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RESEARCH PAPER

Effect of bioturbation on reservoir rock quality of sandstones: A case from the Baram Delta, offshore Sarawak, Malaysia

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Abstract: With the Baram Delta in Malaysia as research subject, the effect of bioturbation on porosity and permeability of reservoir sandstones is evaluated and analyzed based on core and thin section analysis, EDX (energy-dispersive X-ray), FESEM (Field Emission Scanning Electron Microscope), mercury porosimetry and spot permeametry measurement. Samples are from cored intervals of two wells in the Baram Delta, W-1 and W-6. Analysis results indicate that the cored intervals in well W-1 are dominated by Diplocraterion ichnofabrics, intensely bioturbated, sediment packing activity is observed, and fine grade materials (clays and organic matter) from the host sediment are incorporated into burrow fills and linings, thereby decreasing isotropy and sorting of the sediments and reducing the local porosity and permeability in the burrows. The cored intervals in well W-6 are dominated by Ophiomorpha ichnofabrics, highly to intensely bioturbated, sediment cleaning activity by burrowing organisms results in cleaner and well sorted burrow fill materials, and clays and mud are cleaned from the burrow fill and host sediment and concentrated in the burrow linings. Porosity and permeability of reservoir rocks in the Baram Delta have therefore either been enhanced or reduced by bioturbation depending on the type of burrow, fill material and burrowing activity.

Key words: Baram Delta; Sarawak basin; bioturbation; ichnofabric; burrows; rock heterogeneity; porosity; permeability; Ophiomorpha; Diplocraterion

Introduction

Bioturbation is defined as all kinds of displacements within sediments and soils caused by the activity of organisms and plants[1]. Bioturbation can alter the substrate physically by mixing or redistributing grains, leading to homogenization, or new structures by compaction, dewatering, sorting (biostratification), emplacement (biodeposition) and removal (bioerosion)[2]. Bioturbation could take place during sediment deposition or after rock formation. The changes in the original physical sedimentary fabric cause changes to porosity and permeability of reservoirs, and in highly bioturbated reservoir facies belts, bioturbation can be the paramount factor controlling petrophysical properties[3]. Combining sedimentologic and ichnologic signs, Taylor et al.[2] advanced bioturbation index (BI) to characterize the degree of bioturbation. Superimposition of burrows and the subsequent damage to the primary sedimentary fabric would increase the intensity of bioturbation. Fabrics formed as a result of bioturbation are known as ichnofabrics.

Rock heterogeneity refers to the changes of rock physical properties in lateral and vertical directions, for example, porosity, permeability and capillary[4–6]. Reservoir heterogeneity in sandstone bodies occur at various extents and scales, ranging from micrometers to hundreds of meters, and is commonly attributed to variations in depositional facies, diagenesis, and structural features such as the presence of fractures and faults[7]. Bioturbation is one source of micro-heterogeneity in sandstone reservoirs, which influences grain sorting, grain size distribution and isotropy. For sedimentary areas experienced bioturbation, a very important part of facies analysis and reservoir characterization are description and interpretation of bioturbation and ichnofabrics in conventional cores[8]. Bioturbated siliciclastic reservoirs make up an important part of reservoir sandstones all over the world, mainly including the Middle Jurassic Brent Group, North Sea, United Kingdom and Norway[9–10], Lower Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada and Lower Cretaceous McMurray Formation, Alberta, Canada[3], Cycles VI and VI reservoir sandstones of the Baram Delta, Offshore Sarawak, Malaysia[11].

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Generally, it is assumed that bioturbation reduces permeability of sedimentary strata because biogenic churning of laminated sediment lowers the sorting of the sediment preserved in the laminae[12]. However, several examples of enhanced permeability as a result of bioturbation have been reported[13–16]. Tonkin et al.[3] classified the action of bioturbation organisms into six types, namely, sediment mixing, sediment cleaning, sediment filling, pipe-work building and sediment filling, combination of sediment cleaning and filling, and combination of pipe-work building and sediment filling. Sediment filling and sediment mixing type bioturbation commonly reduce porosity/permeability by reducing sorting, while sediment cleaning bioturbation enhances porosity/permeability by enhancing sorting. The effects of the rest three types of bioturbation on reservoir physical properties are highly dependent on the lithological differences between burrow fillings and its enclosing substrate[3].

The main reservoir sandstones of the Baram Delta are the cycles V and VI coastal to coastal-fluviomarine sandstones[17]. Cores from two fields in the Baram Delta have been studied from the petroliferous cycles V and VI reservoir sandstones. Even though previous researchers identified bioturbated horizons in the Baram Delta[11, 18], there is not a comprehensive study on bioturbation and its influence on sandstone reservoirs in the Baram Delta. This study is aimed at evaluating the influence of animal-sediment interactions (bioturbation) on the porosity and permeability of sandstone reservoirs in the Baram Delta, offshore Sarawak, Malaysia.

1. Geologic Setting

The Baram Delta is one of seven geological provinces found offshore the Sarawak Basin and the most oil and gas prolific of all the geological provinces in the basin[11] (Fig. 1). The delta discovered in 1969 is estimated to contain more than 0.48×10^8 m^3 of oil in place with multiple stacked sandstone reservoirs in a shallow offshore environment. Formed at active continental margin[19–21], the shape and size of Baram Delta suggest that it may have developed initially from a pull-apart basin whose length and width were pre-determined by its bounding faults[11]. Nine fields have been found in Baram Delta, which, after over 30 years of production, reached an average recovery factor of about 30%[22–23].

The offshore formations of the Baram Delta (BD) include coastal to coastal-fluviomarine sands deposited in a northwestward prograding delta since the Middle Miocene (from Cycle IV onwards), in which the Cycle V (Middle to Upper Miocene) to Cycle VII (Upper Pliocene) are the most developed[17,11,24].

Bioturbation has been identified as a major cause of reservoir heterogeneity in the study area[25]. The sandstone deposited in a shallow marine environment is associated with bioturbation. Bioturbation is controlled by the intensity of hydrodynamic activity at the delta: high hydrodynamic activity is associated with a lower intensity of bioturbation, whereas low hydrodynamic activity is associated with high hydrodynamic activity.

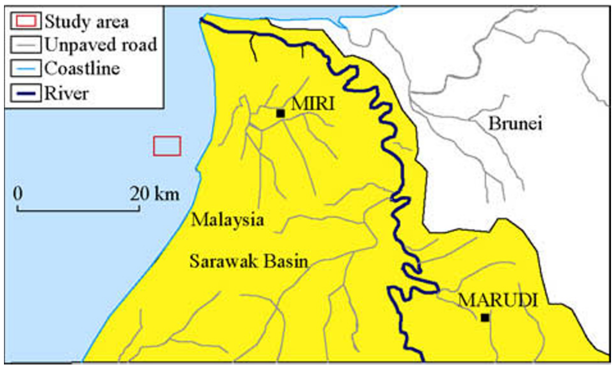

Fig. 1. Location of the Sarawak basin and the study area[19–21].

Sandstone core samples taken from Baram delta have obvious bioturbation features: abundant vertical and horizontal burrows of different textures and colors resulting from the activity of burrowing organisms, which is discerned easily, make the bioturbated sandstones apparently distinct from non-bioturbated sandstones. Some researchers identified three sandstone sub-facies in the Baram Delta, namely poorly- stratified sandstone, bioturbated sandstone and low-angle/parallel bedding to hummocky cross-bedding sandstone[11], also identified bioturbated facies as one of the major facies in the Baram delta[18, 26]. The focus of this paper is the bioturbated sandstone. The different types of burrows depend largely on the types of burrowing organisms and burrowing activity.

2. Materials and methods

Core samples used in this study were taken from two wells (W-1 and W-6) in two fields in the Baram Delta (Cycle V and VI), with bioturbation intensity ranging from no bioturbation (BI = 0) to intense bioturbation (BI = 60-99%)[25]. *Ophiomorpha* and *Diplocraterion* burrows are the most conspicuous ichnofabrics in the core samples, this research will therefore be concentrated on the effects of them on porosity and permeability. A combination of thin section observation, scanning electron microscopy (SEM), mercury porosimetry and spot permeametry measurements were conducted on the core samples.

A 30 m long core sample taken from W-1 (1 473 m–1 503 m) and another 221 m core sample from W-6 between 1581 m and 1 803 m were used in this study (Fig. 3). Specimen 1 (S1) was taken between 1 477 m–1 478 m from W-1 (Fig. 2) and specimen 2 and 3 (S2 and S3) were taken between 1 682 m–1 683 m and 1 689.5 m–1 690 m respectively from W-6 (Fig. 3). Each of the cored intervals is characterized by variable degrees of bioturbation. Sedimentological core logging has been carried out for both wells to observe the texture (sorting, grain size and grain size distribution), micro-structures, colour, fossils and mineralogy. Colour description was done using a Munsell colour chart. 2 cm × 4 cm slices of core were cut from the core slab surface to make into thin sections. Sorting was estimated

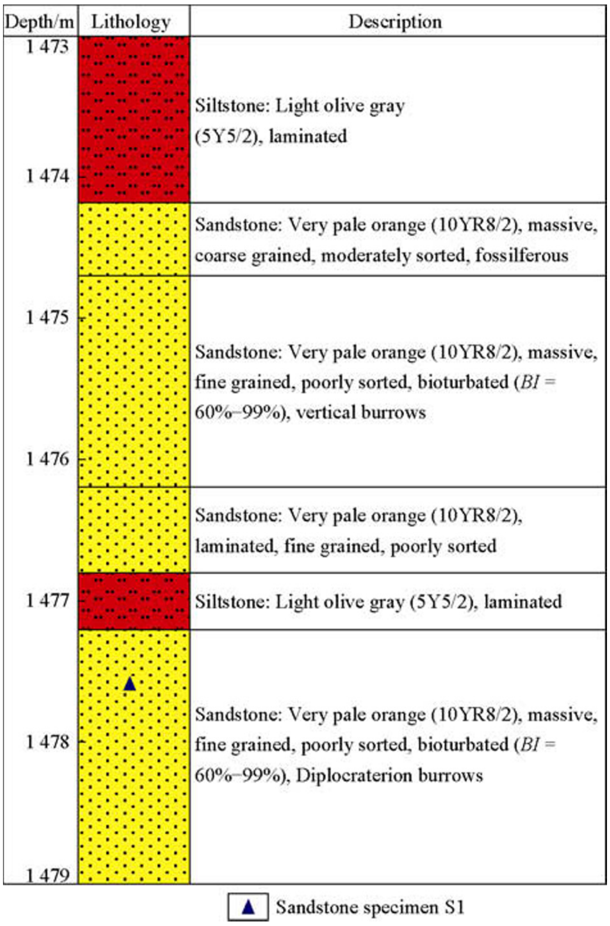

Fig. 2. Simplified graphic log of Well W-1 showing lithofacies distribution and bioturbation intensity.

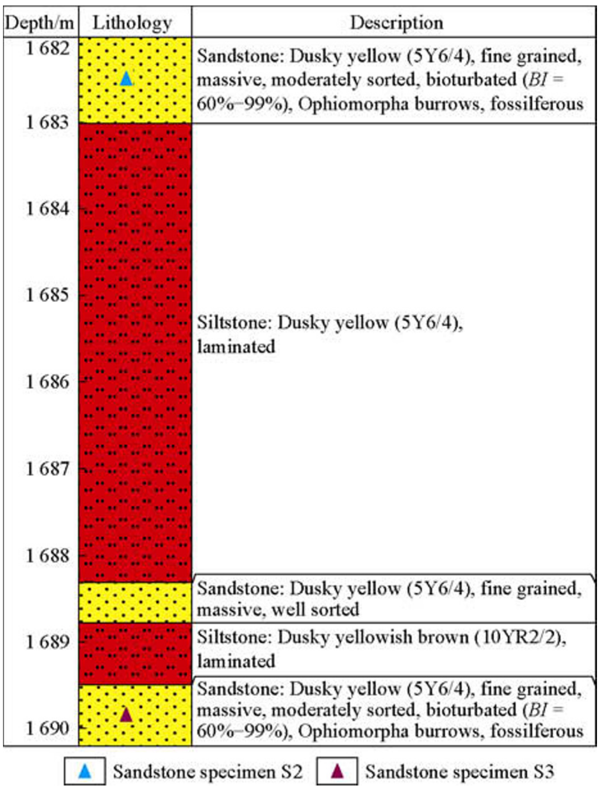

Fig. 3. Simplified graphic log of Well W-6 showing lithofacies distribution and bioturbation intensity.

visually by comparing to a standard sorting comparison chart[27], grain size was also assessed from the observation of thin sections.

Spot/ probe permeability was measured using a CoreLab Profile Decay Permeameter (PDPK^{TM} 300 system). The spot permeameter with a probe tip 5 mm in diameter[28], 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 software attached to the equipment calculated the permeability in milli-darcies (10^{-3} μm^2) 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[12, 29]. 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 nodes on the grid. To ensure accuracy of the values, each point on the grid was measured 3-5 times and the average value was taken. Anomalous values could occur due to leakage of nitrogen gas, which should be removed during the analysis.

A 1 cm × 1 cm cube was cut out of each sample for mercury porosimetry experiment, which was done on a Thermo Scientific PASCAL 240 Series Mercury Porosimeter. In the porosimetry experiment, mercury 13.5 g/cm^3 in density was injected into the sample at increasing pressure from 0 MPa to a maximum pressure of 200 MPa at the test temperature of 25 °C. The porosity of the sample was then measured based on the volume of mercury filling the sample with the gradual increase of pressure.

A specimen of 2 cm × 2 cm from each core slab was taken for scanning electron microscopy (SEM). High magnification photomicrographs of each specimen were taken to better describe the texture and microstructures in the bioturbated zones and the host sandstone. The SEM analysis was done using a Carl Zeiss Supra 55VP FESEM with a pressure ranging from 2 Pa to 133 Pa and probe current between 1 pA to 10 nA. Energy dispersive x-ray spectroscopy (EDX) of specific points in the specimens was taken to determine the elemental composition at these points.

3. Results and discussion

3.1. Bioturbated facies in the Baram Delta reservoirs

Bioturbation is an important source of rock heterogeneity in reservoir rocks of the Baram Delta. Ichnofabric analysis is a very important part in evaluating the petrophysical properties of such bioturbated facies. The major paleoenvironmental factors affecting bioturbation include sedimentation rate, salinity, turbidity, oxygenation, substrate consistency, hydrodynamic energy and event bed deposition[30]. Physical processes that influence sediment deposition, transport and reworking at the delta's coastline control the bioturbation intensity, diversity and distribution of ichnology. Bioturbation is a common phenomenon in most shallow marine environments. Phyico-chemical parameters affecting bioturbation in such shallow marine environments include grain size, turbidity, light, temperature and sediment supply while biological constraints include salinity tolerance of the tracemakers, food supply and burrow morphology[3]. Differences in these physico-chemical processes in the delta controls the types and abundance of trace fossils.

The distribution of trace fossils is intrinsically linked to hydrodynamic energy in all depositional environments. Variations in the intensity of hydrodynamic activity in the delta results in the abundance of trace fossils in some sections of the wells and lack of trace fossils in other sections of the wells. Well W-1 near shore is dominated by the presence of *Diplocraterion* burrows whereas Well W-6 is dominated by *Ophiomorpha* burrows. Shoreface and proximal deltaic facies feature high hydrodynamic energy and rapid sedimentation rate, which are favourable for the creation of *Diplocraterion* ichnofabric observed in Well W-1; while relatively lower hydrodynamic energy and slow sedimentation rate favour the creation of *Ophiomorpha* ichnofabric (for example). While *Diplocraterion* burrows are vertical in morphology, *Ophiomorpha* burrows are a combination of vertical and horizontal burrows. The burrow fillings of *Diplocraterion, Ophiomorpha* and other trace fossils are largely controlled by the depositional environment and feeding modes of the burrow making organisms. Variations in feeding habits would result in the difference of sand or mud fillings in the burrows (of various sorting degree), which in turn influence the porosity and permeability of the host sediments and burrows. It is inferred that the feeding behaviours of trace fossil assemblages in shallow marine environments such as the Baram Delta represent a mixture of suspension, gardening, scavenging and deposit feeding[31–32].

3.2. Bioturbated sandstone in Well W-1

3.2.1. Sedimentologic features and ichnofabric

There are three main lithofacies in Well W-1: sandstone, siltstone and mudstone. The dominant lithofacies in the cored interval is sandstone which consist of three subfacies; massive sandstone, laminated sandstone and bioturbated sandstone.

The bioturbated zones are characterized by the presence of *Diplocraterion* dominated ichnofabrics. Specimen, S1 taken from the bioturbated sandstone in the cored interval of this well is dark greyish orange (10YR8/2) in colour, fine grained, massive and well consolidated, with bioturbation intensity of 60-99%, which is identified as intense bioturbation on the bioturbation classification scheme[2].

Weakly bioturbated lithofacies in the bioturbated intervals are interpreted as beds deposited during periods of intense hydrodynamic activity[33], because intense hydrodynamic activity hinders animal-sediment interaction, resulting in no or low bioturbation in 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 was no or low bioturbation and low hydrodynamic activity (low energy) during which there was strong bioturbation. Moderate energy shoreface environment is a typical example of such environment. The alternating laminae of mud and sand reflect the alternating of low and high energy depositional environments. The laminated sandstone has wavy beddings with planar laminae, and laminated siltstone commonly overlies sandstone.

Specimen S1 is a fine grained sandstone dominated by quartz, with minor amount of clays and iron oxides. Thin section observation shows the grains are moderately sorted, sub-angular to sub-rounded, and the main pores are primary intergranular pores. There is a variation in grain density between the burrow fillings and sandstone matrix (Fig. 4B), the grain density is higher in the burrows than in the matrix. The major diagenetic processes in the sample appears to be mechanical compaction evidenced by a lack of cement and distinct grain edges.

3.2.2. Porosity and permeability of sandstone and *Diplocraterion* burrows in W-1

EDX data of S1 indicates a sandstone composition predominantly made up of quartz and minor amount of calcite and iron oxides (Figs. 4D and 4G). EDX data from the *Diplocraterion* burrows indicates fillings are made up of very high content of iron oxides, clay and quartz (Figs. 4C and 4F). Thin section analysis show poorer grain sorting in the burrows and burrow lining than the host sediments (Fig. 4B). SEM images show the presence of kaolinite and pyrite (FeS_2) in the burrows (Figs. 4H and 4I). Visual assessment of the core slab surface found organic matter trapped in the burrows (Fig. 4A). Burrowing organisms secrete mucus as they move through the sediments, which would capture organic matter or fine grains, or combine with detritus (mud or sand) to create the burrow wall or lining[34]. The clay-organic matter-iron oxides fillings in the burrow suggests a sediment mixing/packing bioturbation type that normally reduce porosity and permeability. Fillings in burrow linings and burrows build up with the feeding activity of organisms in the sediments. This sediment mixing type bioturbation taking in fine grains (e.g., clay and organic matter) from the host sediments into burrow fillings and/or linings, decreases isotropy and sorting of the sediments and locally reduces permeability[3]. The burrow making organism caused localized reduction in porosity and permeability. Porosity data from mercury porosimetry shows the host sediments have a porosity of 27%, while fillings in the burrows have a porosity of 24%. Spot permeability measurement also confirms this point, permeability of the host sediments is the highest of $(158–381)\times10^{-3}$ μm^2, that of sediments in the burrow linings in the second place, and that of sediments inside the burrows lowest. The latter two kinds of sediments have a combined permeability of $(33.8–176)\times10^{-3}$ μm^2 (Table 1), representing a permeability decrease of 78% from host sediments to burrow fillings.

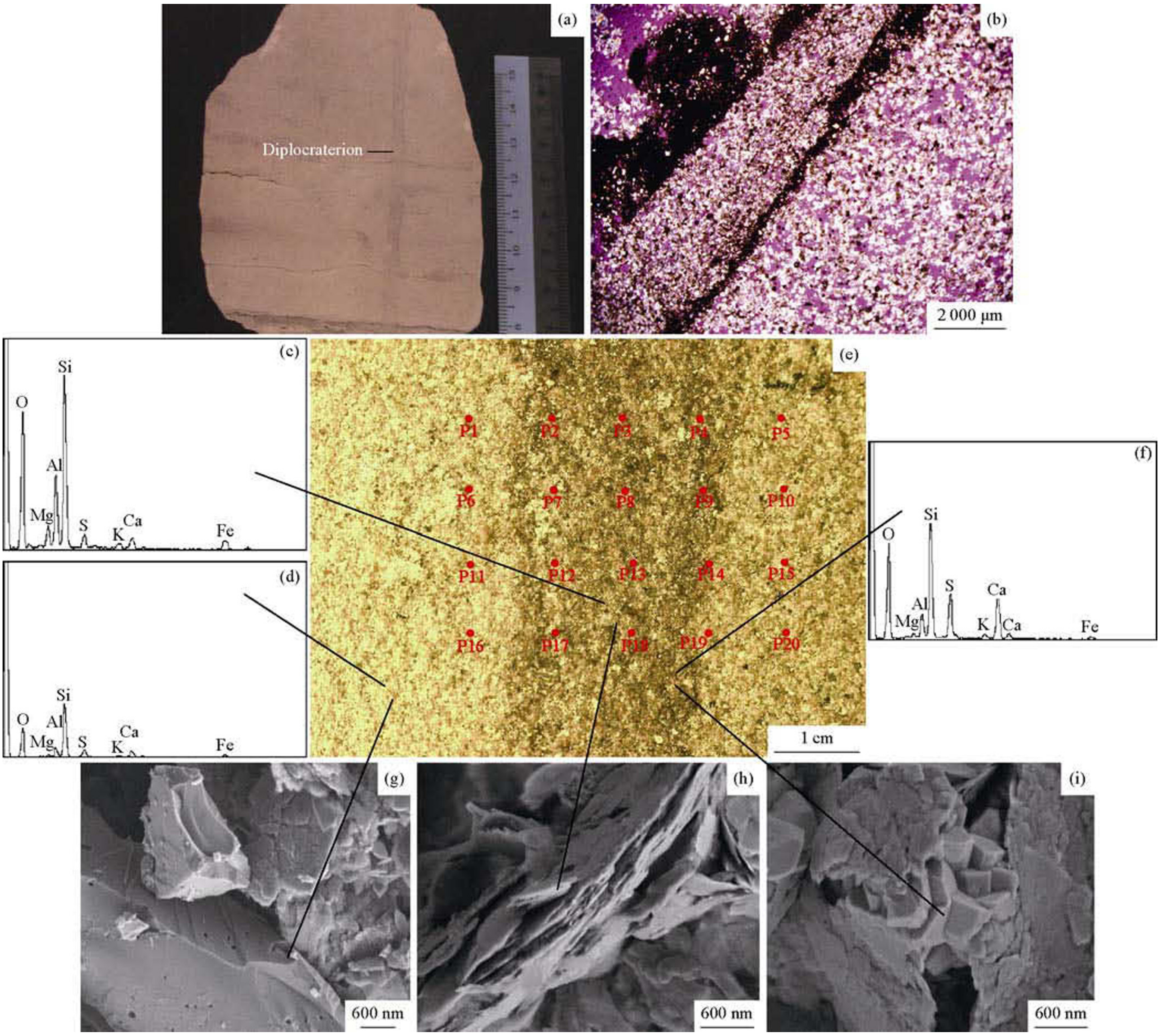

Fig. 4. (a) Core slab of specimen S1 showing *Diplocraterion* burrow; (b) thin section of specimen S1 showing vertical burrow, with porosity in violet and organic matter, iron oxides or pyrite in dark colour; (c) EDX of burrow fillings showing high amount of iron oxides; (d) EDX of host sandstone showing cleaner sediments; (e) core slab of specimen S1 showing measuring points of spot permeability in host sandstone and burrow; (f) EDX of burrow fillings showing the presence of iron sulphide (pyrite); (g) FESEM of host sandstone showing quartz crystals; (h) FESEM of burrow fillings showing kaolinite; (i) FESEM of burrow fillings showing the presence of pyrite.

3.3. Bioturbation of sandstone in Well W-6

3.3.1. Sedimentologic features and ichnofabric

There are three main lithofacies identified in Well W-6: sandstone, siltstone and mudstone. The sandstone facies can be further subdivided into massive, laminated, fossilferous and bioturbated sandstones.

Both taken from the bioturbated interval, S2 and S3 used in this study are yellowish gray (5Y6/4), massive structured, well consolidated and moderately sorted. With bioturbation intensity from 61–99%, they are identified as highly to intensely bioturbated according to the bioturbation index classification scheme[2]. The bioturbated interval is characterized by circular mud lined *Ophiomorpha* burrows.

Specimen S2 and S3 are fine grained sandstone made up of quartz and clay, medium-good in sorting, sub-angular to sub-rounded in grain shape, with primary intergranular pores as the main reservoir space. Similar to specimen S1, mechanical compaction is the major diagenetic process evidenced by distinct grain edges.

3.3.2. Porosity and permeability of host sediments and *Ophiomorpha* dominated burrow mottled ichnofabric in W-6

The dominant ichnofabric in specimens S2 and S3 are mud-lined *Ophiomorpha* burrows (Figs. 5A and 6A). EDX data shows both S2 and S3 are composed of large amount of quartz and minor calcite (Figs. 5C and 6D). EDX data at the burrow linings and burrow walls show the presence of high content of iron oxides and clay (Figs. 5D and 6E), which is confirmed by analysis of the thin sections. These minerals

Table 1. Permeability distribution in specimen S1.

Point No.	Permeability/10^{-3} μm^2	Point location
P1	158	Host sediment
P2	147	Burrow lining
P3	72.6	Burrow fillings
P4	144	Burrow lining
P5	213	Host sediment
P6	200	Host sediment
P7	92.2	Burrow lining
P8	33.8	Burrow fillings
P9	78.2	Burrow lining
P10	305	Host sediment
P11	381	Host sediment
P12	84.2	Burrow lining
P13	67.1	Burrow fillings
P14	176	Burrow lining
P15	289	Host sediment
P16	261	Host sediment
P17	103	Burrow lining
P18	78.9	Burrow fillings
P19	95.4	Burrow lining
P20	252	Host sediment

seem to be more concentrated in the burrow linings and walls than in the burrow fillings and host sandstone (Fig. 6B). There are signs of sediment cleaning type bioturbation in both the specimens. Contrary to the sediment mixing/packing type bioturbation, clay and iron oxides are selectively cleaned/removed from the burrow fillings and concentrated in the burrow linings in the sediment cleaning type bioturbation. Biologically cleaned sandstones are developed as mud and organic matter are preferentially removed from the host sediments, resulting in enhanced sorting and porosity increase[3].

The *Ophiomorpha* dominated ichnofabric in S3 exhibit a ow mottled texture (Fig. 6C). Some researchers have suggested that the burrow-mottled texture makes the primary sediments more isotropic/homogenized, and may enhance sample permeability[35]. This justifies the enhanced permeability recorded in the burrows of this specimen. Porosity and permeability of fillings in the burrows are higher than those of host sediments and much higher than those of the burrow lining. The host sediments have a porosity of 30%, while fillings in burrows 32%. Spot permeability measurement shows enhanced permeability inside the burrows. Permeability of the burrow fillings, burrow lining and host sediments in specimen S2 ranges between (661– 712)×10^{-3} μm^2, (236–267)×10^{-3} μm^2 and (290–606)×10^{-3} μm^2 (Fig. 5B) respectively. Permeability of burrow fillings enhances by 167% and 146% than the burrow lining and host sandstone respectively (Fig.5b, Table 2). In S3, permeability of burrow fillings, host sandstone and burrow lining ranges

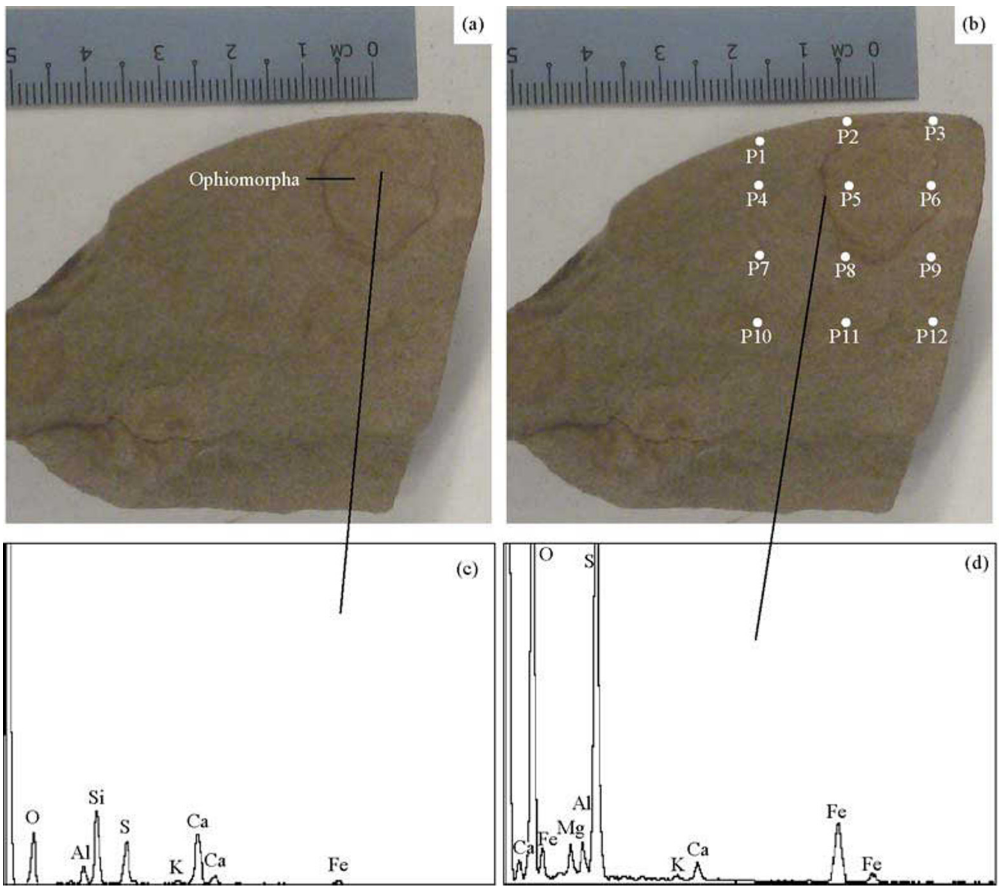

Fig. 5. (a) Core slab of specimen S2 showing *Ophiomorpha* burrow; (b) core slab of specimen S2 showing permeability measurement points in host sediment and *Ophiomorpha* burrow; (c) EDX of burrow fillings showing relatively low iron oxide content of the clean sandstone; (d) EDX of burrow lining showing higher iron oxide content.

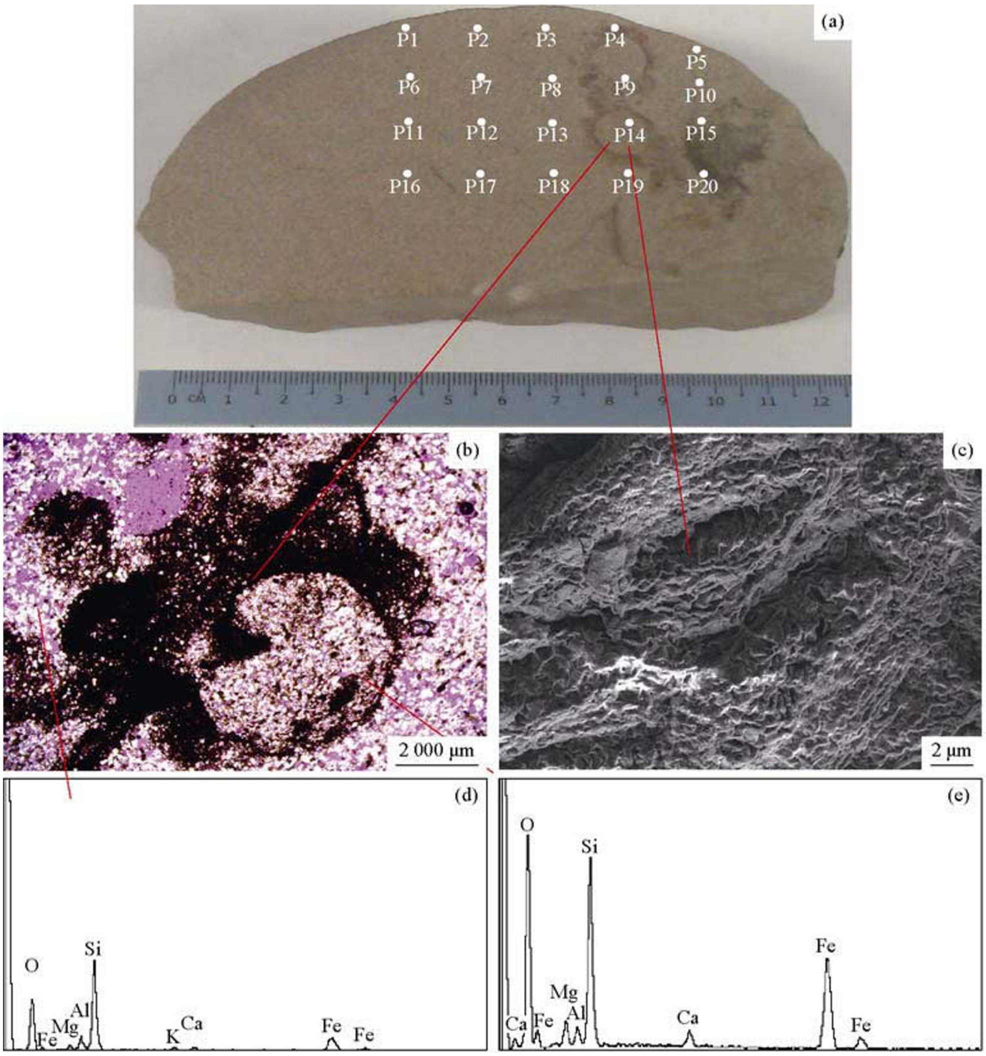

Fig. 6. (a) Core slab of specimen S3 with *Ophiomorpha* burrows; (b) thin section of specimen S3, with porosity in violet, and organic matter or iron oxides in dark colour; (c) SEM image of *Ophiomorpha* burrow in specimen S3 showing burrow mottled texture; (d) EDX of burrow fillings showing the clean sandstone is relatively deficient in iron oxides; (e) EDX of burrow lining showing relatively high content of iron oxides.

Table 2. Permeability distribution in S2.

Point No.	Permeability/10^{-3} μm^2	Point location
P1	366	Host sediment
P2	712	Burrow fillings
P3	236	Burrow lining
P4	439	Host sediment
P5	661	Burrow fillings
P6	267	Burrow lining
P7	357	Host sediment
P8	606	Host sediment
P9	597	Host sediment
P10	290	Host sediment
P11	305	Host sediment
P12	500	Host sediment

between $(572–642)\times10^{-3}$ μm^2, $(176–555)\times10^{-3}$ μm^2 and 95.4×10^{-3} μm^2 respectively (Fig. 6A). The burrow fillings have a permeability 169% and 573% higher than the host sandstone and burrow lining respectively (Fig. 6a, Table 3).

3.4. Differences in bioturbation effect

The bioturbated specimens from the two wells differ in that in specimen S1 bioturbation reduces permeability, while bioturbation enhances permeability in specimen S2 and S3, which is caused by the different types of burrowing activity and burrow fillings. While sediment cleaning activity is observed in S2 and S3, sediment packing is observed in S1. In S2 and S3, clay and organic matter have been selectively cleaned from the sandstone matrix in the burrows and concentrated in the burrow lining, leaving the sandstone matrix with better sorting and higher isotropy (Fig. 6b), and thus resulting in localized increase in permeability within the burrows. The sediment filling activity observed in S1 is a result of burrowing organisms incorporating clay, iron oxides and organic matter into the burrow fillings from the sandstone matrix, thereby reducing the sorting and isotropy of grains in the burrows previously hydrodynamically sorted grains, leading to a localized reduction in permeability within the burrow (Figs.

4a-h).

Table 3. Permeability distribution in S3.

Points	Permeability/10^{-3} μm^2	Point location
P1	425	Host sediment
P2	327	Host sediment
P3	521	Host sediment
P4	642	Burrow fillings
P5	452	Host sediment
P6	239	Host sediment
P7	305	Host sediment
P8	218	Host sediment
P9	95.4	Burrow lining
P10	463	Host sediment
P11	555	Host sediment
P12	176	Host sediment
P13	489	Host sediment
P14	572	Burrow fillings
P15	460	Host sediment
P16	240	Host sediment
P17	500	Host sediment
P18	506	Host sediment
P19	532	Host sediment
P20	424	Host sediment

The results of this study reflect the effect of bioturbation on the reservoir rocks in the Baram Delta. Permeability is an important reservoir parameter, so factors affecting it should be thoroughly investigated. This study shows that in characterizing and modelling the sandstones in the delta, particular attention should be given to the bioturbated sandstone, and this kind of sandstone should not be treated in the same way as non-bioturbated sandstone. Particular attention should be paid to the types of burrowing activity, burrow fillings and burrow. The study shows that sand-filled burrows generally have a positive effect on reservoir rock quality.

4. Conclusions

Animal-sediment interactions in sediments and sedimentary rocks results in a variety of trace fossils, microstructures and ichnofabrics. The organisms rework the sediments, mineral grains and organic matter to alter the primary fabric of sedimentary rocks. Bioturbation can either increase porosity and permeability by increasing sorting and isotropy or decrease porosity and permeability by unsorting sediments and mineral grains. The cored reservoir intervals in Well W-1 and W-6 of the Baram Delta are characterized by *Ophiomorpha* and *Diplocraterion* ichnofabrics. The porosity and permeability of bioturbated sandstone is dependent on the activity of the burrowing organism and the burrow fillings. Sediment cleaning activity by burrowing organisms resulting in cleaner, well sorted burrow fillings enhances permeability of specimen S2 and S3. Permeability of burrow fillings in S3 is 169% and 573% higher than that of the host sediment and burrow lining respectively. Permeability of burrow fillings in S2 is 167% and 146% higher than that of the host sediment and burrow lining respectively. This selective cleaning of fines by the burrowing organisms from the host sandstones and burrow into the burrow lining leads to concentration of iron oxides and clay in the burrow lining, increasing sorting and permeability of the burrow and host sandstone. Sediment packing activity is observed in sample S1. Sediment packers incorporate fine material (clay and organic matter) from the host sediment into burrow fillings and/or linings, decreasing isotropy and sorting of the sediments in the burrows. This causes a reduction of porosity and permeability locally in the burrows as observed in specimen S1. Measured permeability of the burrow fillings in specimen S1 is 78% lower than that of the host sandstone. Therefore, the effect of bioturbation on porosity and permeability of reservoir rocks in the Baram Delta depends on the types of burrow fillings and burrowing activity.

The heterogeneity in permeability distribution indicates that the permeability measured with steady state gas permeameter on whole core plug of highly bioturbated sandstone can not reflect the actual permeability of the sandstone. In highly-intensely bioturbated sandstone, spot permeability measurement will be more meaningful. Spot permeability measurement is very useful in studying the effect of micro-heterogeneity such as bioturbation in reservoir rocks because it has the added advantage of being able to measure permeability at specific points at faster rate.

The main application value of this study lies in the advancement of physical property prediction methods for bioturbated layers in reservoirs: whether the quality of reservoir rocks have been enhanced or reduced by bioturbation can be predicted according to the types of bioturbation activity observed in bioturbated rocks.

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