Reservoir Characterization of Burrow-Mottled Dolomites: Devonian Wabamun Group, West-Central Alberta, Canada

Greg M. Baniak*, Ichnology Research Group (IRG), University of Alberta, Edmonton, Alberta, Canada
baniak@ualberta.ca
and
Murray K. Gingras, S. George Pemberton

GeoConvention 2012:Vision

Introduction

Research has shown that bioturbation can significantly alter the permeability and porosity distributions within a reservoir (e.g. Dawson, 1978; Morrow, 1978; Gingras et al., 1999, 2002, 2004, 2007; Pemberton and Gingras, 2005; Spila et al., 2007; Gordon et al., 2010; Tonkin et al., 2010; Baniak et al., 2011; Lemiski et al., 2011). Within calcareous sediment, chemical and physical alteration of the substrate by burrowing organisms can result in fabric-selective dolomitization. In many examples, these dolomitized burrows have been identified as having significantly higher permeabilities relative to the surrounding lime mud matrix (e.g. Ordovician Yeoman/Red Rivers Formations, Williston Basin, Gingras et al. (2004); Mississippian Debolt Formation, northwestern Alberta, Baniak et al. (in review)). The Wabamun Group in the subsurface of west-central Alberta is another example of burrow-associated dolomitization and is the focus of this study. Within this study, a primary focus was on the facies architecture of the carbonate units. From this, a clearer understanding of the controls bioturbation exerts on reservoir quality can be established.

Study Area

Our study area is the Pine Creek gas field (Township 56-58; Range 19-20W5M) in west-central Alberta (Fig. 1). Producing at depths greater than 3100m, natural gas production in the Pine Creek Field has exceeded 500 BCF. Occurring throughout the Western Canadian Sedimentary Basin, the Wabamun Group is stratigraphically equivalent to the outcropping Palliser Formation in Alberta and British Columbia and subsurface Three Forks Group in Saskatchewan and Manitoba.

Facies Analysis

In this study, eleven cored wells from the Pine Creek Field were examined (Fig. 1). Sedimentological characterization included identification of carbonate grains, fossils, primary and secondary physical structures, and mineralogical accessories. Ichnological data collected included identification of ichnogenera and characterization of bioturbation intensity. Bioturbation intensity (hereafter denoted BI) involved the allocation of a grade of bioturbation and varies from absent (BI of 0 or 0% intensity) to complete (BI of 6 or 100% intensity). Measurement of the BI was adapted from Bann et al. (2004), with concepts from Taylor and Goldring (1993) and Reineck (1963). Within the studied cores, eight different facies were encountered (listed below) and were interpreted to represent a series of shallow water carbonate platform deposits.

Facies 1 Stromatoporoid boundstones (Fig. 2A): Wavy to tabular stromatoporoids forming centimeter to decimeter scale successions characterizes Facies 1. Commonly interbedded with fine-matrix mudstones, intraclastic wackestones, and fragmental packstones-grainstones. Recognized as major indicators of warm, tropical to subtropical climates during the Devonian (Heckel & Witzke 1979). Interpreted to represent the development of small patch reefs throughout the inner platform.

Facies 2 Biolaminated mudstones (Fig. 2B): These laminations within the boundstones are typically either planar or wavy and form centimeter to decimeter intervals. Skeletal fragments, allochems, and sediment reworking is generally rare in this facies. Interpreted to represent an upper intertidal to supratidal environment (Pratt, 2010).

Facies 3 Highly Bioturbated Mudstones-Wackestones (Fig. 2C): The bioturbated areas show a range of intensity (BI 4 to 6). They transition from well-defined tubular burrows several millimeters in diameter to an interconnected, chaotic meshwork of burrows. In rare examples, undolomitized lime peloids and other allochems fill the burrows. These represent burrow-fillings in an intermediate stage between non-dolomitized and completely dolomitized burrow-fillings. Owing to their more porous and permeable composition, the mottles likely acted as conduits for sediment- or rock-penetrating solutions resulting in burrow-selective dolomitization. This facies is characteristic of sedimentation occurring within the platform margin (Tucker and Wright, 1990).

Facies 4 Bioturbated, Fossiliferous Wackestone-Packstone: Facies 4 is rich in complete and fragmented macrofossils (especially ostracods, bivalves, brachiopods, gastropods, and echinoderms), peloids and other intraclastic material. Echinoderm fragments, especially crinoid columnals and plates, along with ostracods, are the most common skeletal grains. Low to moderately bioturbated (BI 0 to 4) and typically non-laminated. Appreciable amounts of carbonate mud, combined with an abundance of bioclasts, suggest low to moderate energy and deposition in a subtidal, open marine setting.

Facies 5 Bioturbated, Fossiliferous Wackestone-Mudstone: This facies is a massively bedded, fine to coarsely fragmental mudstone to wackestone that includes dark-grey irregular shale partings and scattered fossil fragments. Echinoderms, brachiopods, crinoid ossicles, ostracods, and calcispheres are the most common allochems. Bioturbation ranges from low to moderate (BI 1 to 3), with interbedded intervals of higher intensity (BI 4 to 5). Interpreted to represent subtidal sedimentation in a quiet, open marine environment, such as a platform margin-deep basin.

Facies 6 Peloidal Packstones (Fig. 2D): Peloids are the most abundant type of allochem in the Pine Creek gas field. They vary from completely micritic to containing some traces of original skeletal material (echinoderm fragments, bivalves, ostracodes). This facies includes grains of different sizes and shapes (range from 25 to 500 µm, and exceptionally up to 1000 µm). The different shapes, combined with extensive micritization, indicate that these components were micritized in situ or shortly after deposition (Al-Saad and Sadooni, 2001). The presence of large peloids suggest that peloidal packstone was deposited in a shallow water, quiet, lagoonal setting, such as a low-relief subtidal bank (Qing and Nimegeers, 2008).

Facies 7 Fossiliferous, Peloidal Packstone-Grainstone (Fig. 2E): The most abundant allochems in this facies are ostracods, calcareous algae (calcispheres), echinoderms, and peloids. Bioturbation is low to moderate (BI 0 to 3). The grainy texture and low diversity fauna of this facies are consistent with restricted shallow-water settings of moderate energy where microbial flats and low-relief biodetrital mounds develop (Tucker and Wright, 1990). The presence of calcispheres during the Devonian suggests deposition in a shallow-water, restricted marine environment, such as a lagoon (Flügel, 2010).

Facies 8 Peloidal Grainstone (Fig. 2F): Pellets in this facies are rounded to sub-rounded, smaller than 100µm, and display moderate to high sphericity. The characteristic roundness and lack of internal structure suggests a possible fecal origin (Flügel, 2010). Shallow-water, low-energy, semi- to fullyrestricted marine environments (such as the subtidal to intertidal zones of a inner platform) may help lead to rapid lithification and preservation (Flügel, 2010).

Reservoir Characterization

Historically, many of the Wabamun limestone's throughout Alberta have been considered very poor reservoir rocks due to porosities and permeabilities generally ranging below than 1% and 1mD, respectively (Saller and Yaremko, 1994). In turn, the limestone often encompasses chaotically distributed, fabric-selective dolomite that has an effective porosity as high as 5 to 6% and permeabilities up to 500 mD (Gingras et al., 2002, 2004). Within the Pine Creek gas field, there are two primary reservoir facies: (i) Laminated to cross-laminated peloidal grainstones-packstones (Facies 6, 7, and 8); and (ii) Burrow-mottled wackestones-mudstones with preferentially dolomitized burrows (Facies 3).

Analysis of the bioturbated facies occurred though using Micro-CT (Fig. 3) and spot-permeametry (Fig. 4). When a comparison of burrow intensity with permeability was conducted, it was found that the arithmetic mean (*sensu* Freeze and Cheery, 1979) best estimates bulk horizontal permeability (i.e. the burrows) within the reservoir units. This arithmetic relationship suggests that connectivity between the burrows is significant. Due to high burrow connectivity, a continuous flow network between the burrow systems is likely. Micro CT scans showed intricate three-dimensional (3-D) burrow fabrics, where well-defined burrow fabrics can be distinguished from the matrix. This, coupled with high-resolution two-dimensional cross-section slices through imaged samples, provided an excellent opportunity at tracing the fluid behavior throughout the rock fabric.

Due to the large contrasts in permeabilities between the burrows and matrix (Fig. 4), movement of natural gas is anticipated to preferentially migrate through the tortuous burrow fabrics. Significant reserves of natural gas remain trapped within the low-permeability matrix as a result. Matrix interaction with the burrows occurs via diffusion and natural gas may only be produced from the matrix via localized permeability streaks provided by the burrows. The burrows therefore act as biogenic fracture systems. Unlike natural fracture systems, however, interconnected burrow networks have considerably higher surface areas and therefore greater amounts of flow conduits within the lower permeability matrix. Consequently, natural gas movement becomes concentrated within the burrow networks during the production phase of the reservoir. As a result, special care must be taken during production to ensure the lower-permeability matrix does not become isolated and cut-off (as diffusion of natural gas from the matrix into the burrows is very slow).

Conclusions

Sedimentological and ichnological analysis of core samples revealed a shallow marine, low-gradient carbonate platform within the Pine Creek Field. Recognition of two main reservoir facies (i.e. peloidal packstone-grainstone and bioturbated mudstone-wackestone) were identified at different levels within the platform succession. Graphs comparing burrow intensity with permeability show that the arithmetic mean best represents fluid flow through the burrow systems. Micro-CT analysis demonstrated the complex 3-D nature of the burrow fabrics.

Acknowledgements

We would like to thank the following people for their technical assistance and ongoing support of this PhD thesis by the lead author: Mark Labbe, David Pirie, Richard Stern, Aleisha Rosse, Andrew La Croix, Tiffany Playter, and Michelle Mudryk. The Ichnology Research Group (IRG) at the UofA is also thanked for providing fruitful discussions and enjoyable atmosphere. Logistics (i.e. thin-sections) were funded by a Gustavus E. Archie AAPG Memorial International Grant. BP Canada, Devon Canada, ConocoPhillips, and Statoil provided funding for core work in Calgary. The fine people at the ERCB

Core Research Centre in Calgary, Alberta should also be recognized for their excellent work and friendly assistance during our stay at the core lab (July to August, 2010).

References

Al-Saad, H., and Sadoona, F.N., 2001, A new depositional model and sequence stratigraphic interpretation for the upper Jurassic Arab "D" reservoir in Qatar: Journal of Petroleum Geology, **24**, 243-264.

Baniak, G.M., Amskold, L., Konhauser, K.O., Muehlenbachs, K., Pemberton, S.G., and Gingras, M.K., in review, Sabkha and burrow-mediated dolomitization in the Mississippian Debolt Formation, Northwestern Alberta, Canada: Bulletin of Canadian Petroleum Geology.

Baniak, G.M., Gingras, M.K., Burns, B., and Pemberton, S.G., 2011, Petrophysical characterization of bioturbated facies from the Upper Jurassic Ula Formation, Norwegian North Sea, Europe: AAPG Annual Convention and Exhibition Abstracts, Houston, Texas, USA.

Bann, K.L., Fielding, C.R., MacEachern, J.A., and Tye, S.C., 2004, Differentiation of estuarine and offshore marine deposits using integrated ichnology and sedimentology: Permian Pebbly Beach Formation, Sydney Basin, Australia. In: D. McIlroy (ed.). The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society London, Special Publication, **228**, 179-211.

Dawson, W.C., 1978, Improvement of sandstone porosity during bioturbation: AAPG Bulletin, **62**, 508-509.

Flügel, E., 2010, Microfacies of carbonate rocks: analysis, interpretation and application, 2nd Edition: Springer-Verlag, Berlin, 976 pp.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, New Jersey, USA, 604 pp.

Gingras, M.K., Pemberton, S.G., Mendoza, C., and Henk, F.H., 1999, Modeling fluid flow in trace fossils: assessing the anisotropic permeability of *Glossifungities* surfaces: Petroleum Geoscience, **5**, 349-357.

Gingras, M.K., MacMillan, B., and Balcom, B.J., 2002, Visualizing the internal physical characteristics of carbonate sediments with magnetic resonance imaging and petrography: Bulletin of Canadian Petroleum Geology, **50**, 363-369.

Gingras, M.K., Mendoza, C., and Pemberton, S.G., 2004, Fossilized worm-burrows influence the resource quality of porous media: AAPG Bulletin, **88**, 875-883.

Gingras, M.K., Pemberton, S.G., Henk, F., MacEachern, J.A., Mendoza, C., Rostron, B., O'Hare, R., Spila, M., and Konhauser, K., 2007, Applications of ichnology to fluid and gas production in hydrocarbon reservoirs. In: J.A. MacEachern, K.L. Bann, M.K. Gingras and S.G. Pemberton (eds.). Applied Ichnology: SEPM Short Course Notes, **52**, 129-143.

Gordon, J.B., Pemberton, S.G., Gingras, M.K., and Konhauser, K.O., 2010, Biogenically enhanced permeability: A petrographic analysis of *Macaronichnus segregatus* in the Lower Cretaceous Bluesky Formation, Alberta, Canada: AAPG Bulletin, **94**, 1779-1795.

Heckel, P.H., and Witzke, B.J., 1979, Devonian world palaeogeography determined from distribution of carbonates and related lithic palaeoclimatic indicators. In: M.R. House, C.T. Scrutton, and M.G. Bassett (eds.). The Devonian System: Special Papers in Palaeontology, **23**, 99-123.

Lemiski, R.T., Hovikoski, J., Gingras, M.K., and Pemberton, S.G., 2011, Sedimentological, ichnological and reservoir characteristics of the low-permeability, gas-charged Alderson Member (Hatton gas field, southwest Saskatchewan): Implications for resource development: Bulletin of Canadian Petroleum Geology, **59**, 27-53.

Morrow, D.W., 1978, Dolomitization of lower Paleozoic burrow-fillings: Journal of Sedimentary Geology, **48**, 295-306.

Pemberton, S.G., and Gingras, M.K., 2005, Classification and characterizations of biogenically enhanced permeability: AAPG

Bulletin, **89**, 1493-1517.

Pratt, B.R., 2010, Peritidal carbonates. In: N.P. James and R.W. Dalrymple (eds.). Facies Models 4: Geological Association of Canada, St. John’s, 401-420.

Qing, H., and Nimegeers, A.R., 2008, Lithofacies and depositional history of Midale carbonate-evaporite cycles in a Mississippian ramp setting, Steelman-Bienfait area, southeastern Saskatchewan, Canada: Bulletin of Canadian Petroleum Geology, **56**, 209-234.

Reineck, H.E., 1963, Sedimentgefüge im Bereich der südlichen Nordsee: Abhandlungen der Senckenbergischen Naturfoschenden Gesellschaft, **505**, 1-138.

Saller, A.H., and Yaremko, K., 1994, Dolomitization and porosity development in the middle and upper Wabamun Group, Southeast Peace River Arch, Alberta, Canada: AAPG Bulletin, **78**, 1406-1430.

Spila, M.V., Pemberton, S.G., Rostron, B., and Gingras, M.K., 2007, Biogenic textural heterogeneity, fluid flow and hydrocarbon production: Bioturbated facies Ben Nevis Formation, Hibernia Field, offshore Newfoundland. In: J.A. MacEachern, K.L. Bann, M.K. Gingras and S.G. Pemberton (eds.). Applied Ichnology: SEPM Short Course Notes, **52**, 354-371.

Taylor, A.M., and Goldring, R., 1993, Description and analysis of bioturbation and ichnofabric: Journal of Geological Society of London, **150**, 141-148.

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 Bulletin, **94**, 1059-1078.

Tucker, M.E., and Wright, V.P., 1990, Carbonate sedimentology: Blackwell Scientific Publications, London, UK, 482 pp.

Figures

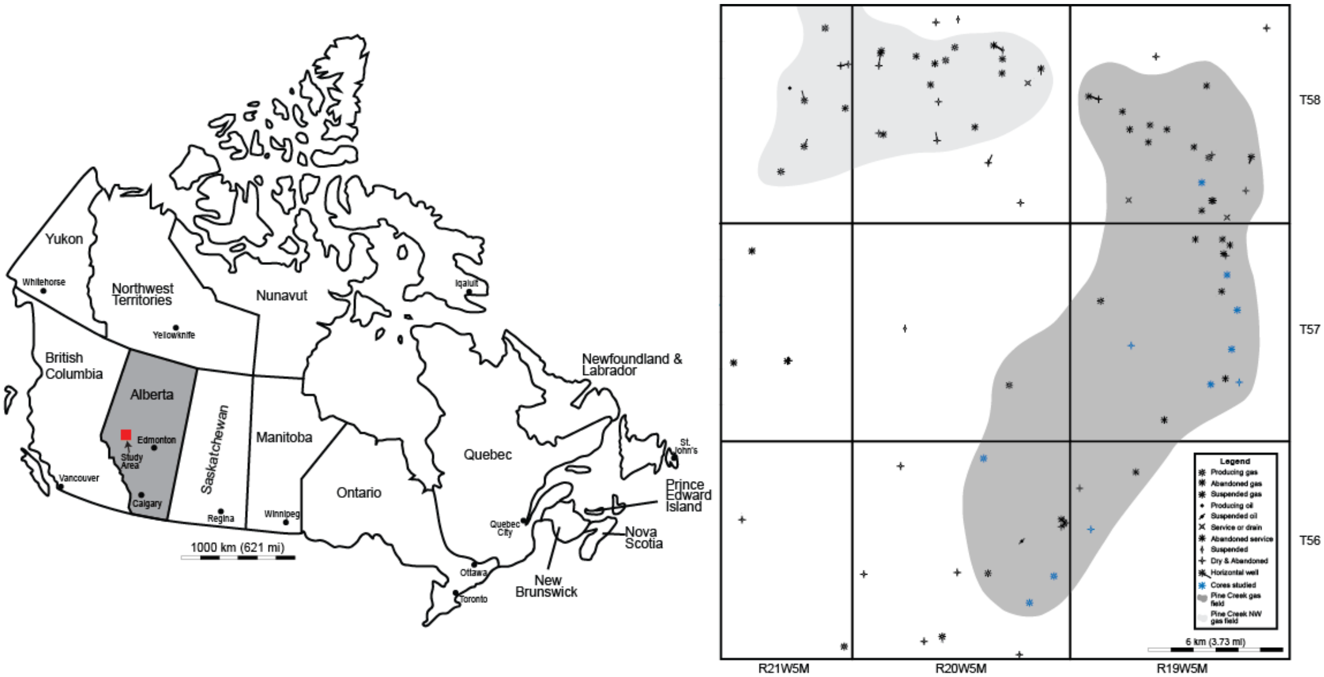

Figure 1: Location map of Canada (left) demarcating the Pine Creek gas field study area in west-central Alberta. The map on the right outlines the 11 cores (in blue) used in this study.

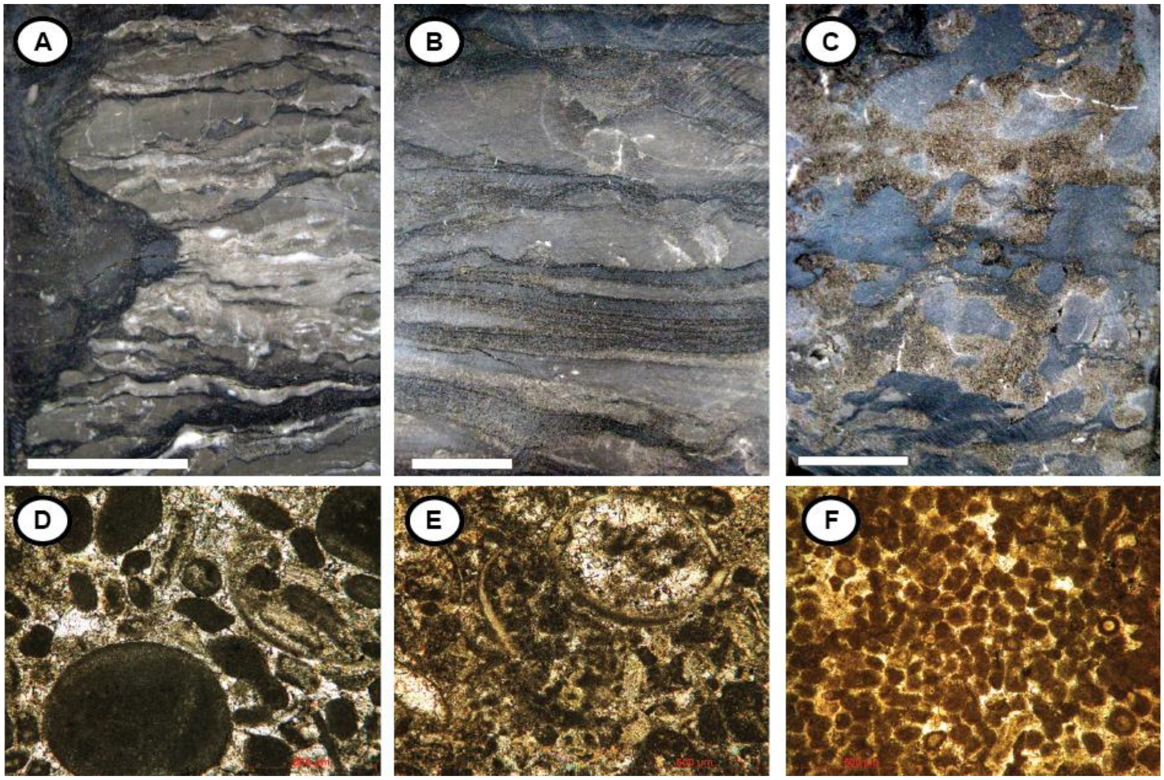

Figure 2: Core photographs. All scale bars are 3cm unless noted otherwise. **A)** Wavy stromatoporoid boundstones demarcated by stylolitization. 9-11-56-20W5M, 3466.00m. **B)** Wavy to planar biolaminated mudstones. 11-26-57-19W5M, 3002.94m **C)** Highly bioturbated mudstone. The dolomitized burrows are surrounded by non-dolomitized lime mud matrix. 9-11-56-20W5M, 3450.30m. **D)** Thin-section photomicrograph of a peloidal packstone with a wide-ranging grain size. 10-17-57-19W5M, 3223.96m. **E)** A photomicrograph of a highly fossiliferous, peloidal grainstone. Fossils include ostracods, calcareous algae (calcispheres), echinoderms, and peloids. 10-17-57-19W5M, 3215.70m. **F)** A photomicrograph of a well-rounded peloidal grainstone. 10-17-57-19W5M, 3195.40m.

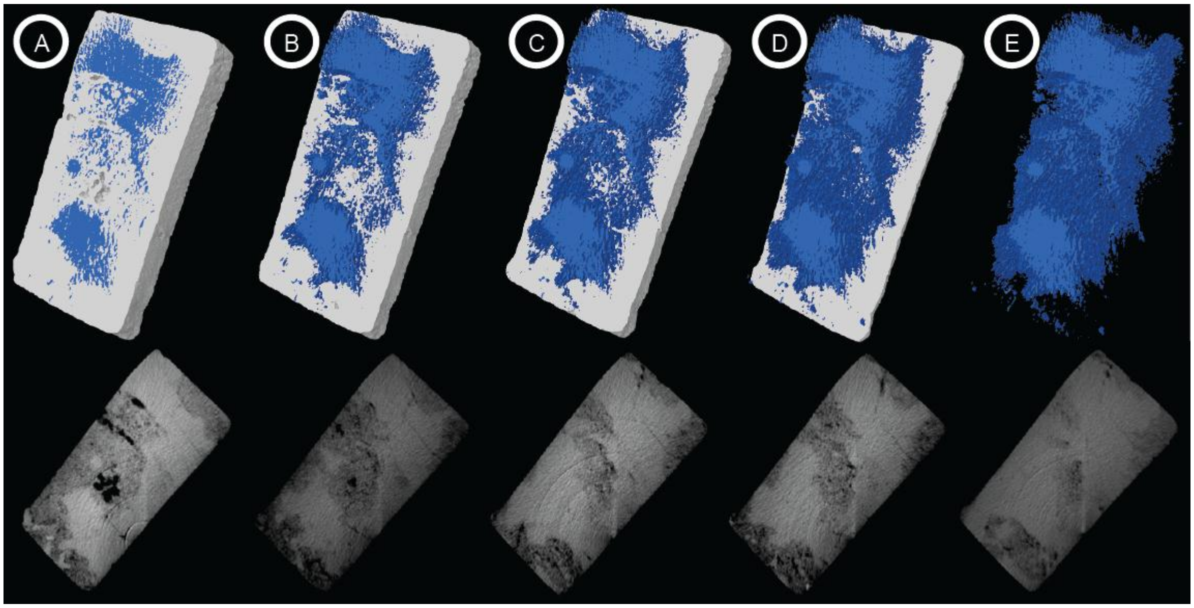

Figure 3: Micro-CT scans at 34 μm resolution from well 10-10-57-19W5M (3180.32m depth). The images at the top represent 3-D visualization of mineral phases through different cross-sections of the samples (A through E). The burrows are dark blue, matrix is grey, and porosity is the unfilled holes. The images at the bottom are the two-dimensional (2-D) cross-sections (burrows are light grey, matrix is dark grey, and porosity is the black space).

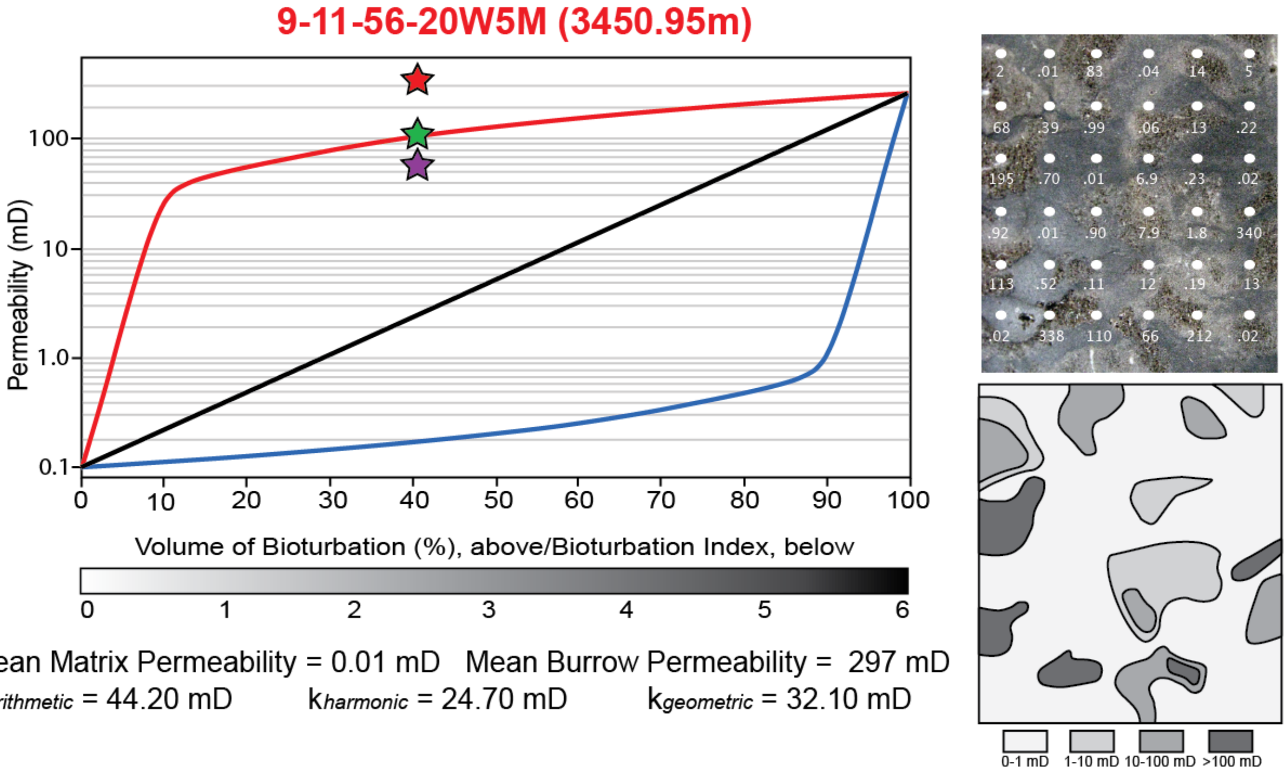

Figure 4: Spot-permeametry of bioturbated fabrics. Within the above sample, the red line is the arithmetic mean, black line is the geometric mean, and the blue line is the harmonic mean. In this example, bioturbation intensity is ~40% (BI ≈ 2.5) in the core sample. From the contour map, it is apparent that the higher permeabilities are localized within the burrows. At 40% bioturbation, the reservoir permeability averaged by the arithmetic mean is ~100 mD (green star). This is within one order of magnitude to the 44.20 mD predicted by the $K_{arithmetic}$ for the reservoir (purple star). The difference is likely due to unconnected burrow networks that act as dead end conduits and effectively decrease the true permeability of the reservoir. The red star (310mD) represents the permeability value for the interval calculated by core laboratories.