nondimensional contours) is primarily derived from trace fossils, and is minimally derived from the adjacent areas.

Dual-permeability flow media have comparatively even poorer reservoir characteristics. The impacts of dual permeability systems in reservoirs and aquifers include (Fig. 2): (1) higher permeability parts of the rock serve as the only effective flow media present; (2) fluid resource may be absent in the tighter rock, but if resource is present, it can only interact with the flow conduits via diffusion; and, (3) secondary recovery (waterflood or CO₂ flood) will isolate large parts of the flow network and result in moribund fluid production. With the exception of gas phases, dual-permeability media permit production only from the higher permeability portions of the rock. In examples of burrow-associated permeability enhancement, burrows commonly occupy 30 to 70% of the rock volume, thus countering some of the conceptual limits imposed by such highly contrasting permeabilities.

In burrow-influenced flow systems, the nature of the bioturbation can influence whether or not a dual-porosity or dual-permeability flow media is present. Bioturbate texture that resulted from animals moving through the sediment generates dual-porosity ichnofabrics (Fig. 1). Open burrows that are

passively filled with coarser grains, or burrows that were actively backfilled with coarse material engender dual-permeability ichnofabrics (Fig. 2). Diagenetic products are variable, but dual-permeability ichnofabrics are favored in those cases. Whether or not the resulting flow media is *typically* dual porosity or dual permeability is the basis for an ichnological classification of biogenic-permeability modification (see below).

GENERAL IMPACTS OF BURROW-INFLUENCED PERMEABILITY

A primary manifestation of burrow-induced heterogeneity is provoked by the presence of complex, 3-dimensional flow networks. Ichnofabrics comprising one type of trace fossil probably can be modeled numerically, so long as some broad assumptions are made (Gingras et al. 1999). In contrast, 3-dimensional characterization of complex fabrics cannot be accurately achieved, especially not from core datasets. The main outcome of a complex fabric is that fluid-flow dead ends, and cutoffs are likely to be abundant (Fig. 2). Thus, a volume of the transmissive rock is rendered ineffective.

It is the assessment of ineffective flow volume that is most problematic in core studies. Up-scaling core samples is misleading because it is unlikely that core comprises an ideal representative elemental volume (REV) (i.e., a volume large enough to contain most fabric heterogeneities common to that rock unit). Exceptions are pervasive fabrics composed of small burrows, including cryptic bioturbation and some subtle biogenic heterogeneities (discussed below). Fabrics comprising larger burrows require the application of analogous datasets, such as those derived from outcrop or modern settings. In the absence of core, gaining a hydraulic understanding of burrowed reservoirs is all but impossible, even if FMI or NMRI logs are available.

The morphological complexity of burrow-controlled flow paths is related to several other characteristics of biogenically modified reservoirs. The most important of these is flow tortuosity. Exaggerated tortuosity causes flow paths to be long and affords increased flow interaction with the lower-permeability matrix. In response, bulk-flow movement is slowed. High morphological

complexity also leads to increased dispersion within the flow media. Dispersion—or dispersivity, if one is referring to the rock property—is related to hydrodynamic spreading of a solute or phase. Low dispersivity suggests that a fluid can be delivered directly through a rock with minimal (primarily mechanical) mixing, and is a characteristic of homogeneous flow media. High dispersivity indicates more flow mixing, and delivers flow less efficiently, which is ultimately related to rock heterogeneity. This was demonstrated by Gingras et al. (2004a), wherein dispersivity was assessed for three rock types: a massive-appearing sandstone, a fractured (dual permeability) limestone, and a burrowed (dual porosity) limestone. The homogeneous sandstone delivered a gas front at a uniform rate, displacing the pore gas comparatively evenly. The fractured limestone showed that gas rapidly moved through the sample, but displaced very little pore gas from the matrix. The burrowed limestone also transported gas rapidly through the high-permeability zones, and the matrix was only slowly 'swept'. Extensive interactions between the burrow- and matrix-zones in the dual-porosity system showed that the burrowed limestone was the most

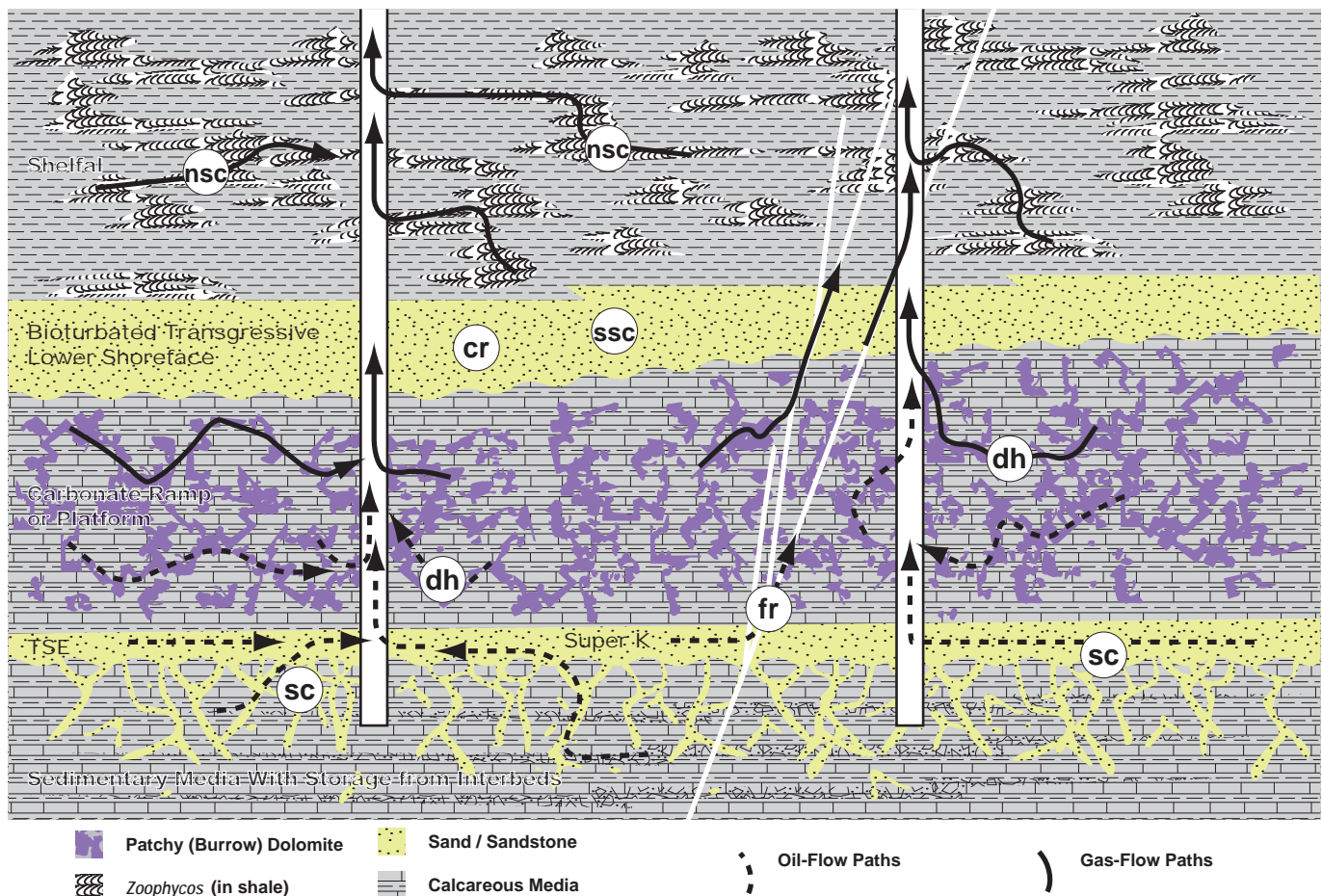


Fig. 3 – Schematic summary diagram illustrating various stratal configurations for biologically influenced reservoir rock. Non-surface constrained (nsc) textural heterogeneities typically occupy 20-70% volume of media, has burrows that display 10 to 1000x higher permeability than matrix, represents a dual permeability system, and generate K_v enhancement over K_h . Cryptic (cr) heterogeneities and constrained indiscrete heterogeneities (ssc = subtle and surface constrained) typically comprise 60-90% volume of media have a 10x higher permeability over the matrix and generates isotropic permeability characteristics. Diagenetic textural heterogeneities (dh), normally comprise 20-60% volume of media; have 10 to 100x higher permeability than the matrix, represent a dual permeability system and show K_v enhancement over K_h . Surface constrained discrete heterogeneities (sc) commonly represent 5-50% volume of media, locally developed super K (1000x higher perm), are most likely to be dual permeability systems and greatly enhance K_v over K_h . Fractures (fr) typically represent <1% volume of media (up to 3%), commonly generate super K and are extreme dual permeability systems. Modified from Pemberton and Gingras, 2005.

dispersive media of the three tested. Admittedly this seems somewhat esoteric, until one considers that dispersivity partly determines secondary recovery efficiency (Gingras et al. 1999; Pemberton et al. 2004a; Pemberton and Gingras, 2005).

The heterogeneous distribution of two permeability / porosity fields suggests that capillary / invasion pressure within the rock is also heterogeneously distributed. Fluid parameters aside, capillary pressure is a function of pore-throat diameter. If pore-throat diameters are unevenly distributed, fluids are likely to be heterogeneously distributed. Although this may be a minor consideration in most gas-charged reservoirs, it profoundly impacts oil resources. In general, the ratio of resource-bearing to barren reservoir will be approximately equal to the ratio of burrows to matrix (Gingras et al. 1999; Gingras et al. 2004a; Pemberton and Gingras, 2005). Without core data, these ratios are exceedingly difficult to assess. However, wireline data that permits the identification of dual porosity systems, such as NMRI, have potential application in the evaluation of porosity and pore-throat distribution associated with bioturbate textures (Gingras et al. 2002; Chen et al. 2004).

BURROW PERMEABILITY CLASSIFICATION

The classification presented below follows that presented in Pemberton and Gingras (2005). That paper presented several case studies that are only briefly outlined herein. Below, we concentrate on the physical characteristics of bioturbation classes and discuss their impact on reservoir quality.

We regard three features of burrow-influenced flow media to have the most impact on reservoir performance: 1) the degree of permeability contrast (i.e., dual porosity versus dual permeability) that exists between the burrow and matrix coupled with the abruptness of the transition between these permeability fields; 2) whether or not the burrowed zone is constrained to an identifiable surface; and, 3) whether the permeability fabric is the result of initial grain distribution or due to diagenetic processes. This is reflected in Pemberton and Gingras' (2005; Fig. 3) classification, which details five biogenic permeability classes: (1) surface-constrained discrete heterogeneities, (2) non-constrained discrete heterogeneities, (3) non-constrained indiscrete heterogeneities, (4) cryptic heterogeneities, and (5) diagenetic heterogeneities. The degree of permeability contrast between the burrow and matrix varies between examples, and burrow architectures do not form a basis for the classification. Thus, the systematics presented in Figure 3 generalizes the range of burrow-influenced permeabilities encountered in reservoir settings.

SURFACE-CONSTRAINED DISCRETE HETEROGENEITIES

Sharp-lined burrows that descend from a specific surface, and infilled with sediment that differs from the matrix comprise surface-constrained, discrete (textural) heterogeneities. This scenario is most common in clastic strata, where sand- or gravel-filled burrows descend into fine-grained media, typically from an identifiable erosional discontinuity (Fig. 4). This is most commonly associated with suites attributable to the *Glossifungites* Ichnofacies. Trace fossil elements are characterized by: the presence of sharply demarcated, unlined burrows; the common occurrence of large-diameter, undeformed burrows; and burrow infills that are derived from above the erosional contact and lithologically different from the encapsulating media (Fig. 4; Pemberton and Frey, 1985; Vossler and Pemberton 1988; MacEachern et al. 1992; Pemberton et al. 1992; Pemberton and MacEachern, 1995; Gingras et al. 2001, 2002; Pemberton et

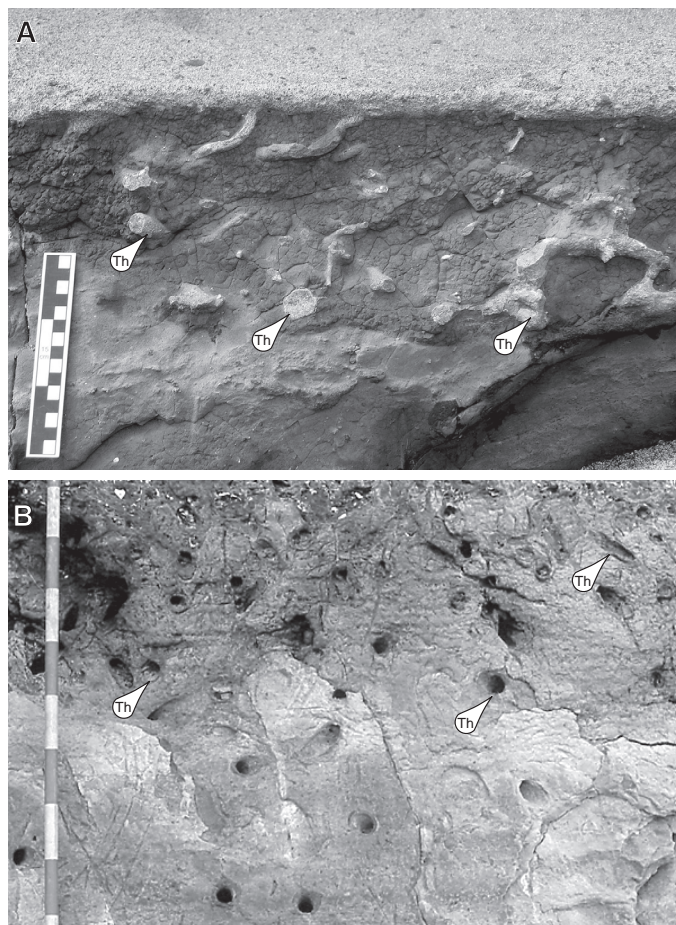


Fig. 4 – Examples of *Glossifungites* Ichnofacies from outcrop settings. A. *Thalassinoides* (Th) subtending from the base of a submarine channel in Eocene strata near Auckland, New Zealand. B. Large-diameter *Thalassinoides* (Th) at the base of a tidal channel. Pleistocene strata, Willapa Bay, WS.

al. 2004; MacEachern et al. this volume).

Due to their potentially higher permeability fills, *Glossifungites* Ichnofacies-demarcated surfaces (henceforth referred to as *Glossifungites* surfaces) may enhance the permeability of a relatively impermeable substrate. In such instances *Glossifungites* surfaces potentially alter the physical character of subsurface hydrocarbon reservoirs. This is an important consideration when heterogeneous elements, such as sand-filled burrows, are discrete and continuous. The resultant flow conduits essentially bypass the groundmass, controlling virtually all of the fluid flow parameters.

Surface-constrained discrete permeability normally represents a dual permeability system (Fig. 5). Burrows are sparse to common, and the proportion of burrowing ranges from 10% to 80% of the sediment volume. Horizontal connectivity is rare until burrow volumes approach 40% (depending on the burrow architectures; Gingras et al. 1999), thus horizontal-permeability enhancement may be limited until higher burrowing densities are reached. Since surface-constrained permeability enhancement is limited to *Glossifungites* Ichnofacies-demarcated discontinuities, they are normally thin and localized. The thickness of the permeability-enhanced zone can be as much as 7m thick (e.g., Pemberton and Gingras, 2005), but it is generally less than 1m thick (MacEachern et al. , 1992; Pemberton and MacEachern,

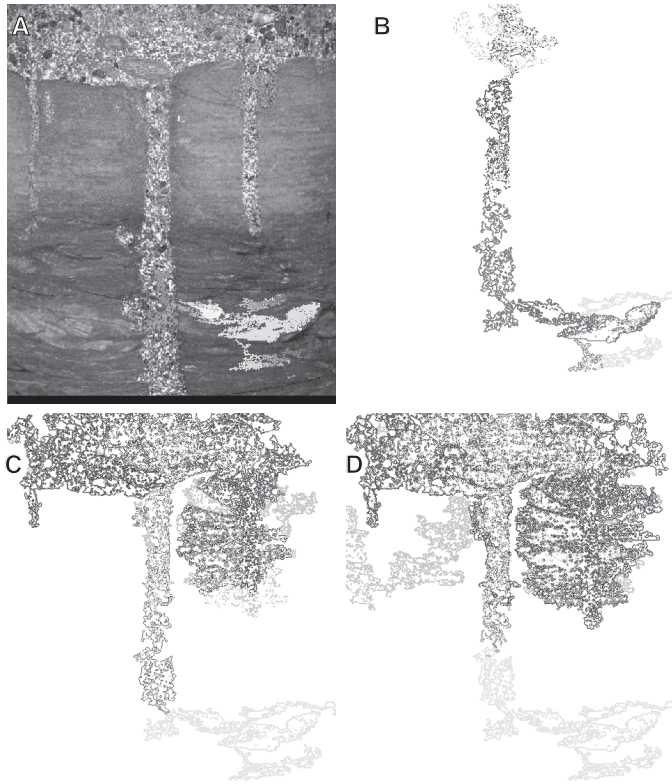


Fig. 5 – Numerical capillary model (from MPATH software) showing the progressive invasion of a fluid into a sand-filled *Skolithos* (in this case, an element of the *Glosifungites* Ichnofacies) in a lower-permeability matrix. A. Core photo of *Glosifungites* assemblage. B-D. The modeled invasion of oil (displacing water) primarily occurs within the burrow and the matrix is only saturated with hydrocarbons locally. This is a typical dual-permeability system.

1995; Gingras et al. 2002; Pemberton et al. , 2004). Additionally, the colonization of firmgrounds depends upon a host of factors (cf. Gingras and Pemberton, 2000; Gingras et al. , 2001), and their stratigraphic expression can be correspondingly discontinuous. This type of permeability enhancement is generally limited in scale to 100s of square meters, with a maximum areal extent of about a square kilometer (Pemberton and Gingras, 2005).

Gingras et al. (1999) investigated Pleistocene examples of *Glosifungites* Ichnofacies-enhanced permeability using field slug tests, laboratory Darcy tests, and numerical models. They reported that three variables determine the flow characteristics of a *Glosifungites* surface : 1) the degree of contrast between burrow permeability (K_b) and matrix permeability (K_m); 2) the amount of burrow connectivity; and 3) burrow density. Their computer simulations indicated that the dominant influences are 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. This was determined from K_b , K_m , and the degree of connectivity. The general formula can be applied in any geologic medium as a simple, first-run approximation:

$$\text{Formula 1: } \log K_{\text{bulk}} = \log [(1-V_b)K_{\text{matrix}} + V_b K_{\text{burrow}}]$$

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

Glosifungites surfaces are preserved in various clastic sedimentary environments, and are thus present in many hydrocarbon reservoirs. Stacked channels and marine shoreface sandstone packages provide common stratigraphic architectures for recognizing *Glosifungites* Ichnofacies-related cross-flow. Suites attributable to the *Glosifungites* Ichnofacies may be situated at the base of marginal-marine and marine channels as well as shorefaces, where compacted, unlithified sediments have been exposed by erosional processes (Pemberton and Frey, 1985; MacEachern et al. , 1992; Pemberton and MacEachern, 1995; Gingras et al. 2001, 2002; MacEachern et al. this volume).

The *Glosifungites* Ichnofacies has 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 *Glosifungites* Ichnofacies-demarcated surfaces were observed (the reader is referred to Mitchell et al. 1988 for a description of Ghawar lithofacies and diagenesis). In the Ghawar, the *Glosifungites* Ichnofacies is represented by firmground *Thalassinoides*, with burrows 1 to 2 cm in diameter, and systems that penetrate up to 2.1 m (7 feet) below the surface. The matrix through which these trace fossils descend 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.

Zonneveld et al. (2004) reported a similar configuration from the Triassic Baldonnel Fm. in western Canada. That report suggested that large diameter (up to 6 cm), deeply penetrating burrows occurred as repeating stratiform units in outcrop. Notably, those burrows are too widely spaced and too large in diameter to have been satisfactorily identified and characterized had they been encountered in a core dataset.

NON-SURFACE-CONSTRAINED DISCRETE HETEROGENEITIES

Non-surface-constrained discrete (textural) heterogeneities also consist of sharply defined burrows that are encased in a fine-grained matrix (Fig. 6). Like surface-constrained heterogeneities, this architecture is more common in clastic strata where sand- (or fossil grains)-filled burrows descend into mudstone. The burrows penetrate downward from several depositional surfaces, and are preserved as an amalgamated, three-dimensional network. Unlike the constrained variant described previously, these systems are not specifically surface dependant. They are generally developed in sedimentary environments characterized by the deposition of mud during ambient sedimentary conditions. This type of permeability enhancement is most common in strata that accumulated in offshore settings.

Non-surface-constrained discrete permeability enhancement provides a dual permeability system (Fig. 7). Burrows are moderately common to abundant, with burrows comprising 30-90% of the sediment volume. Because burrow architectures commonly have horizontal and vertical elements, many systems are likely to be highly interconnected (Fig. 6B). This is a result of the predominantly horizontal and rarer vertical burrow architectures that occur in offshore settings. Horizontal permeability is probably lower than vertical permeability, but moderately burrowed media (e.g., above 40%) should exhibit K_h and K_v that are essentially equal as interpenetrations become ubiquitous.

Thicknesses of permeability-enhanced zones range between 5m and 10's of meters in thickness (e.g., Pemberton and Gingras 2005). Additionally, permeability enhancement is

stratigraphically continuous. Stratal units characterized by non-surface-constrained discrete heterogeneities can exceed several square km in area (Pemberton and Gingras, 2005).

Pemberton and Gingras (2005) provided an example of non-surface-constrained discrete heterogeneities 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. 1994). The field, which contains 1.0 trillion cubic feet of gas, comprises reserves residing in the Lower Paciran Sandstone Member (Late Miocene), the Upper Paciran Sandstone Member (Late Miocene), and the Paciran Limestone Member (Pliocene), the latter of which was thought to be the reservoir seal.

Noble and Henk (1998) focused on the Paciran Limestone Member, and suggested that the Paciran Limestone represents a deep-marine pelagic carbonate deposit. The lower lithofacies are mainly grainstones, wackestones, and packstones, whereas 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 globigerinid tests (Fig. 7) and, because the ichnogenus is deeply penetrative, vertical permeability barriers are breached (i.e., K_v is higher than K_h ; Pemberton and Gingras 2005). Moreover, because the limestone constitutes the seal for Terang-Sirasun, it was demonstrated that the seal was leaky, and that the unit itself contained significant bookable reserves.

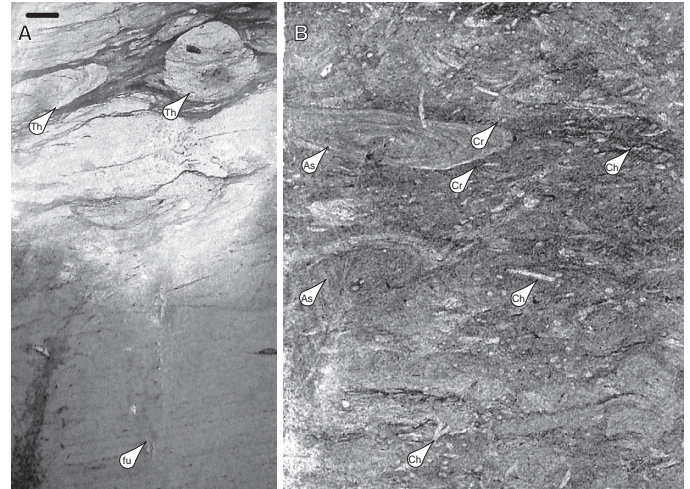


Fig. 6—Non-surface constrained textural heterogeneities. A. *Thalassinoides* (Th) in shale beds immediately above fine-grained sandstone (Whiterose, Jean D'Arc Basin). Fugichnia (fu) is incidentally noted. B. Sand-filled *Chondrites* (Ch) in otherwise low-permeability shaly silt (Hibernia, Jean D'Arc Basin). Also indicated are *Asterosoma* (As).

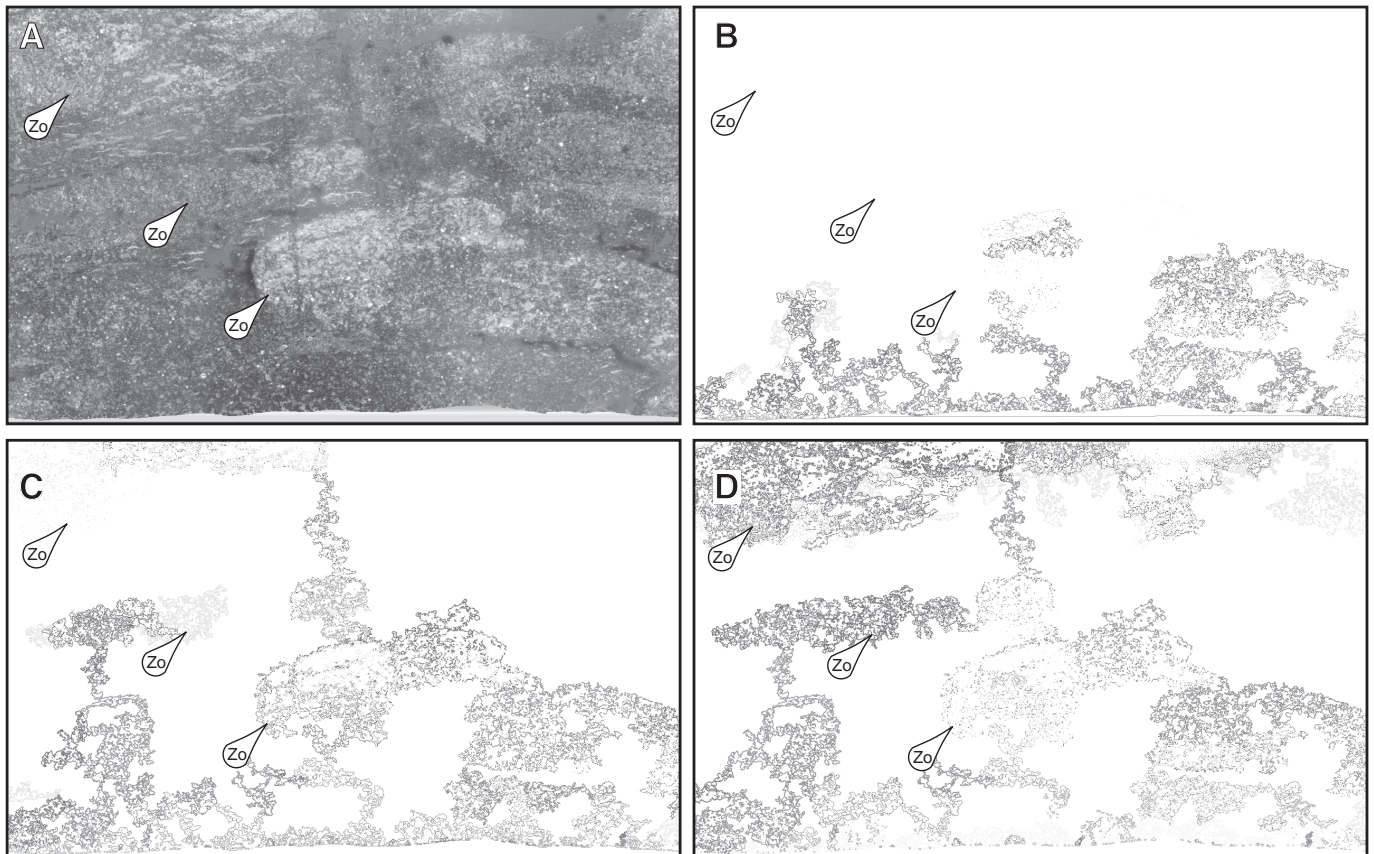


Fig. 7—Numerical capillary model (from MPATH software) showing the progressive invasion of a fluid into foram-filled *Zoophycos* (Zo) enclosed in a lower-permeability matrix. A. Thin section of *Zoophycos* from Terang-Sirasun. B-D. The modeled invasion of oil (displacing water) primarily occurs preferentially within the *Zoophycos*. The matrix is only saturated with hydrocarbons locally. This is also a typical dual-permeability system.



Fig. 8 – *Macaronichnus* (Ma) burrowed sand showing the cleaner sand tubes encapsulated by a comparatively poorer sorted matrix.

WEAKLY DEFINED TEXTURAL HETEROGENEITIES

Burrowed flow media that exhibits only subtle differences in permeability (i.e., less than two orders of magnitude within and between the trace fossils) is referred to as weakly defined textural heterogeneity. This classification is reserved for scenarios where the burrow fill and matrix are of similar lithologies. Various ichnogenera are common in such fabrics, including *Planolites*, *Thalassinoides*, *Skolithos*, and some expressions of *Macaronichnus* (Figs 8 and 9). Defining the permeability fields in such media can be vastly difficult. Additionally, the sedimentary facies that are prone to this style of permeability modification may exhibit subtle variability in the distribution of permeability. This is very important, as definition of the permeability fabric depends upon the mapping of permeability fields that only differ slightly. These fabrics constitute a dual-porosity system (Fig. 10).

Weakly defined textural heterogeneities occur in: shorefaces, rarely in foreshores, sandy bay deposits, delta fronts and mouth bars, estuarine incised valley fills, submarine fans, and fan deltas. Due to the variable sedimentary conditions present in the above-mentioned sedimentary environments, the thicknesses and lateral extents of associated facies are generally limited. In strata hosting these fabrics, affected beds and bedsets are

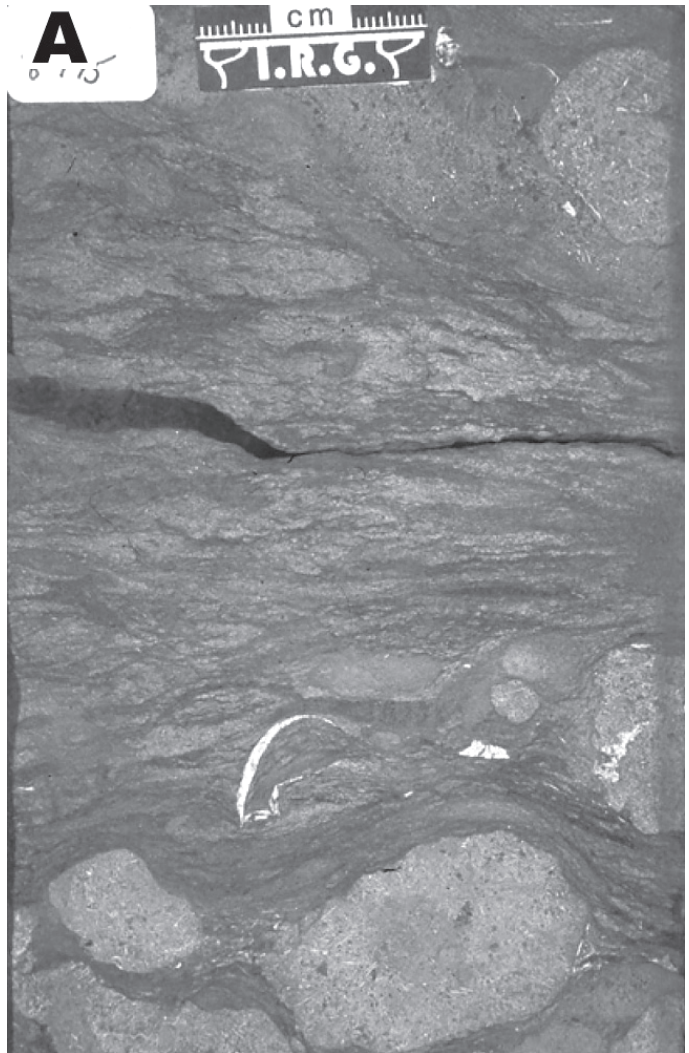


Fig. 9. *Thalassinoides* in a sand laminated with silty sand (Sag River, Alaska).

observed in thicknesses of up to 10m (Pemberton and Gingras, 2005). In contrast, *Macaronichnus* zones are generally less than 1m thick. The lateral extents of subtly burrowed facies range between 100 m and the kilometer-scale.

Pemberton and Gingras (2005) provide two examples of reservoir-hosted, weakly defined, textural heterogeneities: the Sag River Field in Alaska and the Cusiana/Cupiagua Fields in Columbia. The Triassic Sag River includes the sandstone reservoirs of the Triassic Sag River Formation and the Triassic to Permian Sadlerochit Group. The depositional environment is interpreted as a marine shelf for the Sag River Formation, whereas the Sadlerochit Group includes shallow-marine, fluvial, floodplain, alluvial fan-delta, and point-bar deposits (Barnes, 1987).

Within the shoreface deposits of the Sag River Fm, erosional and hiatal diastems are demarcated by suites attributable to the *Glossifungites* Ichnofacies (Henk et al. 2001). Unlike the aforementioned surface-constrained textural heterogeneities (e.g., Willapa Bay and the Ghawar Field), the trace-fossil assemblages consist of sand-filled burrows preserved within sandstones. Differences in grain size, packing, and post-depositional cementation have produced burrow-fills and

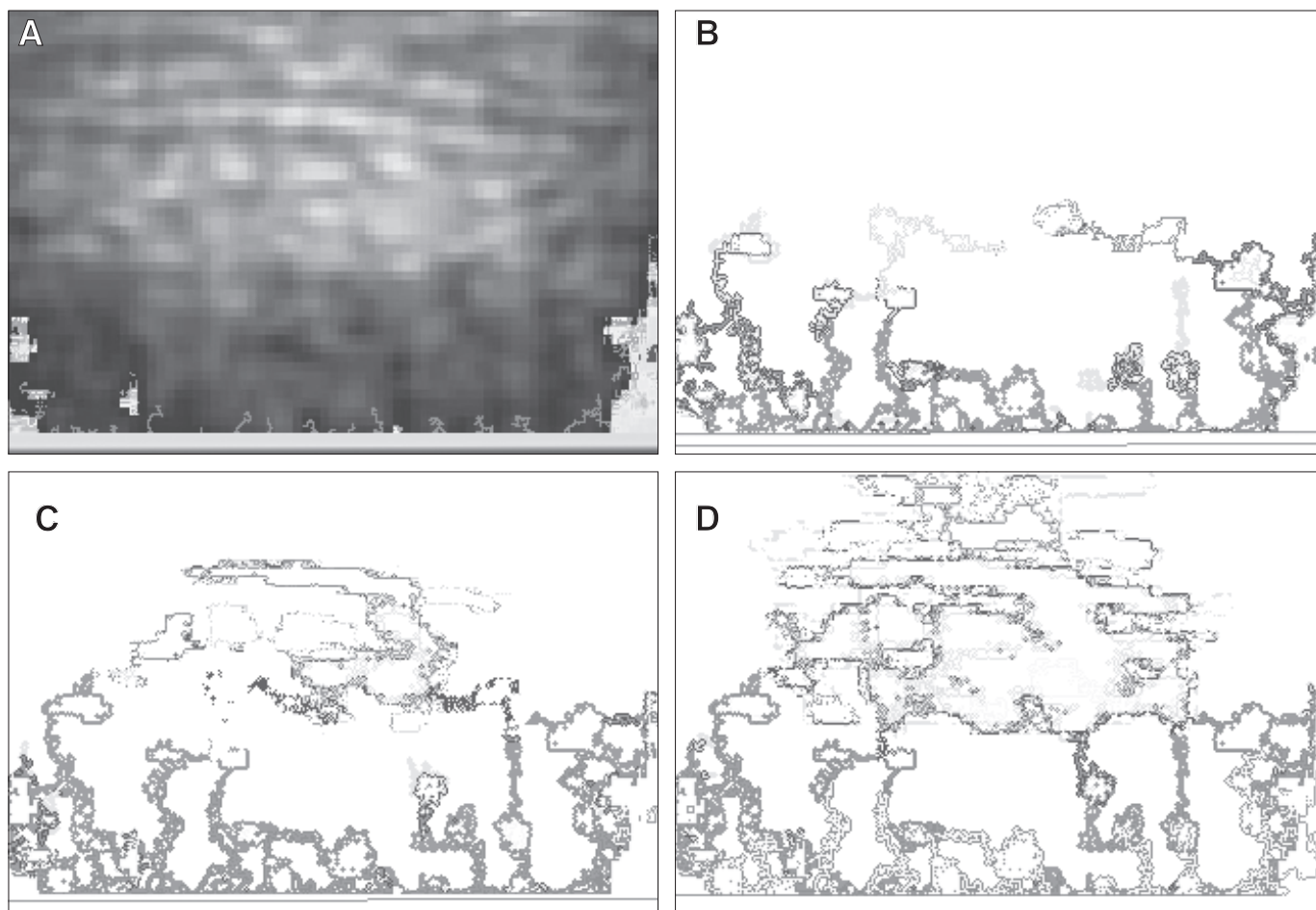


Fig. 10 – Numerical capillary model (from MPATH software) showing the progressive invasion of a fluid into *Macaronichnus*-burrowed sandstone. A. MRI image of *Macaronichnus* showing zones of relatively higher (bright) and lower (dark) porosity. Image modified from Gingras et al. (2002). B-D. The modeled invasion of oil (displacing water) primarily occurs preferentially within and around the burrowed areas. The matrix is ultimately saturated with hydrocarbons around burrowed zones. This is a typical dual-porosity system.

matrices that exhibit differing permeabilities. In the Sag River Formation, ichnogenera of the *Glossifungites* Ichnofacies (*Thalassinoides*, in most cases) display permeabilities 5-6 times greater (i.e., 250-300mD) than matrix permeabilities (i.e., about 50mD). A horizontal well placed within a zone hosting the *Glossifungites* Ichnofacies displayed unusually high production rates (3800 bbls/day versus 2500 bbls/day for an average production well).

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 Lower Cretaceous Guadalupe Group (Warren and Pulham 2001, 2002). Bioturbation is important to the production characteristics of the Mirador Formation reservoirs.

The paleoenvironmental interpretation of the Mirador Formation is controversial. Pulham (1994) and Pulham et al. (1997) interpreted the Mirador to represent incised valley deposits, but this interpretation was later revised, and the lower sandstone was proposed to represent a fluvial system occupying an upper coastal plain. The upper sandstone displays a stronger marine influence, and is interpreted to represent mouth-bar sands in the lower coastal plain (Warren and Pulham, 2001). Higgs

(2002) suggested that the Mirador Formation consisted of deltas deposited in a sea-level-lake.

A suite of the *Glossifungites* Ichnofacies demarcates the bottom of the Mirador sandstone, delineating a basin-wide unconformity. The assemblage is characterized by sharp-walled, unlined firmground *Thalassinoides* systems. Images derived from Computer Tomography (CT) reveal layers of differing density, illustrating the differential porosity of the media. The burrows exhibit the higher porosities. This example demonstrates the difficulty in up-scaling—to reservoir scale—the biogenic fabrics observed in core. However, if the burrows can be shown to be interconnected, the biogenic “plumbing” can be regarded to represent an isotropic flow media.

CRYPTIC BIOGENIC HETEROGENEITIES

Cryptic bioturbation results from one of three processes: 1) meiofauna disrupting sedimentary lamination; 2) some *Macaronichnus* behaviors which preserve vestigial sedimentary texture by implementing grain-selective deposit-feeding behaviors; and 3) eradication of sedimentary lamination by burrowing animals that completely rework the sediment.

Cryptic bioturbation may completely alter a volume of substrate (Fig. 11). Nevertheless, the flow characteristics of such

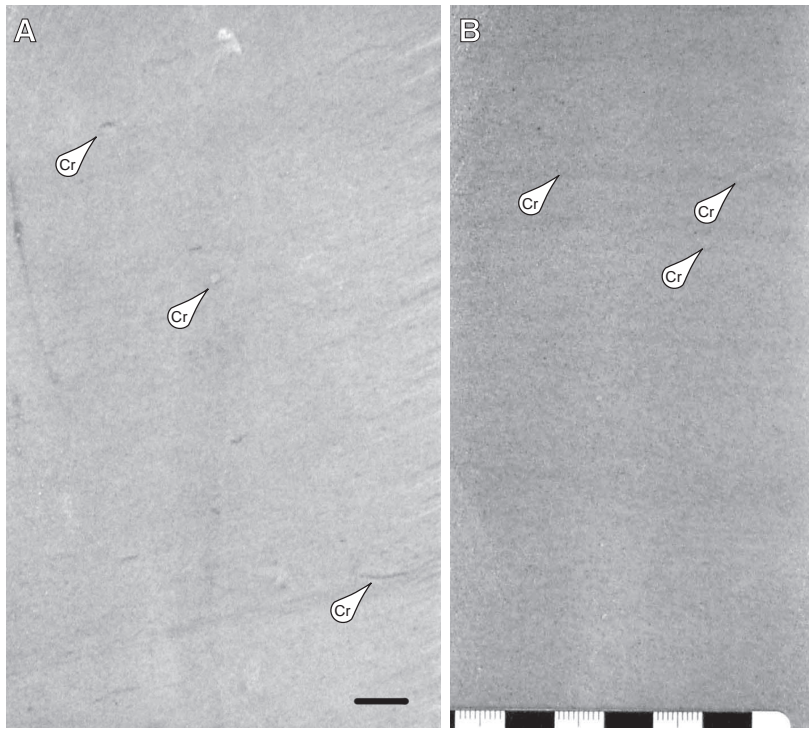
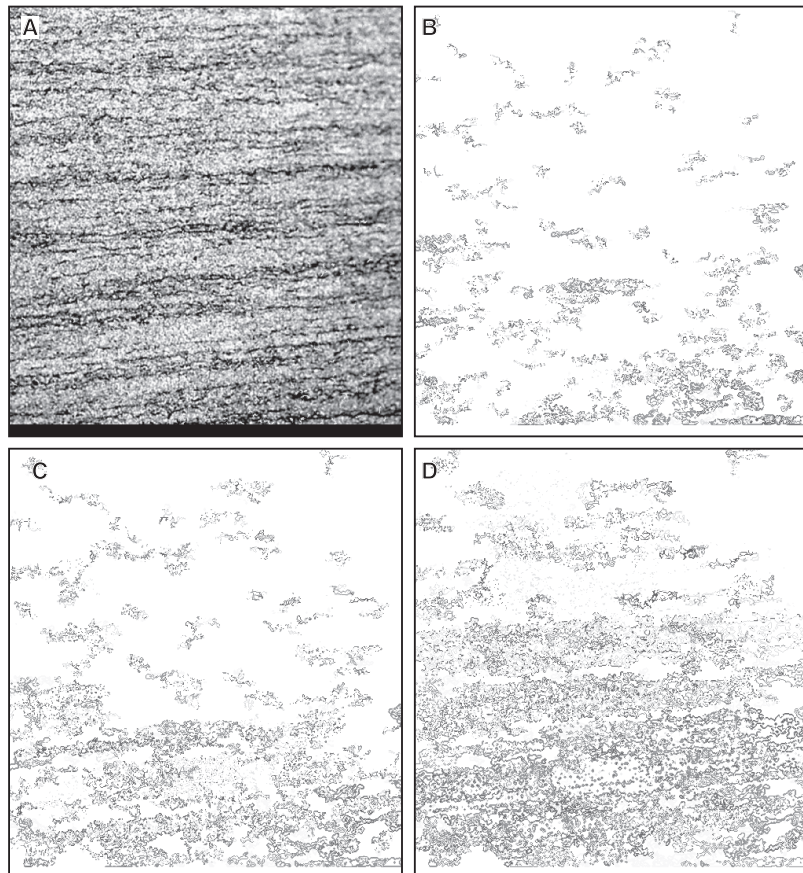


Fig. 11 – Examples of cryptic bioturbation. Both from Whiterose, Jean D’Arc Basin. A. Almost complete homogenization of the sedimentary fabric. Only a few discrete burrows (cr) suggest that the homogenization is due to biogenic processes. B. Similar to (A), but the sedimentary lamination is slightly more visible as vestigial bedding.



burrow-affected media may differ only slightly from unbioturbated media. In general, the sedimentary rock takes on isotropic flow characteristics. In many cases, cryptically bioturbated media have slightly higher porosities than adjacent unburrowed sediment. This may be due to a difference in the bulk composition of the sediment, influencing early diagenesis (Gingras et al., 2002), but this hypothesis is largely untested. Also, mechanical sorting of the grains tends to obliterate some variability within the laminae. In any case, cryptically bioturbated sandstone may provide high-permeability streaks in clastic strata.

Cryptic bioturbation induces a low-contrast, dual-porosity flow network to the sedimentary rock (Fig. 12). Considerations pertinent to fluid production from cryptically bioturbated rocks are that: (1) under high production rates, fluids in higher-permeability conduits can be cut off from the main flow conduits, reducing the overall recoverable resources in a reservoir; (2) the net permeability is a non-linear function of matrix and burrow properties (cf. Gingras et al. 1999); (3) understanding these systems in detail requires appropriate (numerical) modeling and laboratory experimentation; and most importantly, (4) most of the flow media is accessible to secondary production, providing that the rock is reasonably well understood.

Cryptic bioturbation (in sand) is common in clastic estuarine and distributary channels, as well as in upper shoreface deposits. These depositional environments are dynamic, thus their thicknesses and lateral extents are limited. In general, this facies is observed to occur in thicknesses ranging between 10 cm and 10 m. Amalgamated parasequences may generate stacked successions that approach 100 m in thickness.

An example of cryptically bioturbated flow media comes from the Bruce Field in the northern part of the North Sea (Pemberton and Gingras, 2005). Bruce reservoirs represent the Middle Jurassic Brent Delta System. Sandstones of the Bruce Field comprise a thick succession of syn-rift, lower-delta plain, nearshore- and restricted-marine environments (Pulham et al. 2000). The main reservoir sandstones are up to 130 m thick, with permeabilities ranging between 100s and 1000s of millidarcies. One of the most important stratigraphic horizons records a marine-flooding event that resulted in the deposition of high-permeability sandstone across large parts of the field. This unit is characterized by a cryptic bioturbation texture and corresponds to one of the most prolific producing zones in the lower “B” sand.

Fig. 12 – Numerical capillary model (from MPATH software) showing the progressive invasion of a fluid into cryptically bioturbated sandstone. A. Cryptically bioturbated sandstone with some well-preserved laminations (i.e. due to the activities of sediment meiofauna). B-D. The modeled invasion of oil (displacing water) primarily occurs around the burrowed areas until the matrix is saturated with hydrocarbons. This is an isotropic, ideal, dual-porosity system.

DIAGENETIC TEXTURAL HETEROGENEITIES

Diagenetic heterogeneities are typically observed as bioturbated, dolomite-mottled limestones. The dolomitic mottles result from dolomitization of calcareous sediment adjacent to body fossils, sedimentary lamination, and ichnofossils (Fig. 13; Kendall 1975; Zenger 1992; Gingras et al. 2002, Gingras et al. 2004b). The presence of fabric-selective dolomite in association with trace fossils is best attributed to early chemical and physical alteration of the substrate by burrowing organisms.

Physical alteration of the substrate includes modification of grain size, redistribution of grains, compaction, and sorting (Bromley, 1996). 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. Moreover, alteration of grain (crystal) sizes probably influences the geochemical behavior of the media and vice versa.

Burrow-induced diagenesis profoundly alters the rock's physical characters. For instance, permeabilities and porosities are normally different between the burrow-affected and unburrowed zones. Moreover, burrow-dolomite formation is focused in and around generations of interpenetrating ichnofossils. Consequently, the heterogeneity observed in mottled limestones is high. Although a dual permeability network is generally produced (Fig. 14), dual porosity systems are also observed.

Burrow-associated dolomite is commonly observed in Paleozoic carbonates. Diagenetic heterogeneities are exemplified by the Ordovician Chazy Group (Mehrtens and Selleck 2002), the Devonian Palliser Fm (Beales, 1953; Gingras et al. 2004b), the Upper Ordovician Bighorn Dolomite in Wyoming (Zenger 1992, 1996), and the Ordovician Yeoman Fm in the Williston Basin (Kendall 1975, 1977; Pak 2003) of North America. Younger examples are provided in Pedley (1992). Their depositional environments range from platformal offshore (Palliser Fm) to restricted offshore. Successions result in significant volumes of altered/affected strata. Thicknesses typically approach 10 m, however, more or less continuous zones may exceed 100 m thick. Likewise, areal extents are potentially vast, generally falling between 1 km² to 100s km².

Numerical-flow modeling of diagenetic heterogeneities is essential to solving their flow properties. This is generally not conducted, due to difficulties in deriving 3-dimensional data for input into modeling software. The main issues with deriving resources from such complex media include: 1) fluid interactions between the flow media and the limestone matrix are extensive; 2) patchy dolomite and its associated porosity or lack of porosity, are crudely similar to that fractured media; and 3) these fabrics are architecturally more complex than fractured media. Therefore, the potential presence of a complex (diagenetic) reservoir fabric must be considered if enhanced-recovery techniques are planned for a reservoir.

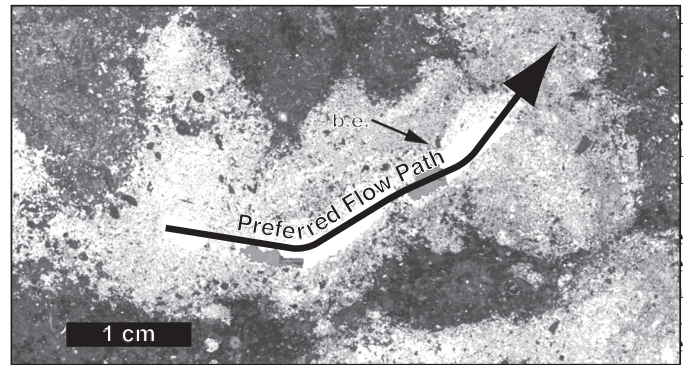


Fig. 13 – Thin section of dolomitized limestone (Tyndall stone, Red River Group, Williston Basin). The extent of the burrow is indicated by b.e. The dolomitized zone (light grey) extends as a halo around the burrow generating porosity around that sedimentary artifact.

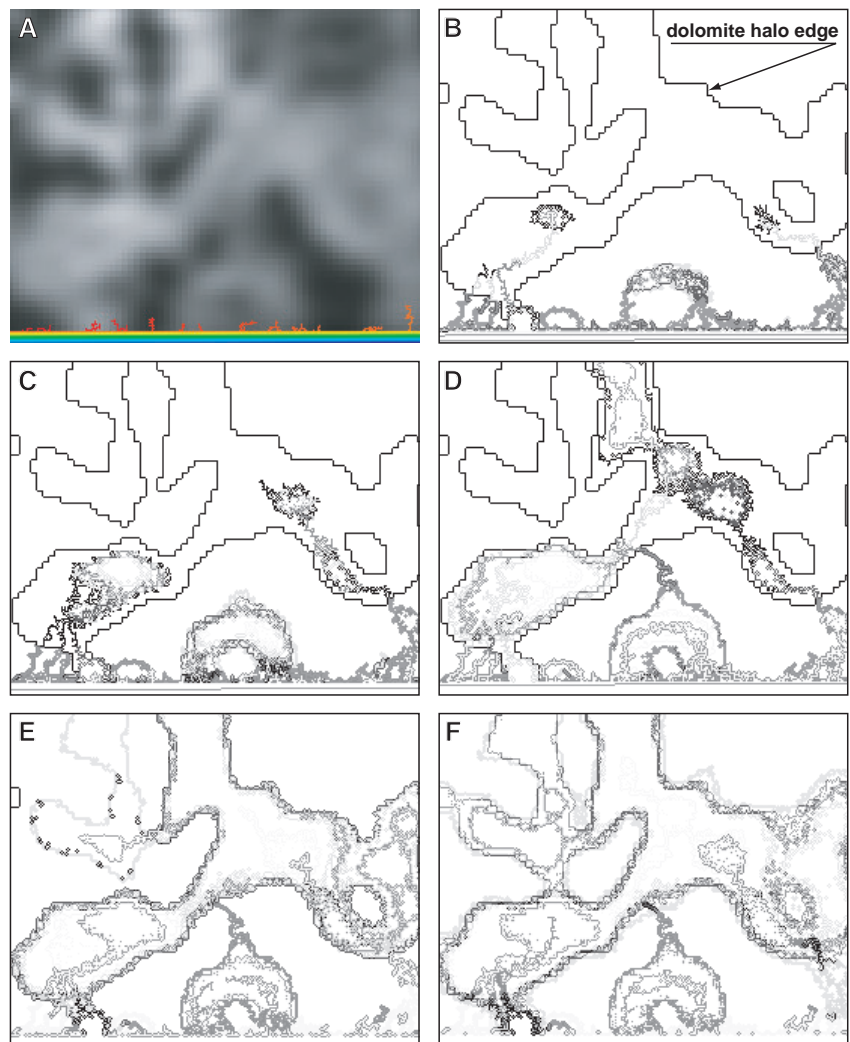


Fig. 14 – Numerical capillary model (from MPATH software) showing the progressive invasion of a fluid into diagenetically modified limestone (Tyndall Stone imaged by MRI; modified from Gingras et al. 2003). A. Cryptically bioturbated sandstone with some well-preserved laminations (i.e. due to the activities of sediment meiofauna). B-D. The modeled invasion of oil (displacing water) primarily occurs around the burrowed areas only the dolomitized areas become saturated with hydrocarbons. This is an isotropic, dual-permeability system.

burrows. Kendall (1977) and Pak (2003) noted that the degree of dolomitic mottling varies locally, but is typically confined to areas adjacent to the burrows.

Mini-permeameter spot-measurements from selected blocks of 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). These data can be used to estimate K_{bulk} by calculating the semi-logarithmic mean of the burrow and matrix permeabilities (Formula 1 above; Marsily 1986; Gingras et al. 1999). Using 45% as a typical value for the proportion of undolomitized matrix (Gingras et al. , 2004a,b), K_{bulk} is approximately 11 mD—ten times that of the average matrix permeability.

Production in the Yeoman Fm. primarily comes from dolomitic phases that occur in layers as thin as 1 m. Although the burrow fabric is locally the contributing reservoir delivery mechanism, permeabilities of up to 200mD can occur in zones where the matrix is dolomitized in preference to the burrow fabrics. In these instances, although the diagenetic relationship is reversed, reservoir heterogeneity is similar.

Another excellent example of burrow-selective dolomitization occurs in the Devonian Palliser Formation (the Wabamum Fm in the subsurface.) of the Western Canada Sedimentary Basin. In general, Palliser rocks have a low-permeability limestone matrix with negligible effective porosities. The limestone encompasses chaotically distributed, fabric-selective dolomite with an effective porosity as high as 5-6% (Gingras et al. 2004b). The dolomite represents diagenetic alteration around physical sedimentary structures as well as ichnofossils (Gingras et al. 2004a,b), and is similar to that observed in the Yeoman Fm.

ASSESSMENT OF BURROW-ASSOCIATED PERMEABILITY

Pemberton and Gingras (2005) have proposed a classification detailing the main configurations of biogenically enhanced permeability. A number of factors strongly influence bulk-flow parameters, and are intrinsic considerations that underpin the classification scheme. The main variables not yet accounted for include burrow density, burrow connectivity and burrow-to-matrix permeability contrast. The burrow surface area and burrow architectures are also important factors, but are less easily quantified. All of these factors are perused below.

BURROW DENSITY

Gingras et al. (1999) conducted a sensitivity analysis on flow responses to a numerical model characterized by different burrowing volumes (1.0%, 2.0%, 10%, 25%, and 50%). Changes in burrow density were shown to have a significant effect on the bulk permeability. This factor seemed to generate high variability in effective horizontal permeability measurements (K_h), and caused systematic (semi-logarithmic) changes in K_v .

As most permeability enhancing burrows possess at least a partial vertical component, vertical permeability is predictably enhanced by increases in burrow density. Weaver and Schultheiss (1983) and Gingras et al. (1999) agreed that K_v is most dependent on burrow density. In fact, Weaver and Schultheiss (1983) showed that open burrows in a clay substrate increased the bulk permeability by as much as eight orders of magnitude. Gingras et al. (1999) demonstrated that K_v values for 1.0% and 2.0% burrow density were essentially equivalent, however, significantly higher degrees of bioturbation (up to 50% by volume) increased effective permeability by almost one order

of magnitude. As with K_v , K_h responds to increases in burrow volume. Gingras et al. (1999) reported, however, that horizontal transmissivity was not notably improved until burrow volumes exceeded 25%.

BURROW CONNECTIVITY

Conceptually, burrow connections occur as: (1) isolated shafts; (2) shafts and burrows that connect to one other shaft or burrow (poorly connected); (3) shafts and burrows that connect to two other shafts or burrows (moderately connected); (4) and shafts and burrows connected to several other shafts or burrows (fully connected). Gingras et al. (1999) demonstrated that K_v was generally unchanged by an increase in burrow connectivity. This behavior was attributed to extensive channeling between the upper and lower surfaces, wherein the vertical components of the burrow systems essentially short circuit the flow paths.

It was further determined that the degree of connectivity plays a significant role in modifying K_h (Gingras et al. 1999). Fully connected burrows resulted in an effective K_h that was comparable to K_v . Moderately connected burrows caused the effective horizontal permeability to decrease remarkably; their effective permeability was one order of magnitude below K_v . Poorly connected and unconnected models exhibited only small increases in K_h , even when $K_{\text{burrow}}/K_{\text{matrix}}$ exceeded six orders of magnitude (Gingras et al. 1999; discussed below). In other words, if there is no horizontal connectivity, K_h approaches that of K_{matrix} .

PERMEABILITY CONTRAST

Various methods of calculating effective permeability can be applied to heterogeneous media. Weighted arithmetic and harmonic means, respectively, describe effective permeabilities for flow along and across layered media (Freeze and Cherry 1979). Various geometric means are used to describe the effective permeability for uniformly random media (Gelhar 1986). Values of K_v increase proportionally with increases in K_{burrow} . Previous analyses using numerical, Darcy flow, and field-based measurements have demonstrated that K_v can be represented by a volumetrically weighted arithmetic mean of the matrix and burrow permeabilities (presented as Formula 1, above; cf. Gingras et al. 1999).

Horizontal flow is not necessarily aided by horizontal flow connections. Thus (1) cannot be used to predictably approximate K_h , which is strongly influenced by the degree of burrow connectivity. Isolated burrows do not favor development of a significantly enhanced K_h . Alternatively, fully connected burrows are reasonably represented by (1), because the connections permit significant lateral flow through the sample. This is especially true where burrow volumes exceed 25% (Gingras et al. 1999). The horizontal permeabilities of fully connected and moderately connected simulations best follow the arithmetic means if the burrow volume is empirically adjusted according to the model's degree of connectivity (Gingras et al. 1999):

$$\text{Formula 2: } \log K_h = \log [(1-Vb^*) K_{\text{matrix}} + Vb^* K_{\text{burrow}}]$$

Where Vb^* is the effective volume of burrows that actively conduct flow. This factor is given by:

$$\text{Formula 3: } Vb^* = 2^x \cdot Vb$$

Where Vb is the fractional volume of burrows within a block, $x=1$ for fully connected systems and $x=2$ for cases where burrows

are moderately connected to two neighbors. Note that Formula 2 reduces to Formula 1 for $x=0$: i.e. $Vb^* = Vb$.

Gingras et al. (1999) explained the rationale for Formula 2 to be that increased burrow connectivity exponentially increases the number of continuous flow conduits—this was, in fact, an outcome of their flow model. In burrow systems fully and moderately connected configurations, continuous flow paths were far more abundant than poorly connected systems. They further stated “somewhat continuous, tortuous conduits are inevitably present in (moderately) connected systems. Fully connected systems are characterized by box-work conduits, all of which may contribute to flow and exhibit a less tortuous flow path than (poorly and moderately) connected systems.”

Unconnected and poorly connected configurations are not characterized in the same way, because no continuous (horizontal) flow paths are expected. With these burrow systems, K_h is dependent upon K_m . The geometric mean of the permeabilities can actually provide estimates for unconnected systems (Gingras et al. 1999). Since the enhancement of K_h is almost negligible, this is probably not worth applying in standard assessments of reservoir behavior. Fortunately, higher degrees of bioturbation (10% or more) generally lead to higher connectivity.

BURROW SURFACE AREA AND TRACE ARCHITECTURE

The presence of permeable burrows in comparatively tight media serves to increase the surface area and, to a lesser degree, the potential volume of flow conduits within reservoirs. For instance, the surface area of 50 burrows/m², (a conservative estimate based on observations from modern settings, which may reach population densities approaching 300 burrows/m²), with 2 cm diameter tubes that descend 50 cm into the substrate, is a little over 1.5 m². This is, of course, 1.5 times the horizontal section, and three times the vertical section. A simple fracture would possess a surface area roughly equivalent to the cross-sectional area of the block. It is easy to imagine extensive burrow-to-matrix interactions with higher burrow densities. In highly burrowed media, the number of burrows per unit volume increases dramatically. The *Macaronichnus* tracemaker, an opheliid polychaete, lives in population densities of up to 5000/m², and extends to a depth of more than 20cm. The surface area of those small-diameter (approximately 4 mm) burrows is about 12 m²!

Storativity within burrow fabrics is simply related to the volume the biogenic fabric occupies. Crustacean-generated traces, such as *Thalassinoides* and *Ophiomorpha*, can occupy up to 43 % of the matrix (Diller and Martin 1995). *Macaronichnus* may easily occupy 70% of the rock volume. Diagenetic fabrics range up to 80% of the volume. These examples illustrate that burrowed horizons not only change flow characteristics within a reservoir, they have an impact on resource production and reserve calculations as well.

In addition to its size, a burrow's overall architecture can influence the degree of connectivity and tortuosity present in biogenically modified flow media. 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. *Zoophycos* of the Sirasun field (above) fall into this category. In such cases, the three dimensional nature of the flow paths may be effective, but awkward, resulting in abundant

flow cutoffs and dead zones while still providing a higher bulk permeability. Cryptic bioturbation is so highly “interconnected” that the flow media is essentially isotropic and permeability dead zones are likely common, but exceedingly small. No focused research has attempted to characterize the impact of burrow morphology on reservoir behavior. We believe it is an estimable parameter.

ANALYTICAL METHODS

The most fundamental source of three-dimensional data, with which one can assess biogenically modified permeability fabrics, is core and outcrop data. These depend on fabric, lithologic contrast, and the presence of diagenetic cements in order to identify physical heterogeneities in sedimentary rocks. From these we derive numerical models for scaling upwards (cf. Gingras et al. 1999; McKinley et al. 2004). Observations that can be made pertaining to rock fabric are limited by the quality of rock exposure or sample available, and this size of the sample referenced. Size is important, as permeability fabrics have to be scaled upwards. Unfortunately, outcrops seldom proffer a three-dimensional understanding of their structure. Thus, core is commonly a good source of permeability data, even though the representative elemental volume is small.

Nondestructive methods can be used to accurately resolve the three-dimensional nature (henceforth 3-D) of sedimentary structures at the hand-sample scale. The most common of these are X-ray and X-ray computed tomography (CT). X-rays provide only “flattened” 3-D data onto a plane. CT-scans are 3-D, but they are not particularly sensitive to the slight variations in density that characterize most rocks (X-ray devices likewise suffer from this limitation). Nevertheless, CT-scans have the potential to yield high-resolution data (see the Cusiana Field data, above) that can be used to establish the 3-D nature of biogenic fabrics (Pierret et al. 2002).

A new technique, microtomography (Micro-CT), has great potential for ichnological applications, because it permits the resolution of micron- through mm-scale density heterogeneities in geological media. It is appropriate, therefore, for the delineation of small to microscopic borings, burrows, and fecal pellets. More importantly, it can resolve the pore distribution in a small volume of sediment, thereby yielding the potential for very detailed spatial resolutions of capillary pressure. Moreover, Micro-CT permits visualization without the presence of a vacuum or coating. This allows the natural specimen structure to be preserved. Notably, objects can be observed under external influence (loading, chemical reactions, interaction with other solids, liquids, gases, etc.).

Micro-CT images are obtained through transmission X-ray microscopy. The combination of X-ray transmission techniques with tomographical reconstruction provides three-dimensional information pertaining to the internal microstructure of the sample. Thereby, the internal area is reconstructed as a set of 2-D cross-sections. These are reconstructed for analysis of the object's 3-D internal and external morphology. Because the technique uses X-ray methods, the contrast in the images is a mixed combination of density and compositional information. Correspondingly, compositional information can potentially be separated from the density information.

Unlike the aforementioned radiographic techniques, magnetic resonance imaging (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 the 3-D mapping of a magnetic resonance signal, providing a tool that geologists can

use to map the pore-space distribution in rocks. Gingras et al. (2002) used MRI to: (1) image the 3-D nature of *Macaronichnus segregatis*; (2) establish the paleontological significance of the burrow interrelationships; and (3) assess the fluid-flow implications of the textural heterogeneities reported herein. In that paper they established the utility of MRI to map very small biogenic flow paths, generally less than 4 mm in diameter, as well as the potential of the method to visualize pore invasion by moving fluids. Imaging fluid imbibition and drainage was subsequently reported in Chen et al. (2003).

SUMMARY

Biogenic fabrics in sedimentary rocks can control the permeability fabric and thus, fluid flow in sedimentary strata. Bioturbation may impose well-defined, highly contrasting permeability fields, referred to as "dual permeability" networks, or subtly contrasting permeability fields, referred to as "dual porosity" networks. Both types of flow media influence the reservoir quality of fluid-bearing rock. Dual porosity leads to complex reservoir behaviors that include: (1) with single-phase flow, the entire rock contributing to fluid or gas production; (2) with the presence of more than one fluid phase, the rock inducing flow in higher porosity/permeability zones; and (3) the fluid in the lower-permeability portions of the rock moving into higher permeability media through diffusion and advection (mechanical movement). Dual-permeability flow media have poorer resource characteristics, resulting in the following: (1) higher permeability areas of the rock comprising the only effective flow media present; (2) fluid resources generally absent in the tighter rock; and (3) secondary recovery typically isolating large parts of the flow network.

Dual porosity and permeability fabrics are a component of the burrow-media classification scheme presented in Pemberton and Gingras (2005), as is the stratigraphic architecture. These parameters more or less define 5 flow-media types: (1) surface-constrained discrete heterogeneities, (2) non-constrained discrete heterogeneities, (3) non-constrained indiscrete heterogeneities, (4) cryptic heterogeneities, and (5) diagenetic heterogeneities. Other factors that influence the overall behavior of the flow-media class are 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.

Due to the complexity of biogenic flow media, 3-D imaging techniques are an essential component of their analysis. We suggest that CT-scan, Micro-CT-scan, and MRI techniques have the most potential in three-dimensional rock analyses. Ideally, an analysis should incorporate all of the above techniques, as each method provides a different type and scale of data. Imaging techniques are currently evolving faster than upscaling methods, a field of application that shows much promise.

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