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Research paper

Porosity and Permeability Modifications by Diagenetic Processes in Fossilferous Sandstones of the West Baram Delta, Offshore Sarawak

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A b s t r a c t

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Baram Delta is the most prolific hydrocarbon province of all the geological provinces in the Sarawak Basin. Major fossilferous intervals have been identified within these units. The objective of this paper is to investigate the impact of diagenetic processes on fossils in fossilferous sandstones and how such modifications to fossils influence porosity and permeability. Seven wells from four fields in the Baram delta were evaluated using thin sections, CT scan imaging, SEM, EDX, spot permeability, core plug porosity and permeability measurements. Intragranular pores have been formed within fossils by dissolution of fossils. The formation of these pores has been facilitated by uplift of the Rajang Group accretionary prism to form the Rajang Fold-Thrust Belt. An increase in porosity and permeability is observed in both spot permeability and core plug porosity and permeability measurements in the fossilferous sandstones. Spot permeability in fossilferous part of the sandstones range between 606mD-879mD whereas the non fossilferous part has spot permeability values ranging between 305-521mD. This represents a permeability enhancement of 50-60% in the fossilferous part. Core plugs from the fossilferous horizons have porosity between 18-30% and permeability ranging between 662mD-683mD whereas the non fossilferous horizons have porosity between 13-27% and permeability ranging between 10-529mD.

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1. Introduction

The measure of the void space in a rock is defined as the porosity of the rock and the measure of the ability of the rock to transmit fluids is known as permeability [1]. Effective porosity refers to the percentage of the total rock volume that consists of interconnected pores [1; 2]. Porosity formed during the predepositional and depositional stage is known as primary porosity whereas porosity that develops anytime after deposition is known as secondary porosity [2]. Porosity and permeability are very important to petroleum geologists and reservoir engineers because they largely control how productive a petroleum reservoir will be. Porosity formed within grains are known as intragranular porosity whereas intergranular porosity refers to porosity formed between grains [2]. Sandstones are normally dominated by intergranular porosity even though additional intragranular porosity may be formed in the sandstone during diagenesis normally as a result of dissolution of minerals such as feldspars and calcite. Such intragranular porosity may add to the total effective porosity of the reservoir rocks depending on whether the pores are connected. This study has been necessitated by recent advances in the studies on formation of secondary and intragranular porosity during diagenesis.

Fossils are the preserved remains or traces of animals and plants. Fossils are a common feature in most marine and shallow marine sedimentary environments such as deltaic environments [3; 4; 5]. Significant fossilferous intervals have been identified in some of the most productive siliciclastic hydrocarbon reservoirs in the world including the Middle Jurassic Brent Group in the North Sea [6; 7], the Jurassic Norphlet formation in the Gulf of Mexico [8], the Triassic Sassendalen Group in the Barents Sea, Norway [9; 10] and Cycles VI and VI Lower to Middle Miocene reservoir sandstones of the Baram Delta, Offshore Sarawak Basin, Malaysia [11].

Fossils form an important part of a rock fabric and is a vital form of rock heterogeneity that can induce textural and mineralogical variations in a rock. Rock heterogeneity refers to vertical and lateral variations in rock fabric such as porosity, permeability, and/or capillarity [12; 13; 14]. Heterogeneity strongly influences reservoir performance by controlling fluid flow and recovery factor [15; 16]. Rock fabric has been defined by several researchers as the spatial arrangement and orientation of fabric elements [3; 17]. [17] identified such fabric elements to include texture (grain size and orientation), microstructures, minerals, fossils and porosity. The concept of the influence of some of these fabric elements such as texture and mineralogy on reservoir rock quality has been well investigated by [8; 18; 19; 20; 21; 22]. However, the influence of fossils as a fabric element on porosity and permeability in reservoir sandstones has not been exhaustively discussed. [19] investigated the impact of the dissolution of calcite (the dominant mineral in fossils) cement on the reservoir quality of sandstones and carbonates reservoirs. They concluded that the prediction of the impact of dissolution of calcite cement on reservoir rocks depends largely on whether the dissolution occurs in an open or closed geochemical system. [19] proposed that diagenetic reactions near the surface may be open and involve significantly changes in sediment composition and formation of secondary porosity caused by high pore-water flow rates of meteoric water or reactions with sea water near the sea floor.

At the time of deposition, sediments will have a primary mineralogical, chemical and textural composition with the primary composition and sorting of clastic sediments related to provenance, climate and sedimentary facies [23]. The deposited sediment composition is modified by diagenetic processes: surface process such as weathering on land, compaction (chemical and mechanical) and cementation on the seabed where biogenic components, particularly of carbonate and silica may be added to the clastic siliceous grains [19]. Three diagenetic regimes were originally proposed by [24] for limestone diagenetic processes: early diagenesis (eogenesis), burial diagenesis (mesogenesis) and uplift-related diageneis (telogenesis). However, this terminology has been adopted by other researchers such as [25; 26] for sandstones since the same processes generally control both clastic and carbonate diagenesis. The objective of this paper is to investigate the impact of such diagenetic processes on fossils in fossilferous sandstones of the Baram delta and how such modifications to the fossils influence porosity and permeability in the rocks.

2. Geological Setting

The Sarawak Basin is most widely believed to have originated as a foreland basin that formed after the collision of the Luconia Block with the West Borneo Basement, and the closure of the Rajang Sea during the Late Eocene [27]. Deformation and uplift of the Rajang Group accretionary prism to form the Rajang Fold-Thrust Belt provide the sediment supply to the Sarawak Basin [28; 29]. The Baram Delta is one of seven geological provinces found offshore the Sarawak Basin and is the most prolific of all the geological provinces in the basin [11] (Fig.1). The delta which was discovered in 1969 is estimated to have more than 400 million stock barrels of oil in place with multiple stacked sandstone reservoirs in a shallow offshore environment and has been in production for the past 30 years [30]. The Baram Delta consists of nine fields with an average recovery factor of about 30% [31]. It 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 [11]. The tectonic style of the delta shows two main types of deformation: gravity-induced growth faults are intersected by wrench-induced , compressional, NE-SW trending folds of Late Miocence or early Pliocene age [11]. Extensive syn-sedimentary growth faulting with very large throws form the principal petroleum traps in this area [32].

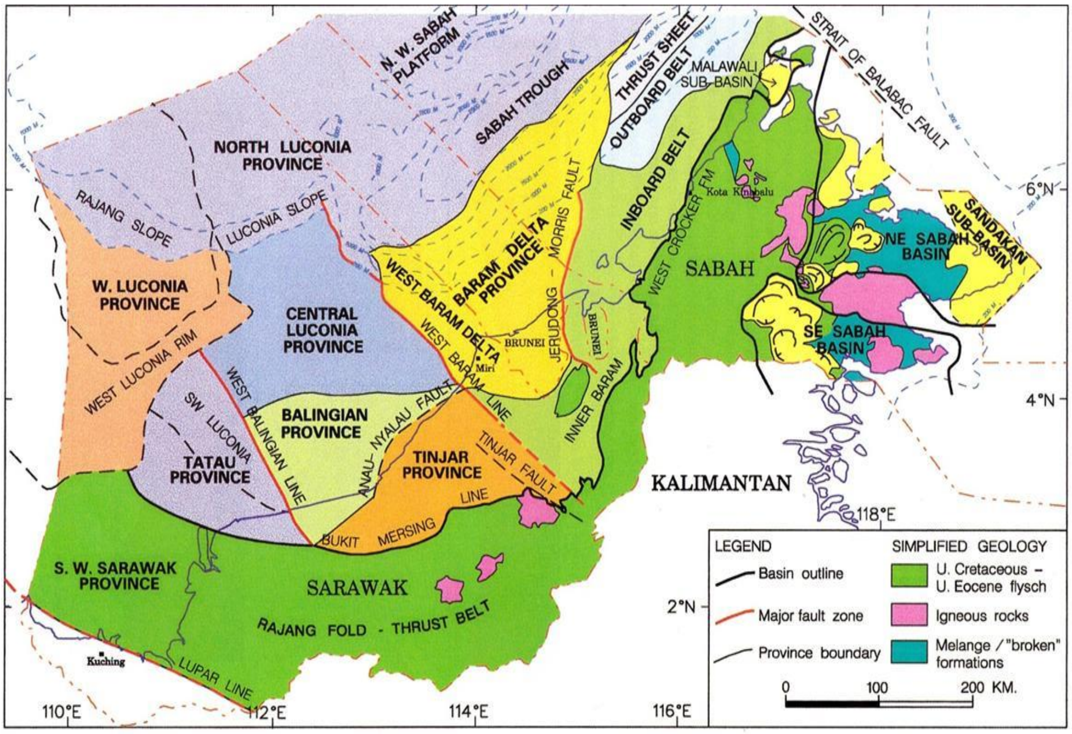


Fig.1: Location map of Sarawak Basin [28]

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 (Fig.2) [11; 29; 33]. Periods of delta outbuilding are separated by rapid transgressions, which are represented by marine shale intervals at the base of the sedimentary cycles [33].

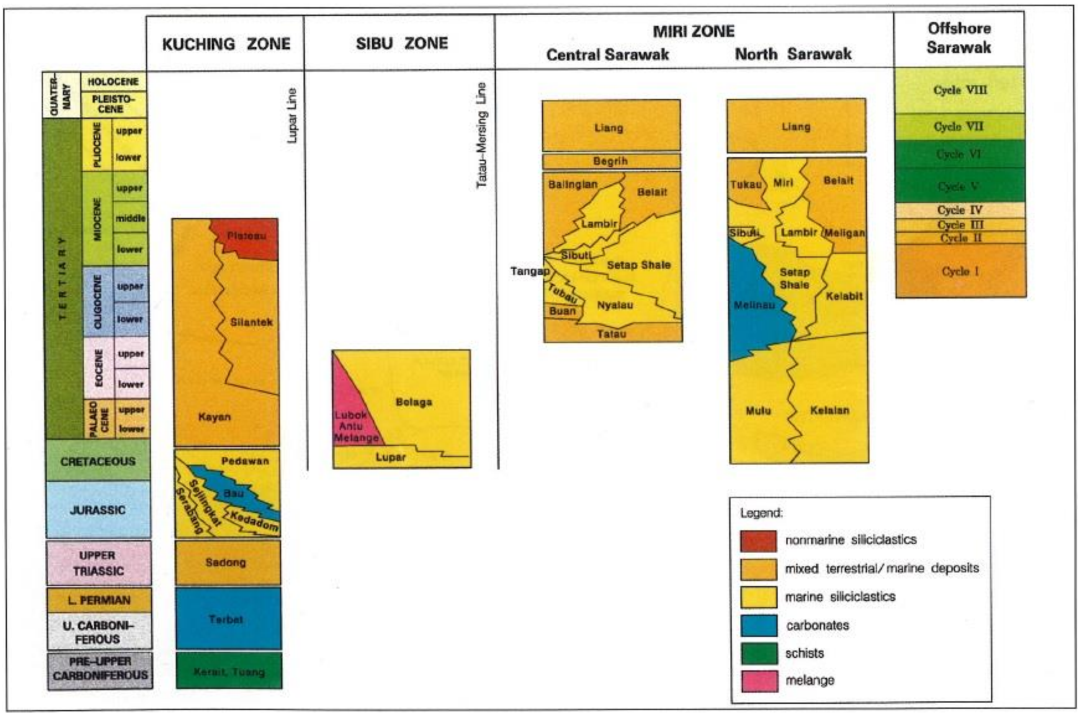


Fig.2: Generalised stratigraphic columns for the onshore structural provinces of Sarawak [34]

3. Materials and Methods

Seven wells from four fields in the Baram delta were evaluated in this study. The depth of the wells range between 792m-1829m. Samples were taken from the fossilferous sections of two wells (Well A and Well B) at 1474m in Well A and 1682m in Well B for further analysis. The sampled intervals are shown in figs. 3a and 3b. The studied reservoir sandstone intervals all belong to the cycles V and VI Upper to Middle Miocene sandstones [11]. Core logging was carried out for all wells 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.

2cm x 4cm slices of core were cut from the fossilferous sandstone samples to make thin sections. Grain sorting and grain size estimation were obtained visually by comparing to a standard sorting comparison chart [35]. Thin section photographs were taken using Olympus SZX16 research stereomicroscope with attached digital camera.

Spot/ probe permeability measurements were measured on the fossilferous sandstone intervals using a CoreLab Profile Decay Permeameter (PDPK^{TM} 300 system). Permeability values were measured in sections of the samples containing fossils and the other parts without fossils. The spot permeameter measures permeability by injecting nitrogen gas into the rock at probe pressure of 20psi and a test (nitrogen gas) pressure of 6psi [36]. A probe tip with a diameter of 5mm 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 [37; 38; 39]. A geometric factor (Go) of 1.83 was used in this experiment [36]. 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 were measured at each point on the grid and the average values were taken. Anomalous values which may be as a result of leakage of the nitrogen gas during the measurements were discarded.

Samples of 2cm x 2cm dimension of each core slab were taken for scanning electron microscopy (SEM). High magnification photomicrographs of each sample were taken for enhanced description of texture and microstructures in the sandstones. The SEM analysis was done using a Carl Zeiss Supra 55VP FESEM with variable pressure ranging from 2Pa to 133Pa and probe current between 1pA to 10nA. Energy dispersive x-ray spectroscopy (EDX) of specific points in the samples were taken to determine the elemental composition at these points.

Core plug permeability was measured using a Vinci Technologies Coreval 30 poroperm equipment. The core plugs used had a 1 inch diameter and 3 inches length. This poroperm equipment is a permeameter and porosimeter instrument used to measure porosity and permeability of core plugs at ambient confining pressure. A software attached to the Coreval 30 also calculates pore volume, Klinkenberg corrected permeability, Klinkenberg slip factor, inertial coefficients, sample bulk volume, grain volume, grain density and gas permeability in mD. The method used in this research is the American Petroleum Institute recommendation practice 40 (API RP 40). A maximum pressure of 400Psi, room temperature ranging between 25-27^{o}C and humidity range of 65-71% were used.

Core plugs of 1 inch diameter and 3 inches length from the fossilferous sandstone intervals were selected for micro computer tomography (CT) scan imaging. The micro CT scan images were taken with an InspeXio Microfocus CT system and processed with a trial version of Avizo 7.1 imaging software. 511 image slices were taken at a voxel size of 0.045mm/ voxel, with an x-ray voltage of 130kv and current of 100μA. The CT scan imaging was done for visualization of the internal structure of the rock fabric and the heterogeneities resulting from the presence of the fossils. The shape and orientation of the fossils in the rock fabric can be seen in the micro CT scan images.

4. Results and Discussion

4.1. Sample description

The dominant lithology in all seven wells studied are sandstones and siltstones with rare intercalations of mudstones in most of the wells. The sandstones can be subdivided into massive, laminated, fossilferous and bioturbated sandstones (figs.3a and 3b). Most of the sandstones are fined grained with a few sections of the well being medium to coarse grained.

The fossilferous sandstones are generally fine grained, moderately sorted, very pale orange (10YR8/2) with subangular grains (figs. 4a, 4d and 4e). EDX data shows a predominantly quartz composition with some amount of iron oxides and calcite. Variations in Ca^{2+} peaks are observed with the highly fossilferous part of the samples having higher Ca^{2+} content (fig.4c) than the low-no fossilferous part (fig.4b).

Well A **Well B**

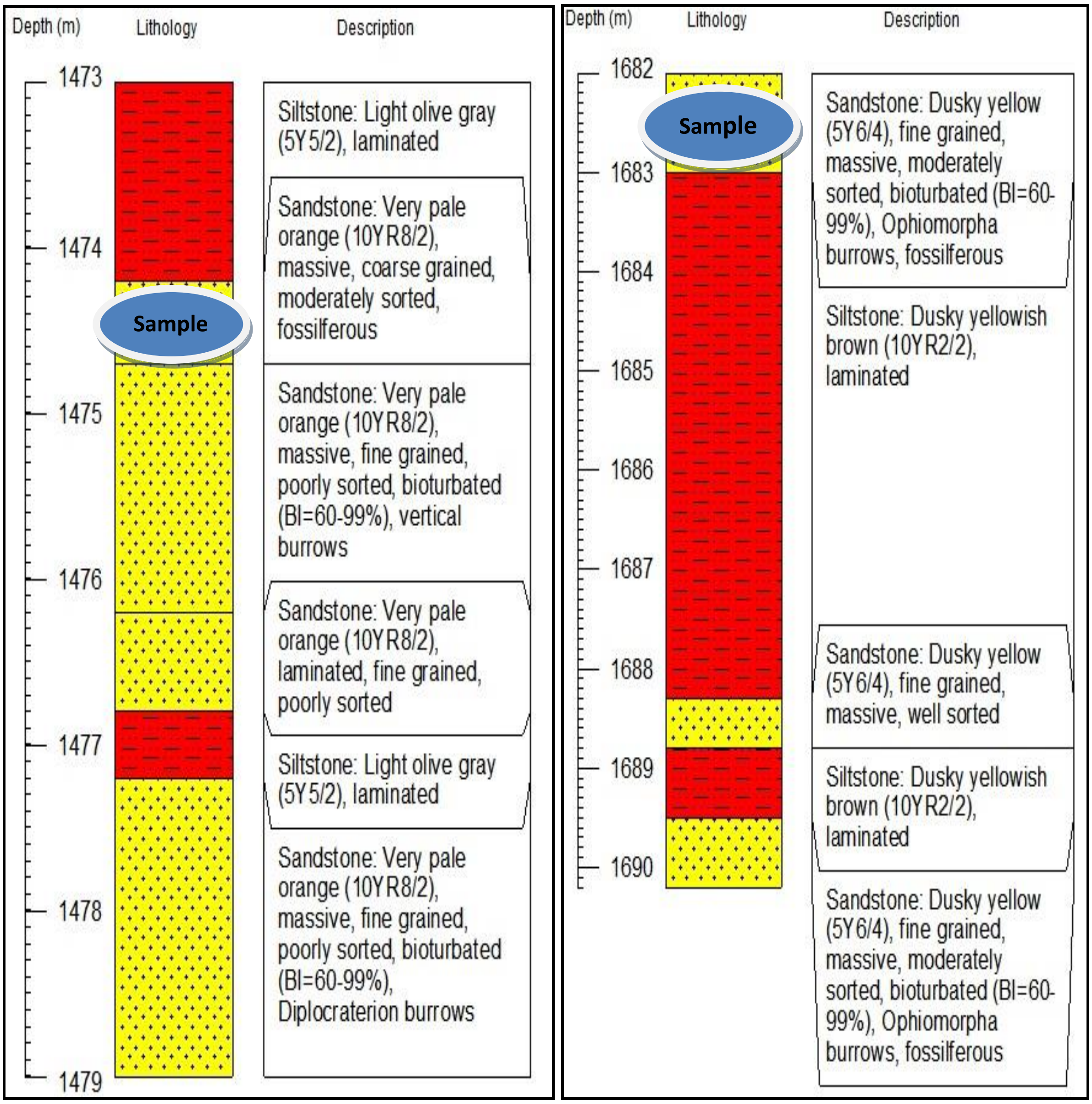


Fig.3: a and b: Simplified graphic logs of the two sampled wells, Well A and Well B

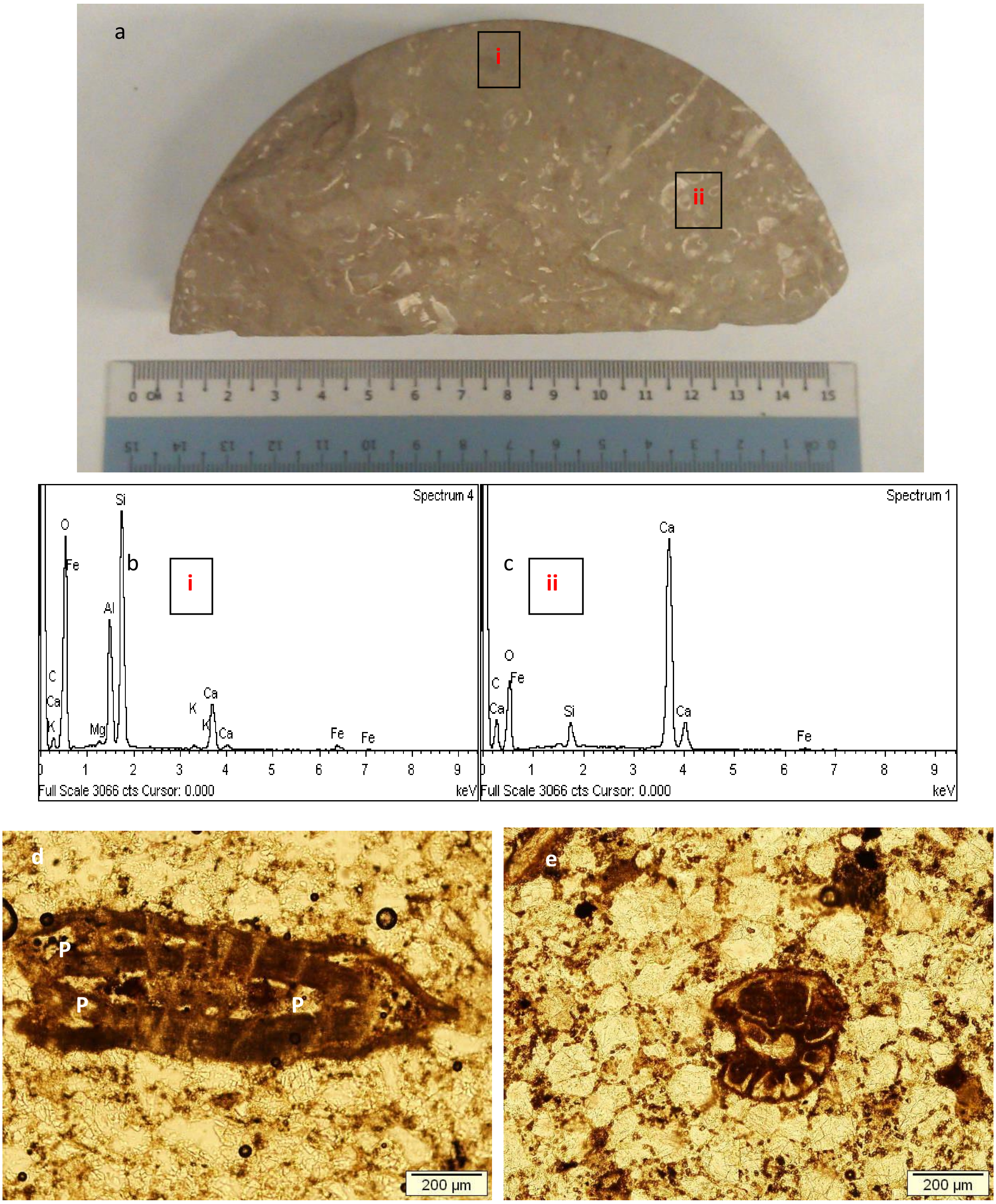


Fig.4: a:Hand specimen of fossilferous sandstone showing variations in the distribution of fossils b:EDX of non-fossilferous part of the sandstone c:EDX of fossilferous part of the sandstone d:Photomicrograph of fossilferous sandstone showing intragranular porosity within fossils (P) e: Photomicrograph of fossilferous sandstone showing subangular grains

The fossils are an important element of the rock fabric in the fossilferous sandstones. CT scan images show that they make up a significant part of the internal structure of the rock fabric and are a vital form of heterogeneity in the rocks (figs.5a and 5b). From the CT scan imaging and thin section photomicrographs, the fossils can be estimated to make up a significant percentage of the fossilferous sandstones (10-20%). Such fossil induced heterogeneities influence the rock texture and reservoir rock quality.

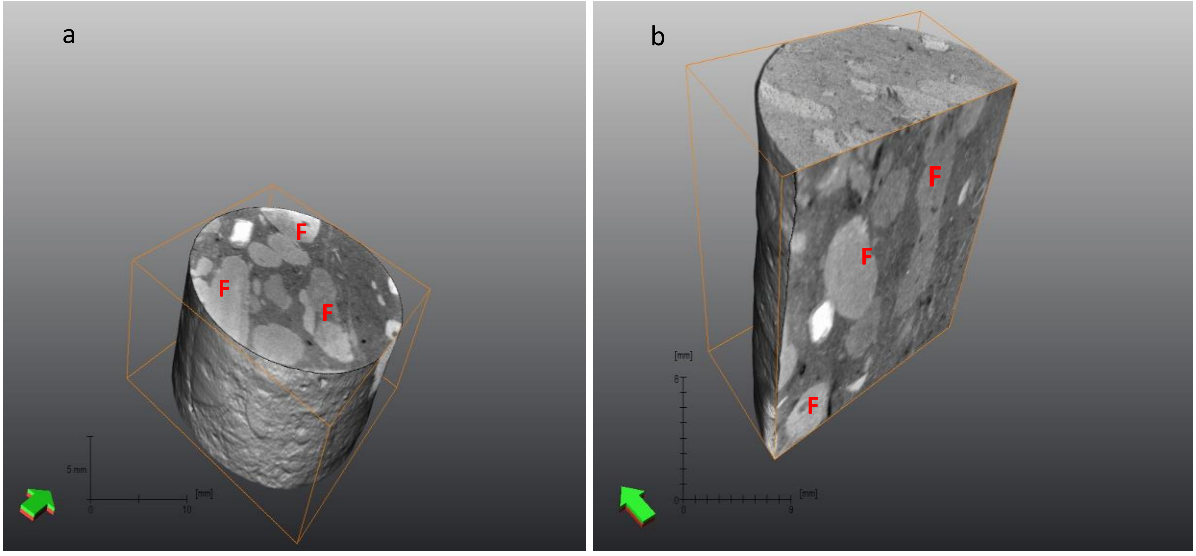


Fig.5: a: Core plug of fossilferous sandstone showing fossils in white and grey colour (F) b: Core slab of fossilferous sandstone showing the internal rock structure and rock heterogeneities induced by the fossil fragments

4.2. Porosity and permeability modifications

Modifications to the pore system in the fossilferous sandstones are observed in the SEM and CT scan images (figs. 5a, 5b, 6b. 6c and 6d). Such modifications affects the fossils embedded in the rock. Additional pores and porosity have been formed within the fossils as a result of diagenetic processes that have affected the sandstones. As you move along the CT scan slices from one slice to another the intragranular porosity formed within the fossils become very visible. For example, in figs 7a-7d, open intragranular pores (OP) which was previously nonexistent in slice 408 begins to form in slice 415 and continues to increase in size through to slices 420 and 428. This phenomenon is again observed in figs.8a-8d from slices 22 through to 19, 10 and 00. Diagenetic processes such as dissolution have been identified to be responsible for creation of such pores within fossils and mineral assemblages [40; 41]. Diagenetic reactions involving carbonate minerals (dominant minerals in fossils) are less dependent on temperature and kinetically faster. They can therefore occur at shallow depth and near surface. Such near surface reactions are sensitive to climate (rainfall) controlling the flow of meteoric water, which may result in a geochemically open system [19].

A review of the available literature shows that creation of such porosity normally occurs at shallow depth (<10-100m) where the ground water flux is high because this allows the pore water to remain constantly undersaturated and capable of leaching minerals [20; 25]. A lot of literature suggest that porosity creation by mesogenetic dissolution in sandstone petroleum reservoirs is insignificant i.e. it represents a relatively minor percentage of the total porosity. The depth of burial of the studied wells and sampled sandstones indicates that the main diagenetic processes are mesogenetic and therefore the intragranular porosity created within the fossils should be insignificant. However, spot permeability measurements show quite a significant increase between the fossiliferous sandstones and non-fossilferous sandstones.

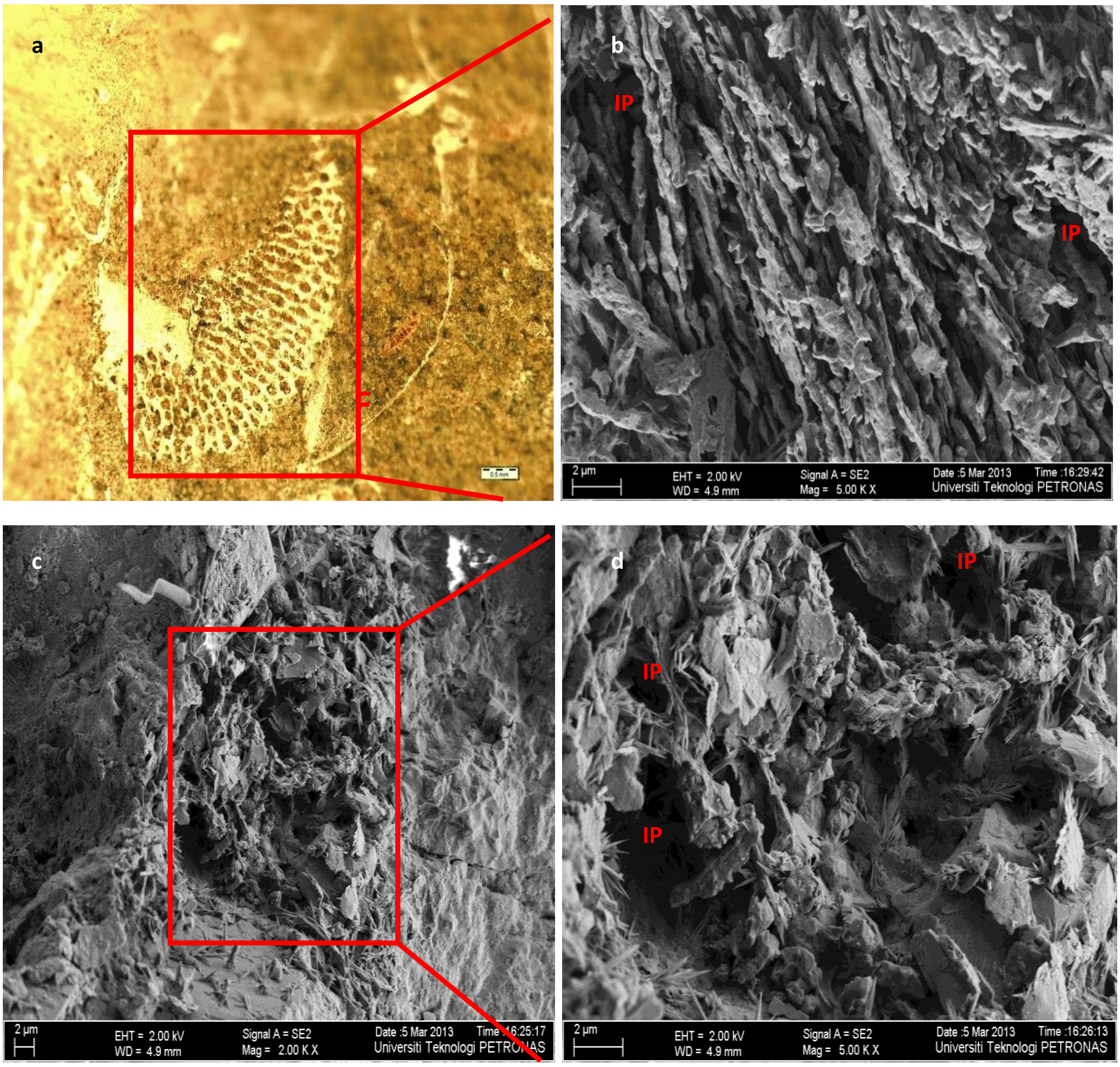
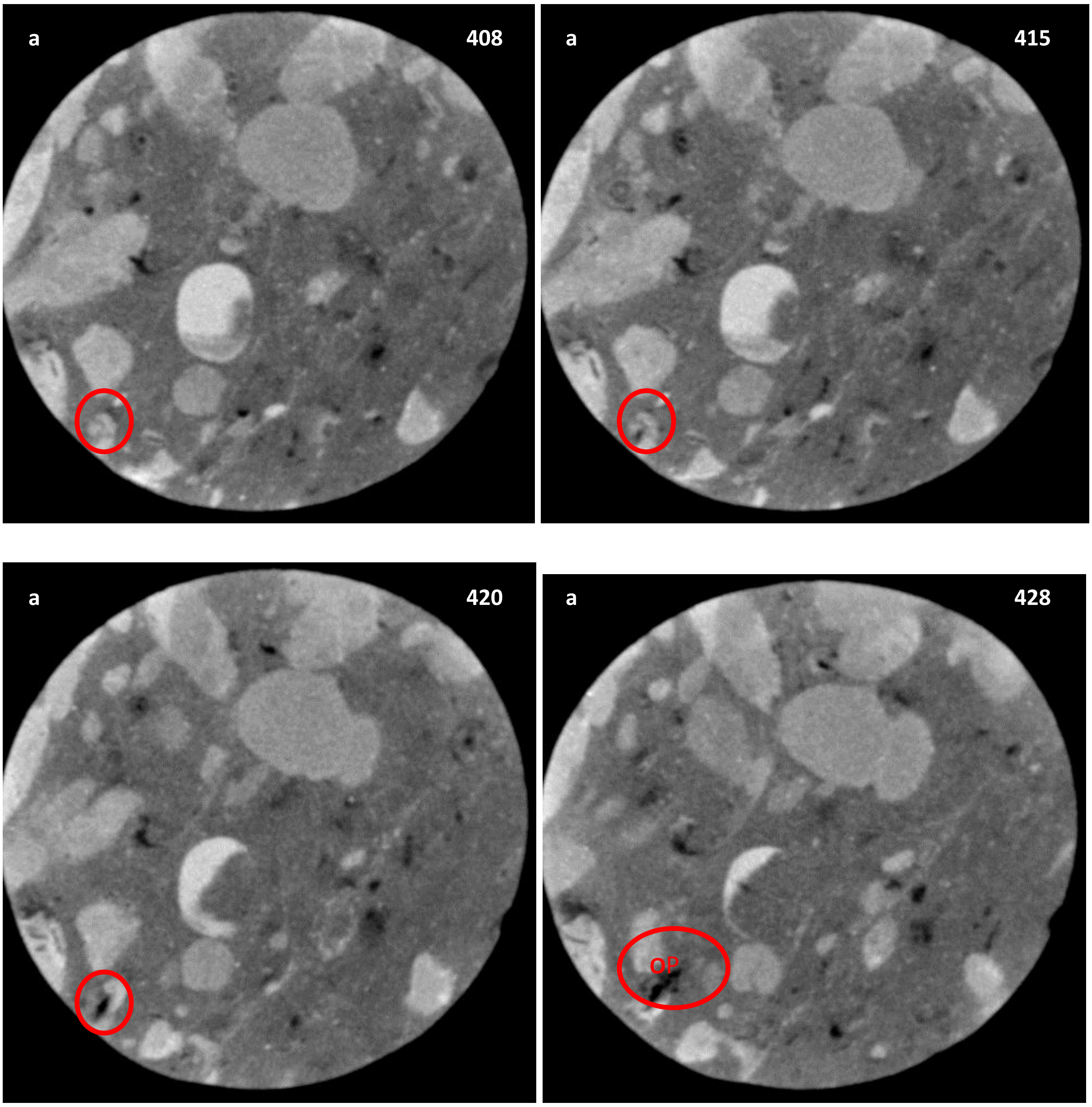
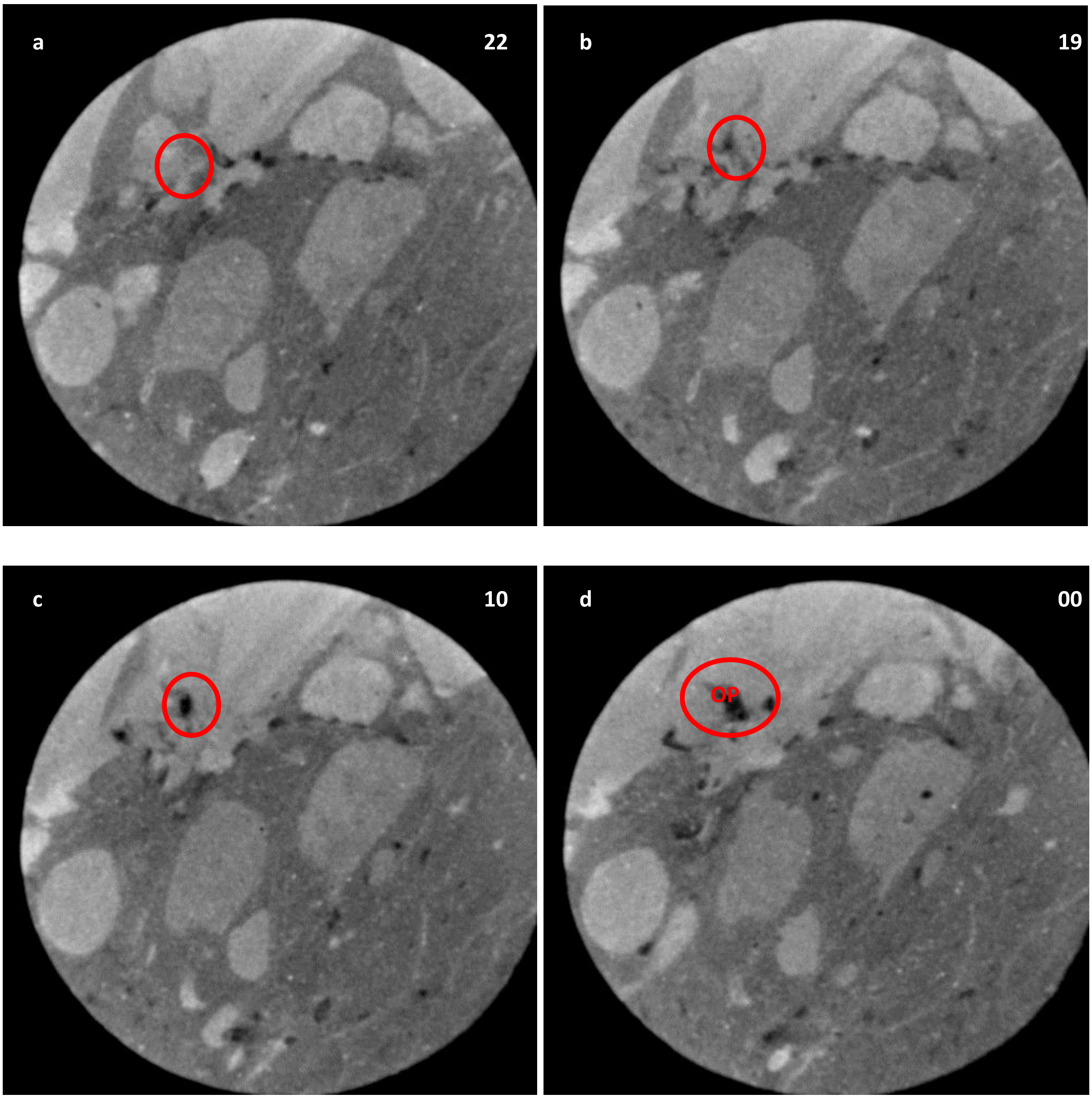


Fig.6: a: Photomicrograph of shell fragments within the rock fabric b: SEM of shell fragments showing intragranular porosity(IP) c and d: SEM of fossilferous sandstone showing intragranular porosity (IP) formed within a fossil at x 2000 and x 5000 magnification

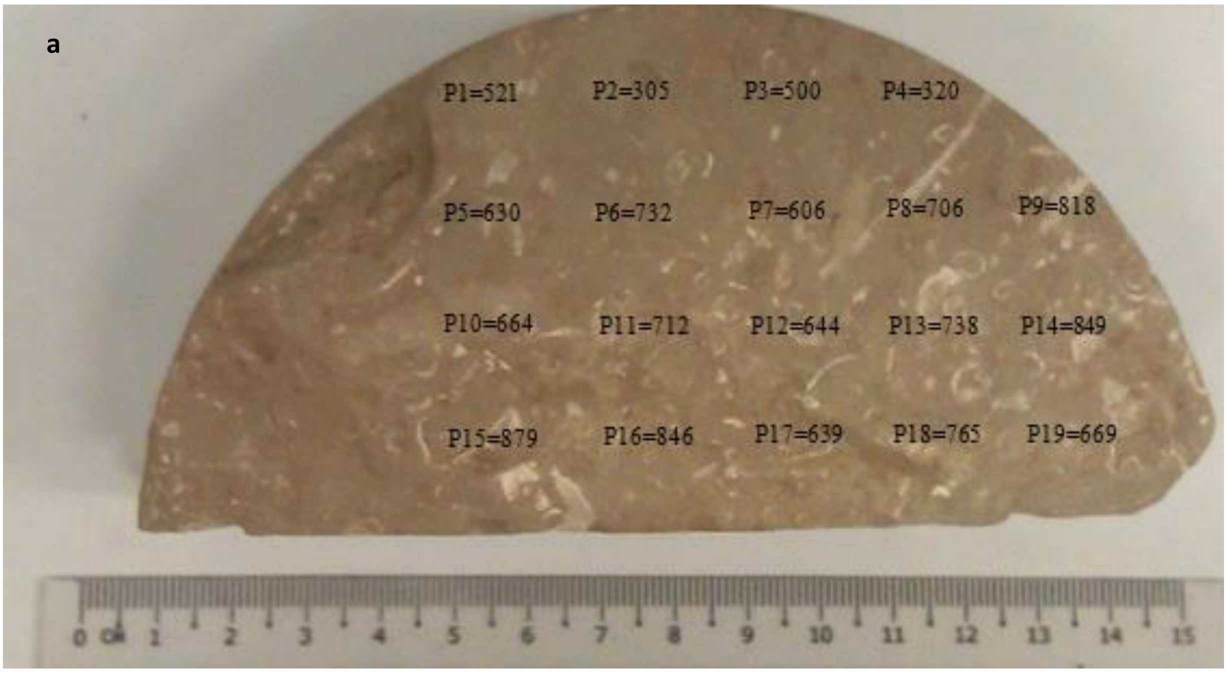


Figs.7a-7d: CT scan slices showing development of intragranular pores within fossils from slices 408-415-420-428



Figs.8a-8d: CT scan slices showing development of intragranular pores within fossils from slices 22-19-10-00

Spot permeability values are50-60% higher in the highly fossilferous part of the sandstones compared to the non fossilferous and low fossilerous part. An example of the spot permeability measurement is shown in Fig.9a. Spot permeability in the fossilferous part of the sandstone ranges between 606mD-879mD whereas the relatively non fossilferous part has spot permeability values ranging between 305-521mD. P1-P4 represents permeability in the non-fossilferous part, P5-P12 and P17-P19 represents the moderately fossilferous part and P13-P16 represents the highly fossilferous part of the sandstone (fig. 9b) (Table 1). This marked increase in porosity in the fossilferous sandstones can be attributed to the intragranular porosity formed within the fossils as observed in the SEM, CT scan and thin section images. The formation of intragranular porosity is interpreted to have been facilitated by the Eocene uplift of the Rajang Group accretionary prism to form the Rajang Fold-Thrust Belt. This uplift is interpreted to have brought the reservoir sandstones into the telogenetic regime where dissolution by meteoric water is the major porosity forming process [24; 26].



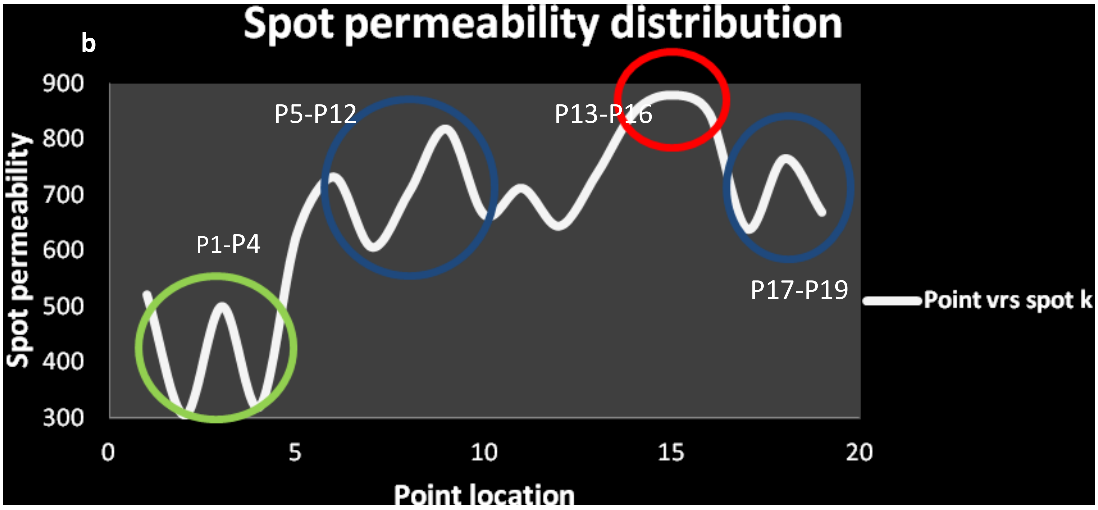


Fig.9: a:Spot permeability distribution in fossilferous sandstone sample b: Graphical representation of spot permeability distribution in sample

Table 1: Spot permeability distribution within fossilferous sandstone sample

Points	Permeability (mD)	Point location
P1	521	Non-fossilferous
P2	305	Non-fossilferous
P3	500	Non-fossilferous
P4	320	Non-fossilferous
P5	630	Moderately fossilferous
P6	732	Moderately fossilferous
P7	606	Moderately fossilferous
P8	706	Moderately gossilferous
P9	818	Moderately fossilferous
P10	664	Moderately fossilferous
P11	712	Moderately fossilferous
P12	644	Moderately fossilferous
P13	738	Highly fossilferous
P14	849	Highly fossilferous
P15	879	Highly fossilferous
P16	846	Highly fossilferous
P17	639	Moderately fossilferous
P18	765	Moderately fossilferous
P19	669	Moderately fossilferous

The poro-perm experiment was carried out to confirm the influence of the fossils in enhancing the porosity and permeability in the fossilferous sandstones. The results from the poro-perm experiment are summarized in figs.10a-10d. The figures show that the fossilferous horizons have a significantly higher porosity and permeability than the non fossilferous horizons. Core plugs from the fossilferous horizons (FH) have porosity between 18-30% and permeability ranging between 662mD-683mD whereas the non fossilferous horizons have porosity between 13-27% and permeability ranging between 10-529mD. The significantly higher porosity and permeability recorded in the fossilferous core plugs emphasizes the importance of the fossils in enhancing the reservoir rock quality.

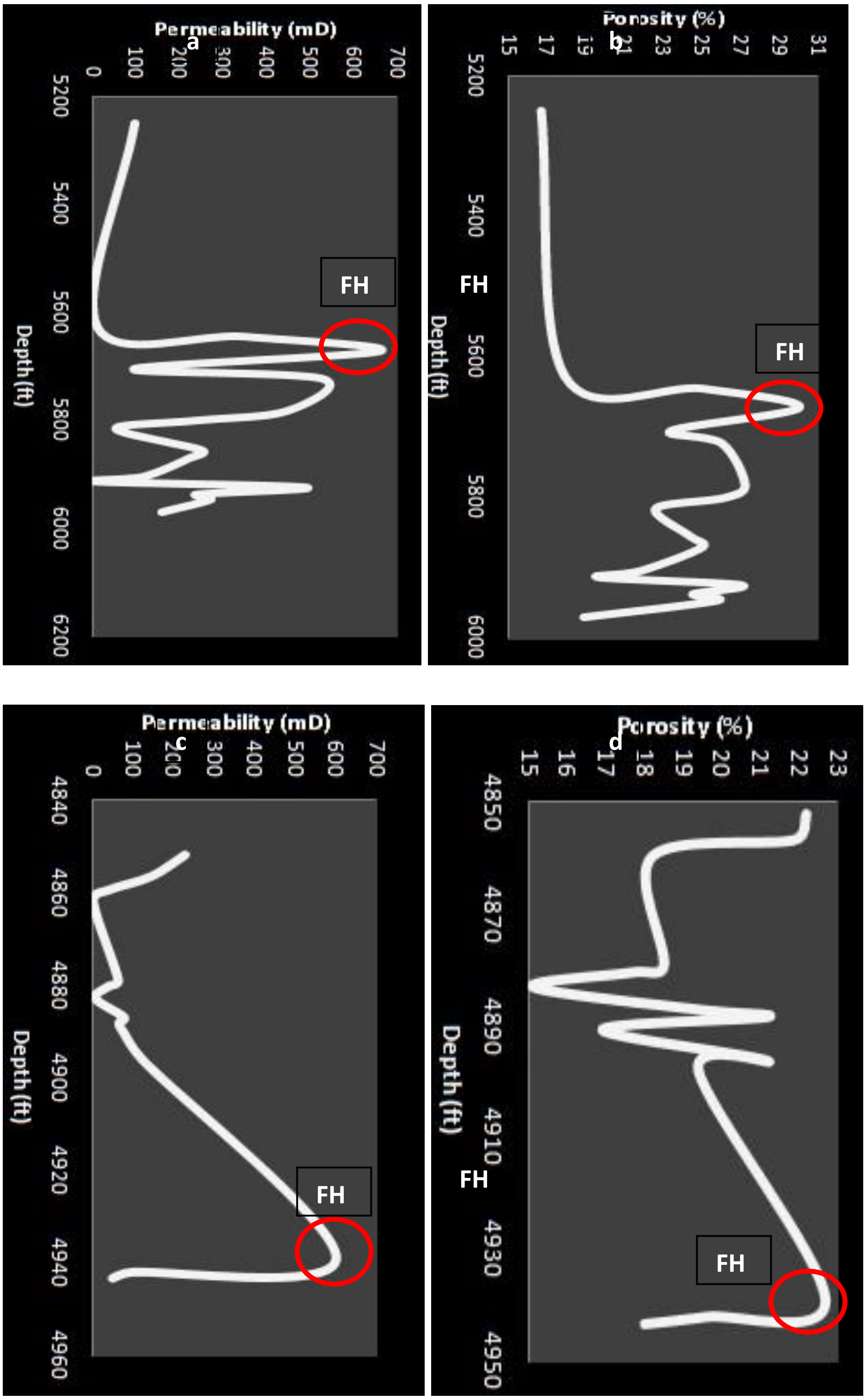


Fig.10: a:Graphical representation of core plug permeability measurements in Well A b:Graphical representation of core plug porosity measurements in Well A c: Graphical representation of core plug permeability measurements in Well B d:Graphical representation of core plug porosity measurements in Well B

5. Conclusion

1. Evidence of creation of intragranular porosity within fossils was observed in SEM images, CT scan images and thin section photomicrographs.

2. An increase in porosity and permeability is observed in both the spot permeability and core plug porosity and permeability measurements in the fossilferous sandstones over the non fossilferous sandstones.

3. Spot permeability in the fossilferous part of the sandstone range between 606mD-879mD whereas the relatively non fossilferous part has spot permeability values ranging between 305-521mD. This represents a porosity and permeability enhancement of 50-60% in the fossilferous part. This enhancement is attributed to the intragranular porosity formed within the fossils by diagenetic processes. This observation is confirmed by the core plug porosity and permeability measurements.

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