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ORIGINAL ARTICLE

The impact of stylolites and fractures in defining critical petrophysical and geomechanical properties of some carbonate rocks

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Abstract Stylolites are partings within rocks that exhibit complex mutual column and socket interdigitization. This study was initiated since the impact of stylolites in defining critical geomechanical, fluid flow and petophysical properties is not well-known. A total of nine carbonate samples from Turkey and seven from Malaysia were used in this study. The carbonate rocks have varied composition and have heterogeneous distribution of certain components such as stylolites, fractures and algal remains. Fabric, presence of stylolites as well as fractures have a controlling effect on the stress response and the contractional strain of carbonates from Malaysia and Turkey. The formation of stylolites and the location of the stylolites are independent of the rock fabric and the applied stress. Faces with stylolites showed a high degree of variability in terms of thermal conductivity when estimated at various points. Samples from Malaysia that consisted of stylolites generally had low thermal conductivity values compared with the non-stylolitic faces. The current study indicates that the stylolites present in these rocks have the potential to increase the permeability of the carbonate rock. It is even more interesting to note that in the region immediately bordering the stylolites, is occupied by fractured calcite crystals. However, the varied surface roughness indicates that the boundary conditions which define fluid flow in porous media would be very different within this stylolitic region.

1 Introduction

Stylolites are irregular surfaces that commonly appear as dark, jagged lines in rocks such as carbonate rocks and originate as a result of solutions that form in such rocks under pressure. The term stylolites is used to describe partings within rocks that exhibit complex mutual column and socket interdigitization (Dunnington 1967). Stylolites are formed perpendicular to the maximum principal stress direction and this mechanism is explained as a plastic deformation in the elasto-plastic spring-network model. The Eshelby Transformation method is used to describe the tensile or shear stress concentrations and angle of brittle fracturing. The orientation of stylolitic surfaces indicate the direction of paleo-stress. The dark lines have been known to comprise insoluble residues. Stylolites are also known to comprise constituents such as clay minerals, iron oxides or organic matter. Stylolites are generally absent in limestones containing more than

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10 % clay. The amplitude and abundance of stylolites is maximum in thin areas, correlating with increased contractional strain accommodated by the layer. The amplitudes of sutures are greater than the diameter of grains in the rock. Stylolites are generally impermeable to fluid flow.

Pressure-dissolution process happens during compaction and has been quoted as the main cause for the formation of stylolites. It has been documented that grains begin to dissolve at point contacts to produce sutured and concavo-convex contacts. Alternatively, it is also known that chemical compaction can also occur in limestones to generate stylolites. A high degree of overburden is generally necessary to produce this structure. In addition to this, tectonic stresses may also produce such pressure dissolution effects.

Stylolites have been reported to form clay-enriched plane-like structures. The average amplitude of stylolites visible in an outcrop indicates the minimum magnitude of contractional strain the rock has experienced. Stylolites can therefore play an important role in modifying the transport properties of sedimentary rocks. Due to the presence of clays and overall reduction in porosity, stylolites can play the role of permeability barier and sometimes permeability drain (Toussaint et al. 2011). This then suggests that stylolites may have an impact on fluid flow as well as heat transfer. They also reflect critical diagenetic processes such as mass transfer and compaction (Tada and Siever 1989). Stylolites are also used to estimate the amount of dissolved material in the rock in which it occurs (Tada and Siever 1989).

As mentioned earlier, stylolites are known to grow perpendicular to the maximum compressive stress direction. These features can exhibit pronounced roughness on several scales (Park and Schot 1968). Orientation of the stylolites and their teeth have been used extensively as an indicator for the direction of the maximum compressive stress (Stel and De Ruig 1989). Description of natural stylolites has been stated as difficult (Park and Schot 1968) since this feature can display a wide range of morphologies and be found in a variety of rocks. It has also been shown that modeling the morphology of stylolites is also difficult and that stylolites are among the least well- explained of all pressure-solution phenomena (Gal et al. 1998). As such, it remains a challenge to utilize the morphologies of stylolites as indicators of paleostress magnitudes and directions.

The study of thermal conductivity in samples having stylolites is interesting. Heat is transferrable via three modes: conduction, convection and radiation (Beardsmore and Cull 2001). In evaluating the permanent heat flow from the Earth's interior to its surface, it was estimated that 17 % of the heat flow can be attributed to the earth's cooling, whereas the balance of the heat flow would be attibuted to radiogenic heat production (Turcotte 1980). Heat flow is defined as a temperature difference between two points resulting in a heat flow q. The magnitude of q depends on the thermal conductivity of the material and the distance between these two points. Thermal conductivity is also a function of the fabric (Masnan 2010) and as a consequence can have an added implication on hydrocarbon distribution (Padmanabhan 2010). Heat flow studies in geological systems are are important in the oil and gas industry since such studies give an indication on the thermal maturity of the hydrocarbon reserves.

Therefore, the overall objective of this work was to evaluate the impact of stylolites in defining critical geophysical and petrophysical properties in some carbonate rocks.

2 Materials and methodology

A total of nine beige limestone samples were obtained from a local limestone processing factory. The factory had imported these samples from Turkey. Thin sections were made at Universiti Teknologi Petronas, Perak, Malaysia. Description was done according to (Flügel 2004). Submicroscopic studies were carried out at the Mechanical Engineering Department, Universiti Teknologi Petronas.

Core plug of 1.5 inch (diameter) × 3 inch (height) dimension was fitted into the triaxial cell of the IPC GLOBAL RT-1000 ROCK TESTER of capacity ranging from 1000 to 10,000 kN. Different confining pressures ranging from 0.5–2.0 MPa were applied at the specified test speed (0.5 m/min for this experiment) until failure occured whereby the data from the stress and strain tests were imported into the UTS025 analysis applications (http://uts025-mohr-analysis.software.informer.com/1.0/) in which Mohr's Circle was automatically plotted. Samples from Turkey were too small for cores to be made to conduct triaxial tests. As such, only the Malaysian samples were subjected to

triaxial tests. The procedure of conducting the standard test methods are in accordance with ASTM D7012-14. The contractional strain is given by Kostrov's (1974) formula:

$$\varepsilon = \frac{1}{A_o} \sum_{i=1}^{N} D_i L_i \qquad (1)$$

where ε = strain, D_i = average amplitude, L_i = Stylolite Length and A_o = original cross sectional area.

Thermal conductivity (k) of the rocks were estimated at 30 °C by using a flexible heater set, T thermocouple probes and a heater source set at 40 W. The thermal conductivity values were estimated for each sample after a thermal equilibration time of 30 min. A multilogger thermometer connected to temperature probes with a temperature controller was utilized for this experiment with ambient operating temperature ranges of 0–50 °C. The themal conductivity (k) was estimated in various directions and a range of values were recorded. The expression used to estimate k is

$$k = -QL/A\Delta T \qquad (2)$$

(Clauser & Huenges, 1995) where Q = heat flow across the material, L = distance across which heat flow was estimated, A = cross sectional area of the sample and ΔT = temperature difference.

3 Results and discussion

3.1 Hand specimen characteristics

The carbonate rock from Turkey is generally beige in color with visible presence of algal remains contributing up to 25 % by volume. No other forms of fossils were detectable in hand specimens. Stylolites were detected in all samples. The stylolites were classified into three types: Type 1 (sharp-peak) has well defined and high density (4 amplitudes per cm) fractures; Type 2 (simple wave-like) is intermediate whereas Type 3 (sutured) has poorly defined and low density (<1 amplitude per cm) fractures. The stylolites generally cover different proportions by volume of the hand specimens.

The seven rock samples from North-west Peninsular Malaysia had a range of differing physical and mineralogical properties. Samples KP1 and KP2 had

numerous natural fractures of lengths ranging from 0.02 to 0.08 m. These fractures were infilled with calcite.

Samples PU1 and PU2 have also iron oxides in trace amounts in addition to calcite grains. Thin fractures ranging in width from 0.005 to 0.001 m with calcite infilling are present. Broken shells (fossil fragments) are present and these are also infilled by calcite. A good portion of the fractures (about 60 % by volume) were observed to be devoid of infillings. In addition to this, sample PU2 had stylolites with simple wave-like (Type 2) amplitudes (10–20 amplitudes per cm).

Samples T1 and T2 had stylolites which were stained by iron oxides in certain places. In comparison to PU1, the degree of infilling in T1 and T2 appears to be less.

The fractures in samples KGP1 and KGP2 were infilled with calcite and range in widths from 0.001 to 0.003 m and lengths of 0.01 to 0.08 m. Caclite veins being part of a secondary intrusion process, were detected to be present in these samples.

Samples SP1 and SP2 show a range in color from light beige to white. Fractures range in lengths from 0.02 to 0.04 m with widths ranging from 0.005 to 0.023 cm were detected across the surface with almost all fractures being infilled by calcite.

In essense, it is evident that the samples from Malaysia show different characteristics from those carbonate rocks from Turkey.

3.2 Optical characteristics

The rocks from Turkey comprise equigranular and subhedral grains of calcite with approximate dimensions of not exceeding 25 μm (Fig. 1a, b, c, d). Grains along stylolites are generally too fine to be distinguished at this magnification. Algal remains are seen interspersed randomly in the matrix with random orientation and distribution. Fossil fragments make up about the bulk of the rock (75–80 %) classifying the rock as packed biomicrite (Folk 1962). Stylolites can be seen easily in thin sections but do not intersect any minerals. Staining along the stylolites is attributed to Fe-oxyhydroxides.

The rocks from Malaysia showed some differences from a petrographical point of view. KP1 is fine-grained wheras KP2 is medium grained limestone. PU1 (dolomitic wackestone) has dominantly the
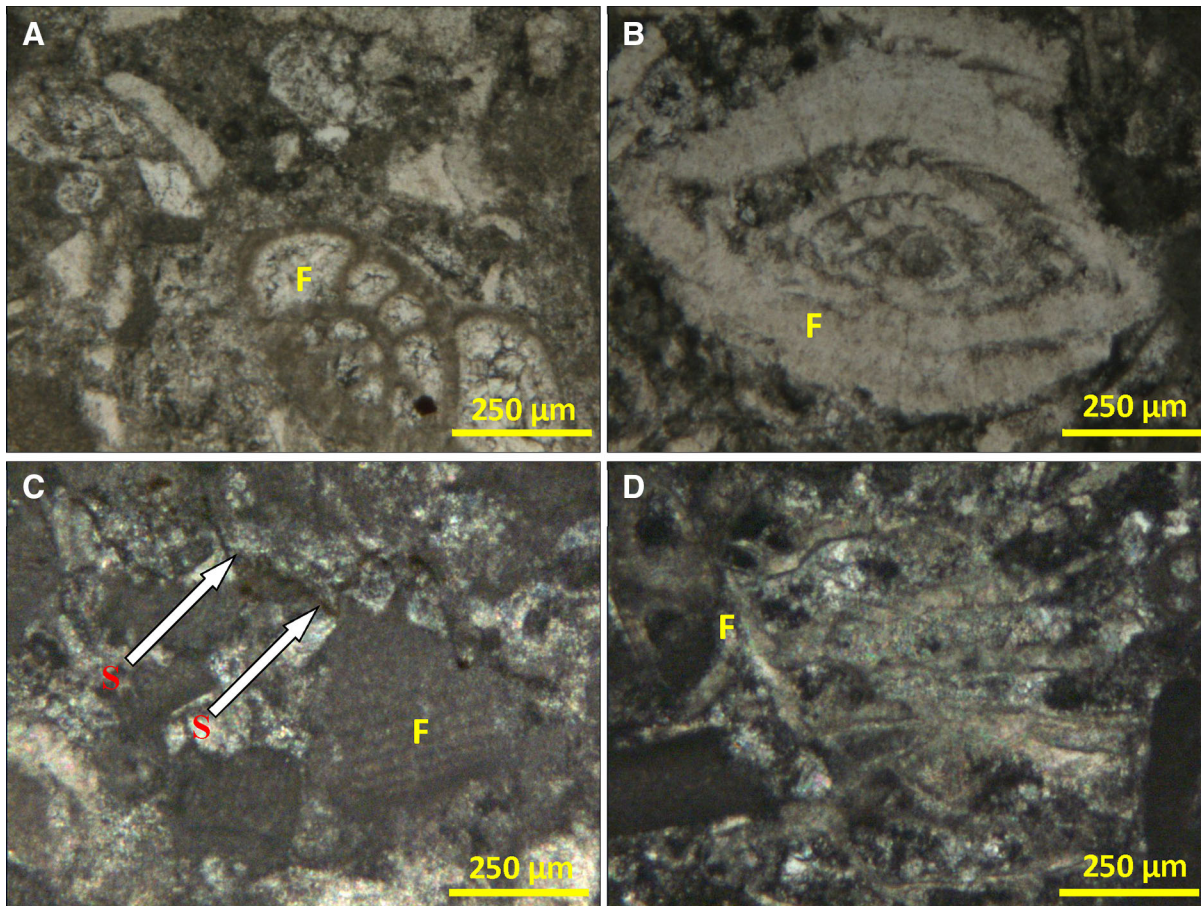
Fig. 1 Thin section micrographs of the limestone from Turkey showing **a** and **b** High fossil content, **c** Stylolites transecting the limestone without cutting through minerals and **d** secondary calcite precipitation

mineral dolomite whereas PU2 is classified as a wackestone and has stylolites of Type 2 (Fig. 2). KGP1 comprises about 30 % calcite and the rest being sparry calcite. This is classified as wackestone. In contrast, KGP2 is classified as a peloidal wackestone with the majority of the minerals being calcite and about 10 % of the matrix constituting peloids. SP1 is a marble and is made up of coarse-size grains of calcite. SP2 is a fine to medium graine calcitic marble with about 90 % of the matrix comprising calcite.

It is evident that samples SP1 and SP2 have undergone metamorphism. The calcite minerals in KP1 and KP2 reflect deformation processes as indicated by the contorted lamellae. Samples PU1, PU2, KGP1 and KGP2 did not show any signs of strain or metamorphism.

3.3 Micro characteristics

Submicroscopy shows that calcite crystals grow perpendicular to the surface of the pressure-dissolution surface (Fig. 2a). The crystals are generally euhedral (Fig. 2b) but tend to vary in size from clay to very fine sand (up to 8 μm). The crystals in the matrix of the rock are up to medium silt size. The crystals are arranged in a compact manner and are generally subparallel to each other. Typically, one face of the pressure-dissolution surface consists of dissolution pits whereas, the other comprises secondary crystal growth (Fig. 2c and d). In all the samples studied, clay mineral deposits were not detected. The overall geometry of the dissolution pits is not concordant with the size of the secondary crystals. Typically, the pits appear to be in the order of at least
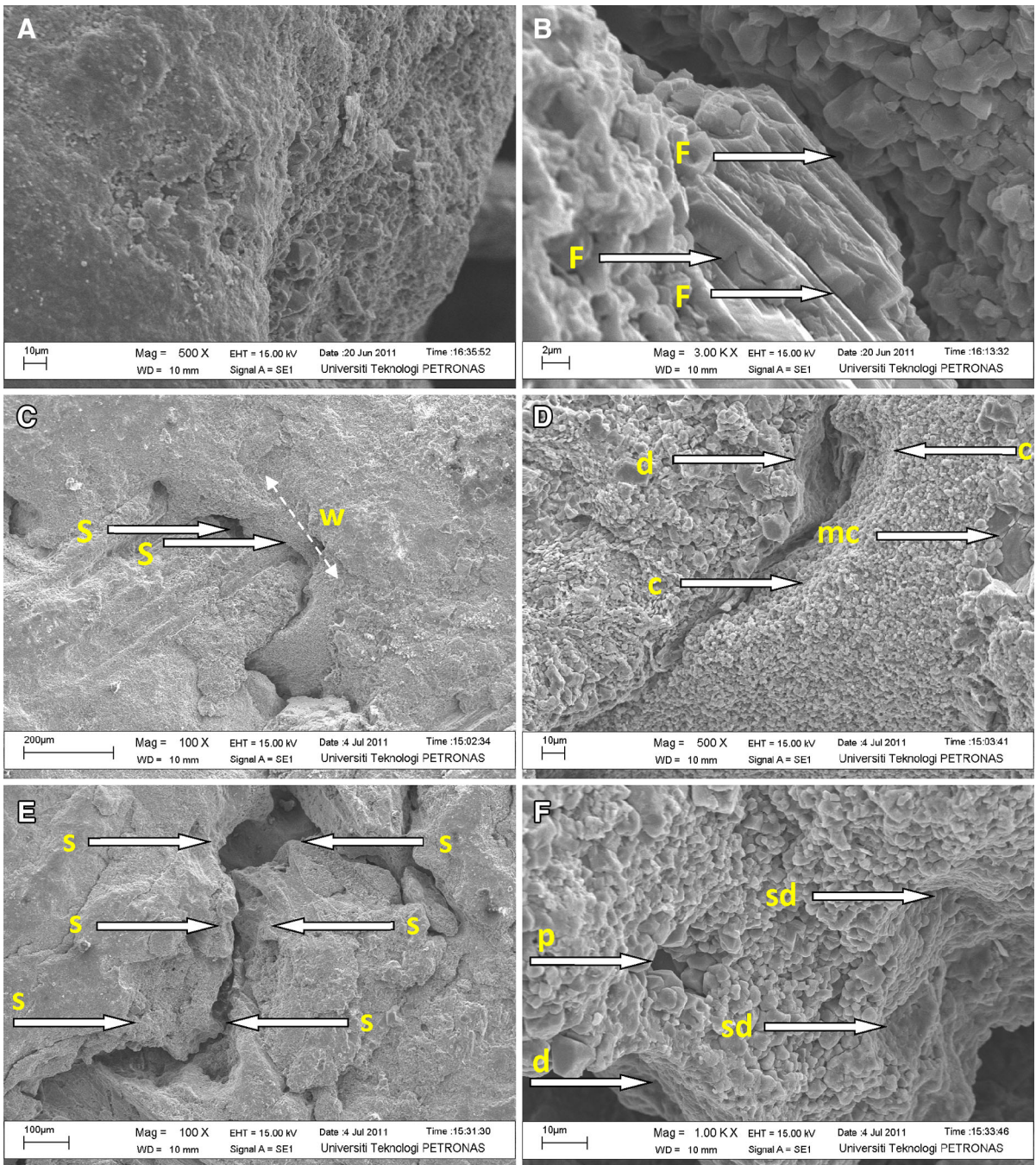
Fig. 2 SEM images of the limestone from Turkey. **a** A view of the stylolites at low magnification. **b** Subparallel fractures (F) developed on the face of a stylolite. **c** Close up of the stylolite (s) showing variations in contact and width (w). **d** Stylolitic face with calcite grains on one side, dissolution (d) faces on the complimentary side and calcite in matrix (mc). **e** Stylolitic (s) face with lesser amplitudes per cm. **f** Development of porosity (p) in stylolitic face filled with calcite and presence of dissolution (d) and secondary dissolution (sd) faces

five times the size of the secondary crystals (Fig. 2d and e). This suggests that more material was dissolved than precipitated in the system. Another conclusion that can be drawn here is that there was a net loss of mass during the development of stylolites in these limestones.

In isolated cases, the external surfaces of the plane containing these secondary crystals appear to have been subjected to another phase of pressure-dissolution (Fig. 2f). This resulted in the formation of secondary dissolution surfaces. Clay minerals were not detected on these surfaces as well. Pores may develop in between the secondary crystals.

At high magnifications, the teeth of the sharp-peak stylolites of Type 1 appear to be 50–200 μm in thickness. Subparallel fractures were also detected in one of the pitted surfaces. These fractures are interpreted to be possibly part of a pull-apart mechanism, possibly post-stylolite development. It is interesting to note that these fractures are not filled up with any secondary deposits.

3.4 Evaluation of contractional strain

The samples from Malaysia (23 cores) were tested for the triaxial compressive test, from 8 different rock facies from four different areas (Table 3). Each of the cores of the different rock facies were tested under different confining pressures ranging from 0.5–2.0 MPa at constant actuator loading rate of 0.5 mm/min. The inherent shear strength, S_o (MPa), internal friction ($\varnothing$) with the different facies type are tabulated are given in Table 3.

Unit SP1 and SP2 has undergone a high degree of metamorphism to yield crystalline marble. Calcite crystals were detected in units KP 1 and KP 2 and showed deformational strains. Sparry calcite occurs as cement material in these were also subjected to moderate degree of metamorphism. Minimum traces of metamorphism were detected in units PU1, PU2, KGP1 and KGP2.

Rocks generally resist shearing by their inherent cohesion and internal friction. Units SP1 and SP2 have the highest shear strength and internal friction values of 13.50 MPa, 52.0° and 12.80 MPa, 49.0° respectively compared to all other samples. These values are comparable with those obtained by Farmer (1968). (Din et al. 1995) in their study had indicated that rocks composed of fine-grained minerals are almost free from shear planes and generated a higher shear strength compared to coarse-grained rocks that have

more shear planes. The higher values seen in SP1 compared to SP2 is attributed to a variety of factors. The presence of coarser grained minerals in SP1 should lower the values. However, the number of original fractures in SP2 is higher than SP1. As such, the deviation of shear strength behavior from norms can be attributed to these geological abnormalities.

The shear strength and internal friction values for units KP1 and KP2 (moderate degree of metamorphism), were 2.95 MPa, 46° and 2.40 MPa and 45.6° respectively. The shear strength values of both these units are the lowest produced from all the samples that were tested. This is attributed to the high degree of fracturing present in these samples. The fracture density (the number of fractures per meter) range from 50 to 54 m.

Units PU1, PU2, KSP1 and KSP2 generated shear strength and internal friction values of 8.70 MPa, 49.4°; 9.30 MPa, 48.5°; 8.90 MPa, 51.5° and 8.50 MPa, 52.0° respectively. The shear strength value of unit PU2 is higher than of unit PU1. As mentioned before, PU2 had stylolites. The lower shear strength value of unit PU1 us attributed to the influence of void spaces created by fractures that have no infilling.

KGP2 had exhibit more fracture lines than of cores of KGP1. KGP2 is thinly bedded and therefore is believed to have experienced more compression forces (Din et al. 1995) as shown by the presence of higher fracture density values compared to KGP1. The shear strength for unit KGP2 is lower than KGP1.

The results indicate that the degree of metamorphism has a subordinate effect on the shear strength compared to grain size, composition and fracture/ stylolite density.

The contractional strain for the samples from Turkey were evaluated as follows. The lengths and maximum amplitudes of the stylolitic topography measured are given in Table 1 and compared with values generated by Benedicto and Schultz (2007). The results indicate that the contractional strain varies between 0.02 and 0.2 for all the samples evaluated. It is worthy to note again that the nine samples are from the same rock outcrop but have different types of stylolites. Therefore, it can be concluded that the contractional strain as deduced from the geometry of the stylolites can vary spatially in rock formation such as in this rock. This variation can be attributed to differences in overburden pressure as well as variation

Table 1 Dimensions of stylolites and contractional strains calculated from these dimensions for the samples from Turkey

Sample number	D_{avg}	L	A_o	$\in$
1	0.2	12	20	0.12
2	0.3	20	40	0.15
3	0.2	10	40	0.05
4	0.1	2	30	0.01
5	0.05	25	60	0.02
6	0.01	5	50	0.00
7	0.1	20	125	0.02
8	0.1	30	85	0.04
9	0.3	10	200	0.02

D_{avg} average amplitude, L stylolite length, A_o original cross sectional area of the block, $\in$ strain

in the fabric of the rock. In comparing these values with those from other studies (Benedicto and Schultz 2007; Palchik 2006), it can be seen that the differences in values can be attributed to the presence of faults, different carbonate rock types as well as different locations (implying different ages and tectonic settings). Palchik (2006) used Haldane's distribution function to predict the stress–strain relationship over the pre-failure strain range by using only one datum point. In comparing with the results shown by Palchik (2006), it appears that there are some difficulties in predicting stress and strain using this approach in the samples from Turkey. This also indicates that more work is required for carbonate rock samples, especially those with stylolites.

In evaluating the relationships between contractional strain and the stylolite type indicates that the relationship is not very clear. This indicates that the formation of stylolites and the location of the stylolites is controlled largely by the fabric of the rock and to a subordinate extent the applied stress. The anisotropic nature of the type and distribution of stylolites is then concluded to be determined by the heterogeneity in the rock fabric.

3.5 Thermal conductivity

Ranges in k values were obeserved in the non-stylolitic (k) faces of the rocks studied (Table 2). Estimates range from 0.5 to 9.3 $Wm^{-1}K^{-1}$. These variations are attributed to the variations in microfrabrics. Microfabrics in this case refers to the size, shape, composition and orientation of individual

component crystals and pores. Estimates of k for stylolitic faces (k_s) appear to have a similar distribution as the non-stylolitic faces and range from 0.4 to 4.4 $Wm^{-1}K^{-1}$. It should be noted that actual variations of k_s in each sample is different in comparison to the respective k. Currently, it appears to be difficult to establish some sort of relationship between the type of stylolites and k or k_s. The lack of trends is attributed to the small number of samples used in this study and also the fact that the relationships between styloilites and such features are not very clear.

The mean k_s for Type 1 is about 2.71 $Wm^{-1}K^{-1}$. The mean k_s for Type 2 is 3.35 $Wm^{-1}K^{-1}$ whereas that for Type 3 is 1.53 $Wm^{-1}K^{-1}$. In contrast, the mean for k for Type 1 is 4.88 $Wm^{-1}K^{-1}$ whereas that for Type 2 is 6.35 $Wm^{-1}K^{-1}$ and that for Type 3 is 3.05 $Wm^{-1}K^{-1}$.

Variations in k values can best be explained by the variations in the density of stylolites in the measured sections. In addition to this, the fabric of the infilling crystals determines to some extent the k values. In all the samples studied, the size distribution of the crystals appears similar. However, the presence of more than one phase of pressure dissolution surfaces was found in only certain cases and appears to reduce the perturbation effect of stylolites.

The distribution of the thermal conductivity across the nine samples in the non-stylolitic faces shows that fabric controls k values even within a single type of limestone. Therefore, it becomes very challenging to specify a single value for the k of such rock types. However, the distribution of k_s does not appear to be as wide as for k in terms of absolute values. The results show that a property such as thermal conductivity can at the very best be estimated rather than determined or measured.

Considering also the perturbation of the thermal conductivity values by the stylolites and the variations in the fabric of the stylolites, it is proposed that the presence of stylolites by termed as a fabric anomaly and be appended to the existing proposal for fabric anomaly (Padmanabhan and Mohd Pauzi 2011).

The values of thermal conductivity for eight samples from study area Kisap, PENS Industries, Kang Giap Quarry and OMYA Quarry are given in Table 3. The mean value for PU1 was 4.14 $Wm^{-1}K^{-1}$ (the major mineral identified within this unit is dolomite). Numerous intrusions of calcite veins and presence of small pores were observed in PU1. PU2

Table 2 The thermal conductivity of stylolitic and non-stylolitic faces, classification and characteristics of the stylolites and difference in k values between the stylolitic and non-stylolitic faces

Sample number	Thermal conductivity k (W m^{-1}K^{-1})		Stylolite classification and characteristics	% reduction in k due to stylolites
	Stylolitic face	Non-stylolitic Face		
1	4.42	4.42	Type 1; sharp peak; 4–5 amplitudes cm^{-1}	0
2	2.74	5.75	Type 1; sharp peak; 4–5 amplitudes cm^{-1}	52
3	3.97	5.67	Type 1; sharp peak; 4 amplitudes cm^{-1}	30
4	4.34	9.31	Type 2; simple wave; 1–2 amplitudes cm^{-1}	53
5	2.11	4.07	Type 1; sharp peak; 4–5 amplitudes cm^{-1}	48
6	2.56	8.96	Type 1; sharp peak; 5–6 amplitudes cm^{-1}	71
7	1.53	3.05	Type 3; sutured; <1 amplitude cm^{-1}	50
8	2.36	3.38	Type 2; simple wave; 1–2 amplitudes cm^{-1}	30
9	0.46	0.46	Type 1; sharp peak; 4–5 amplitudes cm^{-1}	0

had a mean value of 3.93 Wm^{-1}K^{-1} (the major mineral identified is calcite). All measurements in this sample were done across stylolites where a significant percentage of dolomite crystals were identified within boundaries or stylolites. According to Clauser and Huenges (1995) the thermal conductivity value for calcite at 30 °C is 3.16 and 4.78 Wm^{-1}K^{-1} for dolomite. It can be therefore, interpreted that thermal conductivity values falls within the range of established values of calcite and dolomite. The role of porosity in reducing the values of estimated thermal conductivity is not excluded in this interpretation.

The mean value for KP1 is 3.80 Wm^{-1}K^{-1} and that for KP2 is 3.81 Wm^{-1}K^{-1}. The dominant mineral in these samples is dolomite. The mean thermal conductivity values for both KP1 and KP2 exceed that of calcite which is 3.16 Wm^{-1}K^{-1} but lower than dolomite crystal 4.78 Wm^{-1}K^{-1}. This is attributed to the presence of multiple calcite veins that transect the dolomite matrix and possibly slight variations in grain size of minerals in both specimens. KP1 is dominantly fine-grain whereas sample KP2 is predominantly medium-grain in size. Porosity is also acknowledged as an additional factor that influences the values for thermal conductivities in these rocks.

SP1 has of coarse grain texture with the mean thermal conductivity value of 3.13 Wm^{-1}K^{-1} while SP2 is made up of fine to medium grain minerals with a mean thermal conductivity of 3.02 Wm^{-1}K^{-1}. The difference in thermal conductivity values between SP1 and SP2 is attributed to variations in grain size. Due to metamorphism, porosity has been obliterated in these samples.

Padmanabhan and Mohd Pauzi (2011) in his study that indicated thermal conductivity estimation is point-dependent. Robertson (1988) had mentioned in his study that increase in temperature would generally decrease the thermal conductivity value and conversely increasing pressure would increase the value of thermal conductivity. However, he also mentioned that thermal conductivity values are heavily dependent on rock physical properties.

3.6 Stress–strain characteristics of carbonate rocks

The stress–strain model based on Haldane's distribution function (Haldane 1919) relates the axial stress (or normalized axial stress) to the square of an exponential function where the exponent is axial strain. Wang and Park (2002) have shown that the permeability was not constant, but varied with the stress and strain states in the rocks. Prior to the peak strength, the permeability decreases with increasing load. A dramatic increase in permeability occurs during the strain softening period Figs. 3, 4, 5.

At the various confining pressures (Fig. 6), stress appears to be linearly related to strain in all the facies studied. However, this trend varies with the applied confining pressure. As the number of samples used in this study is small, it is not possible to provide a reliable tend for these relationships. At higher confining pressures, the samples with stylolites (PU2) tend to have a more linear relationship between stress and strain. It is worth noting that none of the samples with stylolites fractured along the stylolitic planes during

Table 3 Thermal conductivity, shear strength, internal friction values, e and maximum axial stress values for some Malaysian carbonates

Sample	Facies	Thermal Conductivity (Wm⁻¹k⁻¹)				Inherent Shear Strength S_Θ MPa	Internal Friction Φ	e Conf stress = 500 kPa	Max axial stress = 500 kPa kN	e Conf stress = 1000 kPa	Max axial stress = 1000 kPa kN	e Conf Stress = 2000 kPa	Max axial stress = 2000 kPa kN
		Line 1	Line 2	Line 3	Mean								
KP1	Ca-dolomite	3.89	3.71	3.78	3.80	2.95	46.0	0.0073	54.329	0.0099	81.890	0.0159	49.486
KP2	Ca-dolomite	3.81	3.63	3.98	3.81	2.40	45.6	0.0081	37.798	0.0048	25.183	0.0081	94.440
PU1	Dol-Wackestone	4.10	4.11	4.21	4.14	8.70	49.4	0.0086	97.391	0.0092	77.490	0.0093	113.200
PU2	Wackestone	3.90	4.01	3.89	3.93	9.30	48.5	0.0197	90.919	0.0083	97.670	0.0093	113.200
KGP1	Packestone	3.21	3.10	3.00	3.10	8.90	51.5	0.0143	165.950	0.0112	113.560	0.0175	209.650
KGP2	Peloidal pack	2.89	2.95	3.13	2.99	8.50	52.0	0.0198	244.760	0.0154	225.890	0.0168	221.570
SP1	Crystalline coarse	2.99	3.21	3.20	3.13	13.50	52.0	0.0104	137.330	0.0114	167.680	n.d.	n.d.
SP2	Crystalline fine	3.04	3.12	2.89	3.02	12.80	49.0	0.0079	92.470	0.0133	159.140	0.0098	106.840

*e* strain, *Conf stress* confining stress, *Dol* dolomitic, *Pack* packstone, *n.d.* not determined
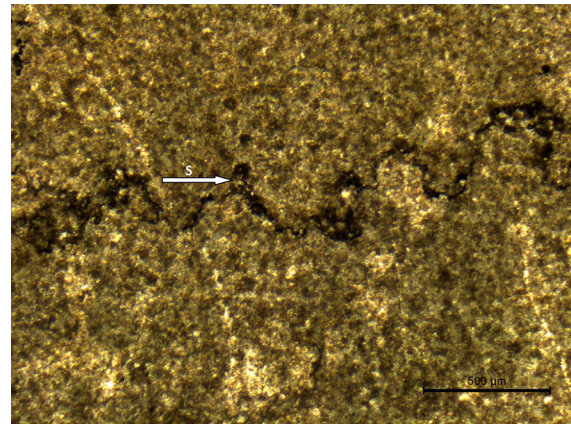
Fig. 3 Stylolites (S) in PU2 with amplitudes of about 0.000025 m. Stylolites infilled with iron oxides

the trixial tests. This is explained by the fact that these stylolitic planes have been recemented by secondary minerals such as clays, calcite, dolomite and even iron oxides. Ranjth et al. (2004) and Wasantha et al. (2015) showed that the presence of fractures reduced the strength of the rocks studied.

It is also to be noted that the several samples from Malaysia are scattered in this plot. This indicates that different types of carbonate rocks will tend to have different stress–strain relationships. The apparent linear trend that can be seen in this figure indicates possibly a general relationship between the two parameters for the samples evaluated. However, a larger population size is needed in order to verify if this apparent relationship is characteristic of Malaysian samples.

3.7 Impact on fluid flow

Stylolites are believed to have an impact on regional fluid flow either by decreasing the porosity and permeability of the host rock or by acting as a permeability barrier (e.g., Dunnington 1967; Nelson 1981; Burgess and Peter 1985; Koepnick 1987; Finkel and Wilkinson 1990; Dutton and Willis 1998; Alsharhan and Sadd 2000). Knowledge of the impact of stylolites on regional fluid flow is critical in petroleum geology. Enhanced porosity zones can also develop along the stylolites (Carozzi and von Bergen 1987; Dawson 1988; Raynaud and Carrio-Schaffhauser 1992; Van Geet et al. 2000; Gingras et al. 2002; Harris 2006). These zones of enhanced porosity have been hypothesized to enhance the circulation of fluids
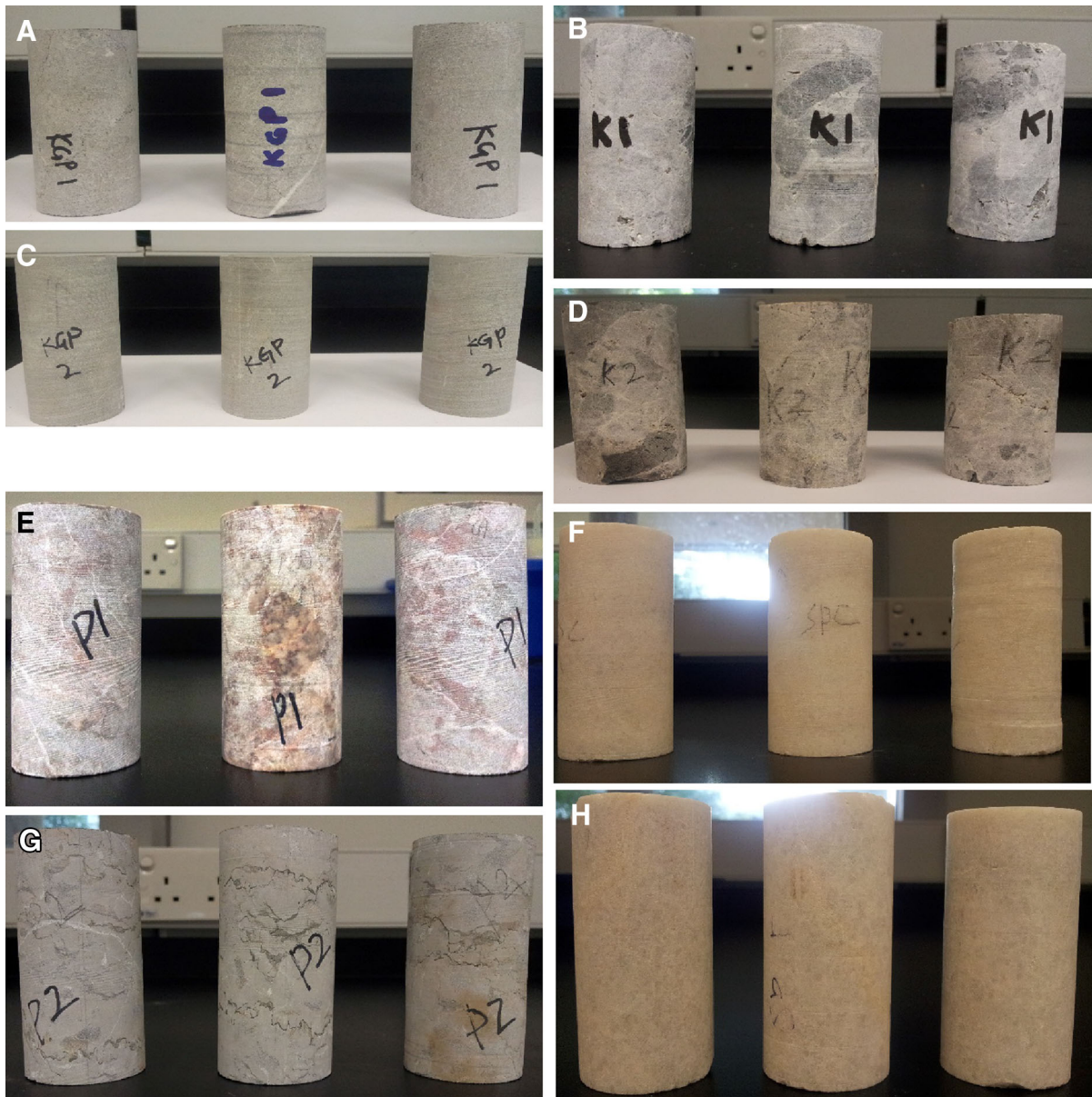
Fig. 4 Cores of the various carbonate rocks from Malaysia. **a** KGP1, **b** K1, **c** KGP2, **d** K2, **e** P1, **f** SP1, **g** P2, **h** SP2

(Carozzi and von Bergen 1987; Van Geet et al. 2000). Therefore, there are differing opinions with regards to the impact of stylolites on fluid flow. Lind et al. (1994) found that the permeability of high porosity chalk samples containing stylolites did not differ from the adjacent stylolite-free material unless the stylolite was associated with fractures.

Variations in the degree of porosity surrounding stylolites has been attributed to dissolution, mass transfer of solute from the stylolite area to the zone of

cementation fabric-selective secondary porosity (Dawson 1988; Raynaud and Carrio-Schaffhauser 1992; Carozzi and von Bergen 1987; Braithwaite 1989; Vajdova et al. 2012). Studies have shown that stylolites can act as conduits for fluid flow gas permeability ranges from 10^{-19} to 10^{-14} m^2.

The current study indicates that the stylolites present in these rocks have the potential to increase the permeability of the carbonate rock (Fig. 5a–d). This is due to the fact that the cavity in the stylolites are
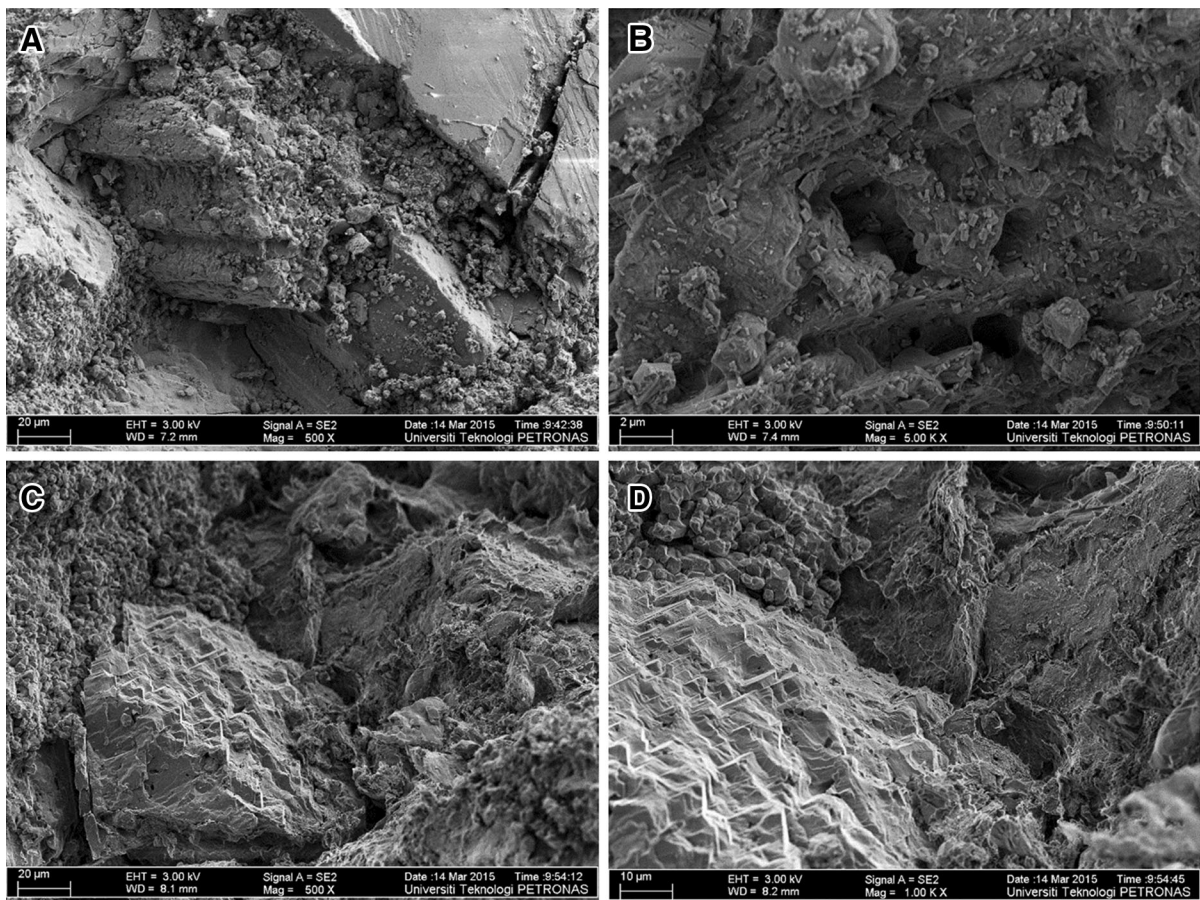
Fig. 5 SEM image of stylolites present in samples from Turkey. **a** Fractures present in stylolitic regions, **b** Micropores in stylolites that have the potential to facilitate fluid flow, **c** & **d** Varied micro-topography and surface rougness on stylolitic regions

generally devoid of clay particles despite comprising of interlocking crystals that formed from the pressure-dissolution mechanism. It is even more interesting to note that the region immediately bordering the stylolites is occupied by fractured calcite crytals. In addition to that, it is worthwhile to note that the surface roughness in the stylolitic region is variable. This then indicates that the boundary layer that defines flow characteristics in porous media is highly variable in stylolitic regions. There is a lack of information on this region globally. This indicates that the stylolites and the mechanism of developing stylolites in these rocks have created an avenue for fluid flow.

3.8 Gaps in knowledge

Apart from stylolites and other natural fractures, it is evident that the region adjacent to these features merits further study. It still remains unclear as to how the different types of carbonate rocks will respond to these critical tests in the presence of stylolites. The nature of stylolites in such rocks need to be studied as well. As pointed out in the text, a larger sampling size is needed to verify certain relationships that will help define stylolites morphology, paleostress magnitudes and directions, heat transfer patterns among others.

4 Conclusions

It has been shown that stylolites that occur in carbonate rocks have different morphologies even in the same matrix. This then contributes to a variety of petrohysical and geomechanical behaviors as seen in this study.

It is evident that thermal conductivity estimation is point-dependant. The perturbations created by the
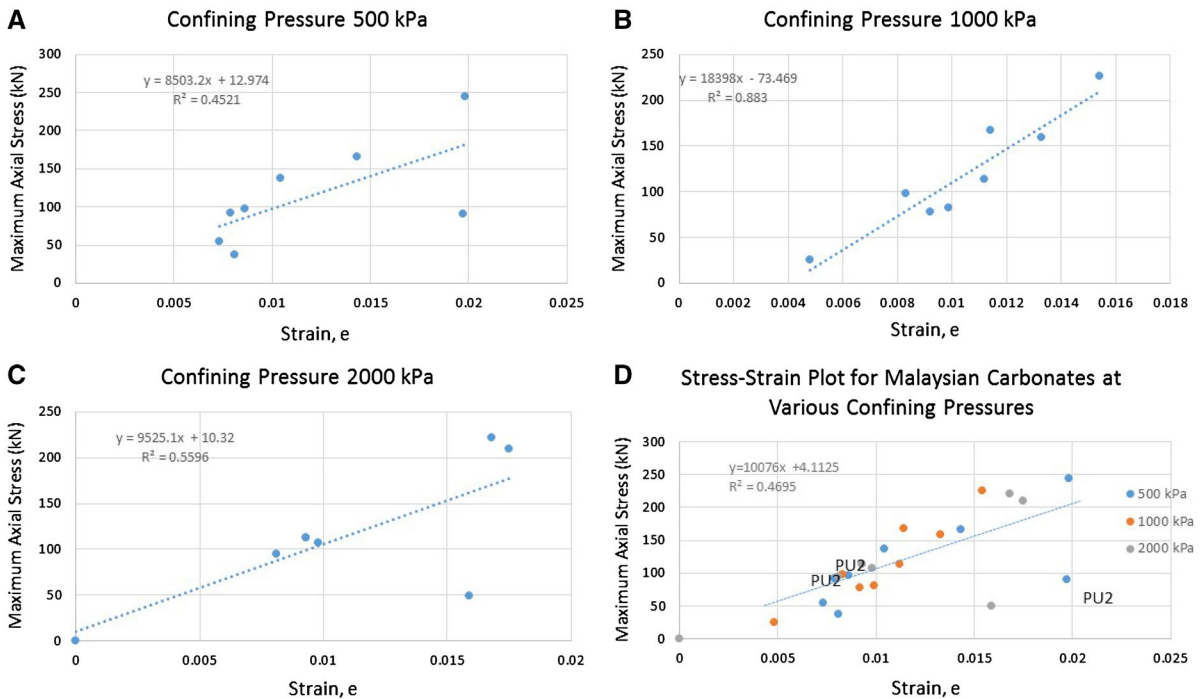
Fig. 6 Stress-strain relationships for carbonate rocks from Malaysia. **a** at confining pressure of 500 kPa, **b** at confining pressure of 1000 kPa, **c** at confining pressure of 2000 kPa and **d** for all confining pressures collectively

stylolites would result in spatial variations in thermal conductivity with possible implications of differences in thermal maturation of hydrocarbon resources at the micro-site levels. The study also shows that thermal conductivity is a spatially variable property and as such should at the very best be described as estimated and not as determined or measured. The perturbation caused by stylolites merits due consideration. Therefore, it is proposed that the presence of stylolites by appended to an earlier proposed definition for fabric anomaly.

This study also indicates that utilizing stylolites as a predictive tool to decipher paleo-stress magnitudes and directions can be ardous. There is possibly a relationship between the type of stylolites and the configuration of the feature. However, due to limited sampling population size, this relationsip remains to be established.

The ability of carbonate rocks such as those used in this study to conduct fluid in the presence of stylolite appears to have been increased. This is understood from the submicroscopic evaluation of the fabric within and surrounding the stylolites. However, an interesting observation has been noted with regards to the dissolution of the material within the stylolites rather than

culminating from a precipitation event. This then suggests a possible post-stylolitic compression leading to further pressure-induced dissolution of the material within the stylolites. This opens up an entirely new subject matter that will not be pursued in this study.

In conclusion, it is contented that stylolites have an impact on defining critical petrophysical properties and to some extend the geomechanical properties in carbonate rocks. The use of stylolites as paleo indicator of stress is an important field that merits further attention. More work needs to be done to establish relationships between the critical properties and features discussed in this study.

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