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Impact of Bioturbation on Reservoir Quality: A Case Study of Biogenically Reduced Permeabilities of Reservoir Sandstones of the Baram Delta, Sarawak, Malaysia

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Abstract: Baram Delta is one of seven geologic provinces in the Sarawak basin and is the most prolific. Bioturbation is an important source of reservoir heterogeneity and has an impact on porosity and permeability of reservoir sandstones. There is still a lack of knowledge on the impact of bioturbation on porosity-permeability characteristics of reservoir rocks in the Baram Delta therefore this study is aimed at evaluating the impact of bioturbation on porosity and permeability of reservoir rocks of the Baram Delta. Reservoir sandstones were analyzed using thin sections, spot permeability, scanning electron microscopy and energy dispersive x-ray. Sample, S1, from the studied core interval is dominated by *Diplocraterion* ichnofabric. S1 is highly to intensely bioturbated with bioturbation index between 60-99%. Spot permeability values range between 158-381 mD in the host sediment and 33.8-176 mD in the burrow and burrow lining, respectively. This represents a permeability decrease of 78% between host sandstone and burrow. Sediment packing activity was observed in S1. Sediment packers incorporate iron oxides, clays and organic matter from the host sandstone into burrow fills and linings, thereby decreasing isotropy and sorting of the sediments resulting in a reduction of porosity and permeability locally in the burrow relative to the host sandstone.

Key words: Scanning electron microscope, sediment, sandstone, bioturbation

INTRODUCTION

Bioturbation is defined as all kinds of displacements within sediments and soils produced by the activity of organisms and plants (Richter, 1936). Bioturbation can redistribute grains and cause sorting or mixing and this physical modification of the primary sedimentary fabric causes changes to porosity and permeability in reservoir facies (Tonkin *et al*., 2010). Taylor and Goldring (1993) defined the term Bioturbation Index (BI) as the grade to be allocated to the degree of bioturbation and this index integrates the sedimentology and ichnology, where the higher grades of bioturbation result from increased burrow overlap and the subsequent loss of the primary sedimentary fabric. In highly bioturbated reservoir facies, bioturbation can be the most important source of heterogeneity and the most important control on petrophysical properties (Tonkin *et al*., 2010). When characterizing a bioturbated reservoir, detailed account of the degree of bioturbation, its effect on reservoir quality (porosity and permeability) and ichnofabrics (fabric resulting from animal-sediment interactions) in both core and laboratory studies is important. Some important bioturbated siliciclastic reservoirs include the Lower Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada and Lower Cretaceous McMurray Formation, Alberta, Canada (Tonkin *et al*., 2010).

Tonkin *et al*. (2010) classified the action of bioturbators into sediment mixing, sediment cleaning, sediment packing, pipe-work building and sediment packing, combination of sediment cleaning and packing and combination pipe-work building and sediment packing. They further suggested that sediment packing and sediment mixing styles commonly reduce porosity/permeability while sediment cleaning bioturbation style enhances porosity/permeability. The general belief is that bioturbation reduces permeability of sedimentary strata because biogenic churning of laminated sediment lowers the sorting of the sediment preserved within the laminae (Gingras *et al*., 2012), however, several examples of enhanced permeability as a result of bioturbation have also been reported (Dawson, 1978; Gingras *et al*., 2004; Pemberton and Gingras, 2005; Gordon *et al*., 2010;Tonkin *et al*., 2010). Bioturbation is commonly overlooked in intensely bioturbated media because of a

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lack of lithological definition and because of the complex fabrics that are sometimes present (Gingras *et al*., 2012).

Even though previous researchers such as Tan *et al*. (1999) identified bioturbated horizons in the Baram Delta, a detailed study of bioturbation and its influence on reservoir sandstones in the Baram Delta has not been thoroughly discussed in any literature. The objective of this study, therefore, is to study cores within the petroliferous cycles V and VI reservoir sandstones of the Baram Delta, offshore Sarawak, Malaysia and to access the influence of animal-sediment interactions (bioturbation) on these reservoir sandstones. The research focuses on porosity and permeability modifications induced by mud lined Diplocraterion ichnofabrics which is the dominant ichnofabric within the studied interval.

GEOLOGIC SETTING

The Baram Delta is one of the seven geological provinces found offshore the Sarawak Basin and is the most prolific of all the geological provinces in the basin (Tan *et al*., 1999). The area which consists of nine fields was discovered in 1969 and is estimated to have more than 400 million stock barrels of oil in place with multiple stacked sandstone reservoirs in a shallow offshore environment (Sudirman *et al*., 2007). The Baram Delta was formed on an active continental margin with its shape and size suggesting that it may have developed initially as a pull apart basin whose length and width were pre-determined by its bounding faults (Sudirman *et al*., 2007). The offshore stratigraphy of the Baram Delta is characterized by the occurrence of coastal to coastal-fluviomarine sands which have been deposited in a northwestwards prograding delta since the Middle Miocene (from Cycle IV onwards) with the Cycle V (Middle to Upper Miocene) to Cycle VII (Upper Pliocene) being well developed and prograding over thick diachronous pro-delta shales (Ho, 1978; Tan *et al*., 1999; Hutchison, 2005).

Tremendous spatial and temporal variations have been observed in the formations in the Baram Delta (Ramli and Padmanabhan, 2011). Lambiase *et al*. (2002) also identified heterogeneities in reservoir sandstones of the Baram Delta and identified five sedimentary facies. These five facies are cohesive mud, soft mud, sandy mud, muddy sand and sand and were characterized based primarily on lithology, grain size and sedimentary structures. Tan *et al*. (1999) identified three sandstone sub-facies in the Baram Delta namely poorly-stratified sandstones, bioturbated sandstones and low-angle/ parallel laminated to hummocky cross-stratified sandstone.

MATERIALS AND METHODS

Cored interval from wells in the Baram Delta have been studied. For this purpose, the well will be referred to as W1. 30 m of core from well W1 between 1473 and 1503 m. Sample 1 (S1) was sampled between 1478-1479 m (Fig. 1). The studied interval is characterised by mud lined Diplocraterion ichnofabrics (Ben-Awuah and Padmanabhan, 2013). Core logging was carried out with emphasis on texture (sorting, grain size and grain size distribution), micro structures, colour, fossils and mineralogy. Colour description was done using a Munsell colour chart.

About 2×4 cm slices of core were cut from the core slab surface to make thin sections. Grain size estimate and degree of grain sorting were obtained from the thin sections.

Samples of 2×2 cm dimension of core slab was taken for Scanning Electron Microscopy (SEM). High magnification photomicrographs of the sample was taken for enhanced description of texture and microstructures in the bioturbated zones and the host sandstones. The SEM analysis was done using a Carl Zeiss Supra 55VP FESEM with variable pressure ranging from 2-133 Pa and probe

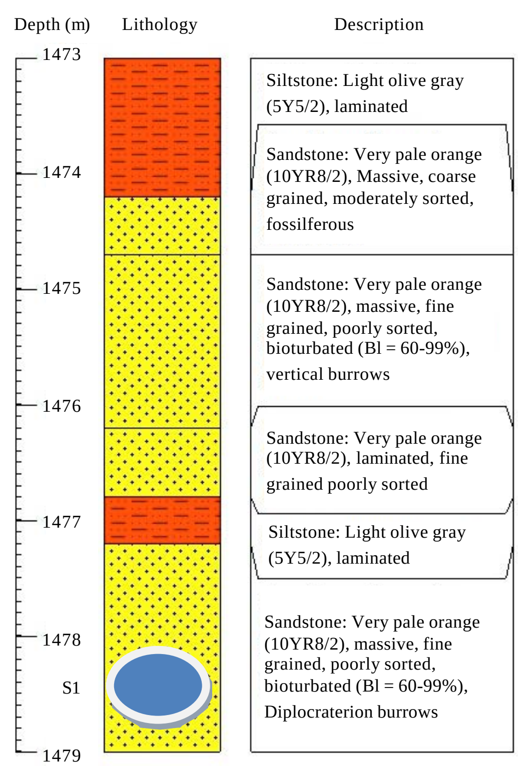

Fig. 1: Simplified graphic log of well BD01 showing lithofacies distribution and sample point (S1) of well W1

current between 1-10 nA. Energy Dispersive X-ray spectroscopy (EDX) of specific points in the sample was taken to determine the elemental composition at these points.

Spot/probe permeability measurements were measured using a CoreLab Profile Decay Permeameter (PDPK™ 300 system). The spot permeameter measures permeability by injecting nitrogen gas into the rock at probe pressure of 20 psi and a test (nitrogen gas) pressure of 6 psi. A probe tip with a diameter of 5 mm was used. A software attached to the equipment calculated the permeability in milli darcies (mD) using an appropriate form of Darcy's equation modified by the half-space solution of geometrical factor (Go) as a function of the probe-tip seal thickness (Goggin *et al*., 1988). A geometric factor (Go) of 1.83 was used in this experiment. A grid pattern was drawn on the core slab and permeability measured at points on the grid. To ensure accurate values as possible, 3-5 points are taken at each point on the grid and the average values are taken. Anomalous values which may be as a result of leakage of the nitrogen gas during the measurement are discarded.

RESULTS AND DISCUSSION

Sedimentology and depositional environment: Well W1 is made up of three main lithofacies: Sandstones, siltstones and mudstones. The dominant lithofacies in the cored interval is the sandstones which consist of three subfacies; massive sandstones, laminated sandstones and bioturbated sandstones. The bioturbated zones are characterized by the presence of Diplocraterion dominated ichnofabrics. Sample, S1 which is from the bioturbated sandstones within the cored interval of this well is very pale orange (10YR8/2) in colour, fine grained, massive structured, well indurated and well sorted (Fig. 2). Bioturbation intensity of sample S1 ranges between 60-99% which can be characterized as intense bioturbation after (Taylor and Goldring, 1993) bioturbation index classification scheme. Sandstones of variable degrees of bioturbation from no-low bioturbation intercalates the high to intense bioturbated zones. Sparsely bioturbated lithofacies within bioturbated intervals are interpreted as beds which were deposited during periods of intense hydrodynamic

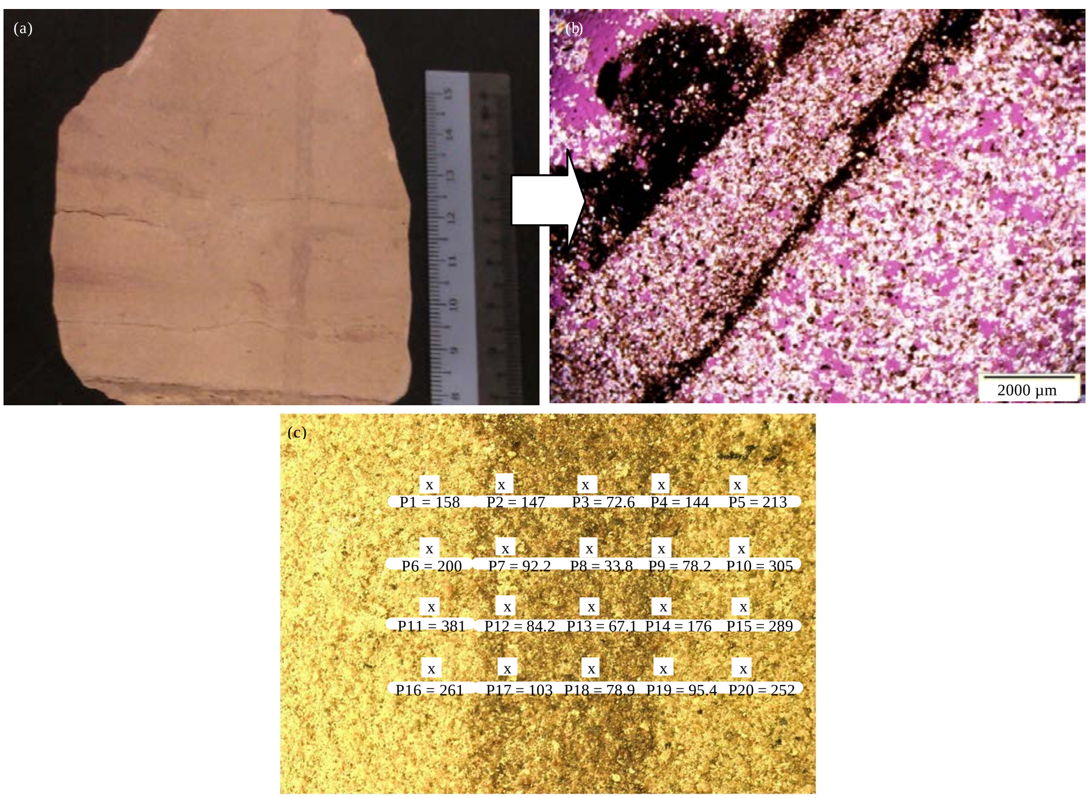

Fig. 2(a-c): (a) Core slab of sample S1 showing Diplocraterion burrow, (b) Thin section of sample S1 showing vertical burrow with porosity as violet and dark colour as organic matter, iron oxides or pyrite sediments, (c) Core slab of sample S1 with spot permeability distribution in host sandstone and burrow activity (Aigner, 1985). Such intense hydrodynamic activity hinders animal-sediment interactions resulting in no-low bioturbation within intervals of the well deposited during such periods. The depositional environment is therefore characterized by alternating periods of high hydrodynamic activity (high energy) during which there is no-low bioturbation and low hydrodynamic activity (low energy) during which there is intense to complete bioturbation. Such depositional environments are characteristic of moderate energy shoreface environment.

Porosity and permeability of host sandstone and mud-lined Diplocraterion burrow: EDX data of sample S1 from well W1 indicates a sandstone composition predominantly made up of quartz and minor amount of calcite and iron oxides (Fig. 3a, b). The EDX data from the Diplocraterion burrow indicates fill material made up of very high amount of iron oxides, clay and quartz (Fig. 3d, f). Thin section analysis show poorer grain sorting within the burrow and burrow lining compared to the host sandstone (Fig. 2b). The SEM images show the presence of kaolinite and iron sulphides in the presence of pyrite (FeS_2) within the burrow (Fig. 3c, e). Visual assessment of the core slab surface shows organic matter trapped within the burrow (Fig. 2a). Burrowing organisms secrete mucus as they move through the sediment, use mucus to trap organic matter or fine grains, or incorporate detritus (mud or sand) to create a burrow wall or lining (Bromley, 1990). The clay-organic matter-iron oxides fill in the burrow suggests a sediment packing bioturbation style that normally reduce porosity and permeability. Concentration of this fill material into burrow linings and burrows usually takes place during feeding activity of organism in the sediment. Sediment packers incorporate fine grade material (e.g., clay and organic matter) from the host sediment into burrow fills and/or linings decreasing isotropy and sorting of the sediment and locally reducing permeability (Tonkin *et al*., 2010).

The burrow making organism created localized zones of porosity and permeability reduction. Spot permeability measurements confirms this observation indicating higher permeability values in the host

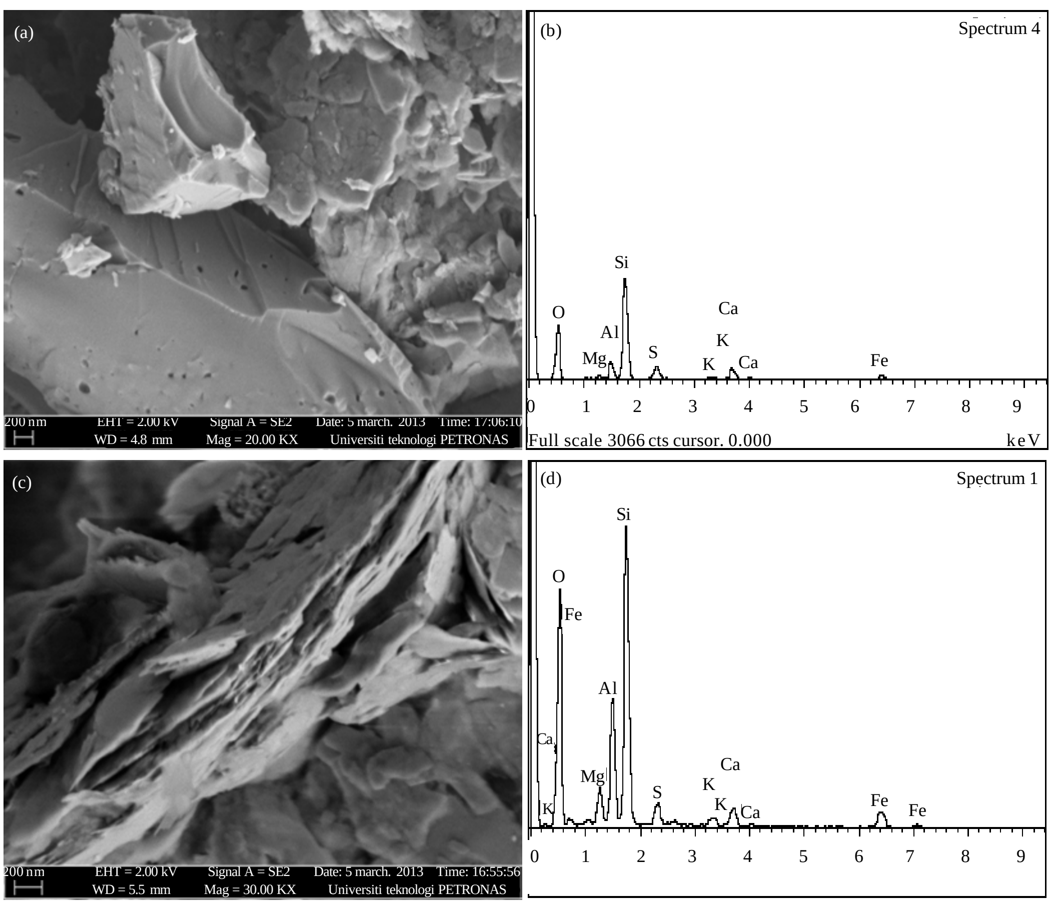

Fig. 3(a-f): Continue

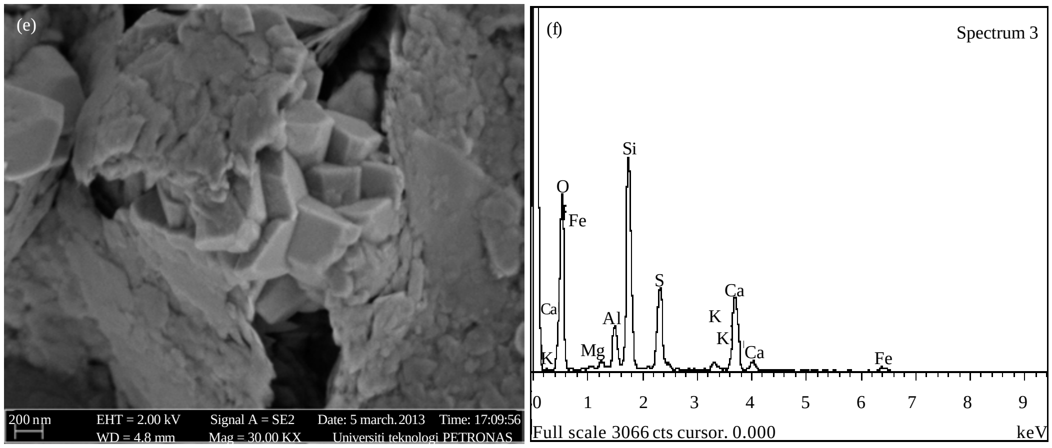

Fig. 3(a-f): (a) FESEM of host sandstone showing quartz crystals, (b) EDX of host sandstone showing cleaner quartz crystals, (c) FESEM of burrow fill showing the presence of pyrite, (d) EDX of burrow fill showing high amount of iron oxides, (e) FESEM of burrow fill showing kaolinite and (f) EDX of burrow fill showing the presence of iron sulphide (pyrite)

Table 1: Permeability distribution in sample S1

Points	Permeability (mD)	Point location
P1	158	Host sediment
P2	147	Burrow lining
P3	72.6	Burrow fill
P4	144	Burrow lining
P5	213	Host sediment
P6	200	Host sediment
P7	92.2	Burrow lining
P8	33.8	Burrow fill
P9	78.2	Burrow lining
P10	305	Host sediment
P11	381	Host sediment
P12	84.2	Burrow lining
P13	67.1	Burrow fill
P14	176	Burrow lining
P15	289	Host sediment
P16	261	Host sediment
P17	103	Burrow lining
P18	78.9	Burrow fill
P19	95.4	Burrow lining
P20	252	Host sediment

sediments which decreases towards the burrow margins and is lowest inside the burrow (Fig. 2c). Permeability values in the host sediment range between 158-381 mD whereas permeability in the burrow and burrow lining ranges between 33.8-176 mD (Table 1). This represents a permeability decrease of 78% between host sandstone and burrow.

CONCLUSION

Bioturbation in sediments and sedimentary rocks results in a variety of trace fossils and microstructures. The organisms rework the sediments, mineral grains and organic matter to alter the primary fabric of sedimentary rock. Bioturbation can decrease porosity and permeability by unsorting sediments and mineral grains . The porosity and permeability of the bioturbated sandstones is dependent on the activity of the burrowing organism and the burrow fill material. Sediment packing activity is observed in sample S1. Sediment packers incorporate fine grade material (clay and organic matter) from the host sediment into burrow fills and/or linings decreasing isotropy and sorting of the sediments in the burrow. This results in a reduction of porosity and permeability locally in the burrow relative to the host sandstone as observed in sample S1. A permeability reduction of 78% in the burrow over the host sandstone is recorded.

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