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Development and scaling relationships of a stylolite population

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Abstract

The frequencies, amplitudes and insoluble residue thicknesses of 4639 stylolites have been measured from ~674.3 m of core from four vertical wells in the Khuff Formation, a Permo-Triassic carbonate reservoir, offshore Abu Dhabi. Although there are similar numbers of stylolites per metre of core in dolomites and limestones, the stylolites in the limestones have approximately double the cumulative amplitudes and insoluble residue thicknesses than the stylolites in dolomites. This indicates that stylolites in the limestones have grown at approximately twice the speed or for twice as long as the stylolites in the dolomites. Stylolite amplitudes in dolomites and limestones together appear to obey a power-law scaling relationship over about one order of magnitude (~20–150 mm). Stylolite amplitudes in dolomites, however, have a higher power-law exponent than those in the limestones, and appear to obey a power-law down to ~10 mm. This indicates that stylolites in the limestones have merged more than the stylolites in the dolomites. The amount of pressure solution, and possibly the scaling of a population of stylolites, may also be controlled by location within the fold, with less pressure solution in the hinge region, into which hydrocarbons migrated earlier than in the limbs.

Keywords: Stylolite; Population; Growth; Scaling

1. Introduction

Stylolites are surfaces on which insoluble residues are concentrated as pressure solution removes such soluble minerals as calcite or quartz (e.g. Stockdale, 1926). The teeth of stylolites point in the shortening direction, and, assuming the stylolites initiated as flat planes and did not propagate out of plane, their amplitudes represent a minimum estimate of the amount of shortening (compaction) that has occurred (Fig. 1; e.g. Fletcher and Pollard, 1981; Rispoli, 1981). Assuming the insoluble material was initially evenly distributed in the rock and that there has been no contamination by circulating fluids, the thickness of insoluble residue along a stylolite would be proportional to the amount of material dissolved and would therefore be proportional to the displacement across the stylolite. Fletcher and Pollard (1981) regard stylolites as a form of fractures with mode-I displacements (cf. Katsman et al., 2005). It is therefore possible to carry out displacement analysis, as for faults.

There has been considerable interest in the relationship between different scales of geological structures. For example, the geometries and mechanics of microscopic fault zones have been shown by Tchalenko (1970) to closely resemble those of continental scale fault zones. Faults are therefore described as being *self-similar* or *scale-invariant*, with the geometry at one scale being very similar to the geometry at other scales. The development of the concept of *fractals* (e.g. Mandelbrot, 1967, 1982; Turcotte, 1990) has provided a method for describing the self-similarity of different scales of structures. For example, the power-law scaling relationship of fault displacements is given by $N = cU^{-D}$, where N = number of faults with a displacement greater than U, c = a constant, and D = the power-law exponent (e.g. Childs et al., 1990; Scholz and Cowie, 1990). The power-law scaling

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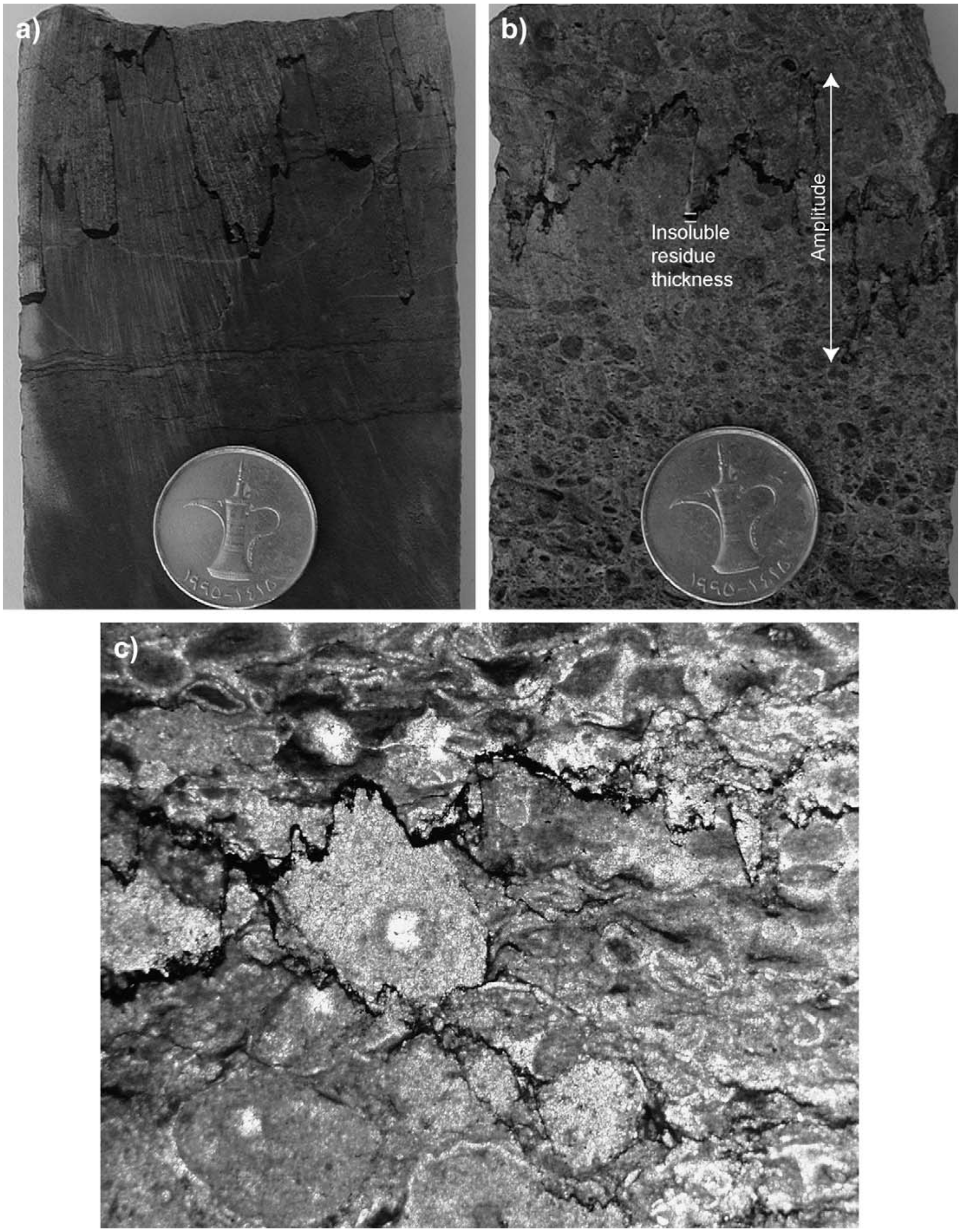

Fig. 1. Examples of stylolites observed in slabbed core from the Khuff Formation. (a) Different lithologies occur on either side of the stylolite, illustrating why stylolite amplitude gives a measure of the minimum amount of material removed by a stylolite. (b) Porosity is greatly reduced near a stylolite, with stepping portions of the stylolite linked by sub-vertical calcite veins. Amplitude and insoluble residue thickness are marked. (c) Photomicrograph of stylolites in the Khuff Formation, illustrating the microscopic nature of many stylolites, and the merger of smaller stylolites to form larger stylolites. The field of view is ∼5 mm across.

relationship for fault displacements has been used to estimate the numbers of faults above and below the scale of resolution of a particular survey, and hence to estimate the total fault-related extension or contraction in a region (e.g. Marrett and Allmendinger, 1992; Walsh and Watterson, 1992). Other examples of the self-similarity of faults include fault trace lengths (e.g. Villemin et al., 1995) and the ratio of fault trace lengths to maximum displacements for a fault population (e.g. Dawers et al., 1993). Note, however, that it is possible some fault populations show non-fractal (e.g. negative-exponential, log-normal, etc.) size-frequency distributions for displacements or trace lengths (e.g. Nicol et al., 1996; Spyropoulos et al., 1999).

Previous work on the scaling of stylolites has focused on the geometries of individual stylolite surfaces and on the spacing between stylolites. Several papers have shown that stylolite planes have fractal geometries (e.g. Hassan et al., 2002; Karcz and Scholz, 2003; Renard et al., 2004). Merino et al. (1983) suggest that stylolites are approximately evenly spaced in initially uniform rock. The Merino et al. (1983) model involves stylolite initiation at grain boundaries in porous rocks, where stresses are high. Precipitation in pores adjacent to the developing stylolite creates a low porosity zone (e.g. Fig. 1b), with a new stylolite tending to initiate in the higher porosity rocks further from the stylolite. This process is repeated to produce approximately evenly spaced stylolites. Railsback (1998) shows, however, that stylolites tend to have an approximately random distribution.

Although there have been numerous papers about the fractal geometry of individual stylolite traces, there does not appear to have been any published work on the scaling of a *population* of stylolites (e.g. relationships between stylolite amplitudes and between insoluble residue thicknesses measured along scanlines). This is possibly because of the problems in measuring a meaningful number of stylolites in an individual exposure or from core. The 4639 stylolites measured from the ~674 m of core from four wells in the Khuff Formation therefore provide an ideal dataset for analysing the scaling relationships of a population of stylolites. This paper describes the scaling relationships of the population of stylolites and relates these to factors that may control the distribution of stylolites and the amount of pressure solution.

2. The Khuff Formation

The Upper Permian and Lower Triassic Khuff Formation consists of shallow marine limestones, dolomites and anhydrites, and is between about 590 m and 920 m thick in Abu Dhabi. It is an important gas reservoir throughout the Gulf and in Saudi Arabia. The Khuff Formation was deposited during the earliest major transgression over shallow continental shelf along the southern margin of the Tethys Ocean. Limestones and dolomites are distributed through the Khuff Formation in zones from ~0.3 m thick to >50 m thick (Fig. 2). The analysed core consists of carbonates (of which ~29% is limestone and ~71% is dolomite) and some anhydrites. It consists of seven reservoir zones, in which porosities are relatively high, separated by anhydrite-rich, low-porosity "dense zones". The four wells analysed are in a large gas field, offshore Abu Dhabi. The field is a domal anticline, with limbs dipping at up to ~4°. The reservoir has matrix porosity of up to ~30%, but fractures add significantly to production.

Almost all of the stylolites observed in core are sub-horizontal, formed by the weight of the overburden (i.e. when maximum compressive stress was vertical). The 4639 stylolites measured over 674 m of core have a cumulative amplitude of ~35.4 m, representing ~5.25% compaction (Table 1). A few steeply dipping or vertical stylolites with amplitudes of a few millimetres have been observed, and these indicate a period when the maximum compressive stress was sub-horizontal.

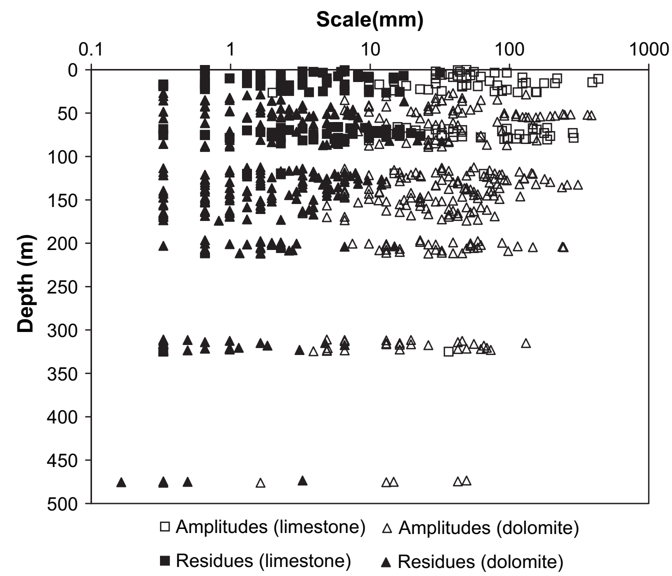

Fig. 2. Stylolite amplitudes (mm) and residue thicknesses (mm) below an arbitrary datum level in well A for limestones and dolomites. Gaps in the data are caused by lack of core coverage.

The core has not been orientated, so the orientations and origins of these steep stylolites cannot be determined.

Stylolites have a strong effect on porosity and permeability in the Khuff Formation. Material dissolved along stylolites is commonly reprecipitated within the pores of the adjacent rocks, thereby reducing porosity and permeability (Fig. 1). There is therefore a strong correlation between stylolite intensity and reservoir quality in the Khuff Formation. Also, insoluble residue along the stylolites is up to several millimetres thick and may hinder fluid flow, and commonly act as barriers to the propagation of joints. Filled macroscopic fractures occur between stepping stylolites (Fig. 1b). Thin section analysis reveals no open microfractures associated with stylolites, although these are commonly described in carbonate rocks elsewhere (Nelson, 1981). Understanding the distribution of stylolites therefore helps in understanding porosity and permeability through a reservoir.

Table 1
Thicknesses and depths of core examined in the four wells

Well	Core (m)	Top (m)	Bottom (m)	% Limestone	Sum of stylolite amplitudes (mm)	% Compaction
A	204.2	3796.6	4529.3	28.9	7845.4	3.8
B	214.6	3994.3	4318.4	31	12129.8	5.7
C	129.4	3774.2	4220.2	36.7	6518.2	5.0
D	126.1	3994.9	4424.2	19.8	8871.5	7.0
Total	674.3				35364.9	5.2

Wells A and C are in the hinge region of the fold, with the core being from approximately 200 m above the core from wells B and D. Percent compaction is calculated from the total stylolite amplitudes divided by the length of core. Wells A and C have the least compaction, with the similarities between wells B and C possibly because well B has a higher proportion of the relatively insoluble dolomite. Well D shows relatively high compaction even though it has a low percentage of relatively soluble limestone.

3. Methods and sampling problems

Approximately 674.3 m of rock have been logged from slabbed core from four vertical wells in a gas field in the Khuff Formation, offshore Abu Dhabi. Wells A and C are near the hinge region of the fold, with core from wells A and C being from locations where the Khuff Formation is ∼200 m topographically higher than from wells B and D, which are on the limbs of the fold and in approximately the same rock sequence (Table 1). These cores were originally logged in feet (e.g. number of stylolites per foot), but the measurements have been converted to metres. Sedimentological logs include information about composition (i.e. limestone, dolomite and anhydrite) and carbonate texture (i.e. boundstone to mudstone). Stylolites have been observed in thin section (e.g. Fig. 1c), but systematic measurements have not been made of microscopic stylolites.

Several problems were encountered in measuring stylolites in core. (1) It is difficult to measure amplitudes and especially insoluble residue thicknesses (Fig. 1b) of smaller stylolites. Amplitudes of <2 mm and insoluble residue thicknesses of <0.5 mm are only estimates. (2) It can be difficult to distinguish stylolites from bedding or primary sedimentary structures in clay-rich rocks. In this study, stylolites were distinguished on the basis of the teeth that indicate pressure solution. (3) Core tends to break along thicker stylolites. The core, however, is generally of good quality and it is usually easy to identify all macroscopic stylolites present. Errors for stylolite amplitudes are probably ∼5% for stylolites with amplitudes of >10 mm. Errors of up to 20% are likely for insoluble residue thicknesses.

4. Controls on the distribution of stylolites

The data suggest that the following factors control the distribution of stylolites in the Khuff Formation.

4.1. Location within the fold

There are more stylolites per metre and ∼50% more pressure solution (indicated by stylolite amplitudes) in well D than in wells A and C (Fig. 3 and Table 1). This may be because earlier gas migration into the hinge region of the fold suppressed pressure solution (Feazel and Schatzinger, 1985). Hydrocarbon emplacement commonly reduces or stops dissolution and cementation in carbonate reservoirs, as reviewed by Worden and Heasley (2000). This seems particularly likely with gas, through which dissolved minerals would be unlikely to migrate. The relatively low values for pressure solution in well B may be because it has a relatively high proportion of dolomite.

4.2. Effects of rock composition

Similar numbers of stylolites per metre occur in the limestones and the dolomites (Fig. 3a), but cumulative stylolite amplitudes (Fig. 3b) and insoluble residue thicknesses per

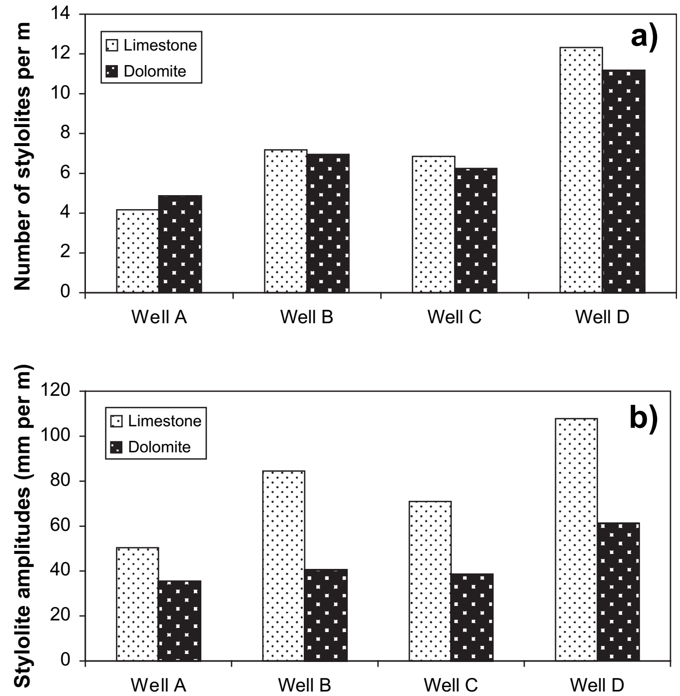

Fig. 3. Stylolite characteristics in the four logged wells. (a) Numbers of stylolites per metre of core in limestones and dolomites, showing no significant differences between the two lithologies. (b) Stylolite amplitudes (millimetres per metre of core) in limestones and dolomites. There is approximately twice as much pressure solution in limestones as in dolomites, indicating that the rate of pressure solution in limestones is twice that in dolomites under mechanical conditions in the Khuff Formation, or that the limestones have been affected by pressure solution for twice as long as the dolomites. There is more pressure solution in wells B and D than in wells A and C, probably because earlier gas migration into the hinge region of the fold suppressed pressure solution.

metre are about twice as much in limestone as in dolomites. Average stylolite amplitudes are 10.17 mm in limestones and 5.75 mm in dolomites. The age of the dolomitisation is uncertain. Fig. 3 suggests that, if dolomitisation occurred before the onset of pressure solution, the rate of pressure solution in limestones is twice that in dolomites under the mechanical conditions in the Khuff Formation. If, however, dolomitisation occurred during pressure solution, then the dolomitisation would have caused a greater reduction in the rate of pressure solution. There are no apparent differences in the textures of dolomites and limestones that may be responsible for the differences in the amount of pressure solution. Limestones tend to have lower porosities, probably because more pressure solution has occurred than in the dolomites. Increased magnesium appears to reduce the rate of pressure solution (e.g. Zhang et al., 2002).

4.3. Rock texture

Boundstones have fewer stylolites than the finer rocks (Fig. 4a), with no evidence of intergranular pressure solution. Low stylolite frequencies correspond with low stylolite amplitudes in boundstones (Fig. 4b). Apart from the boundstones,

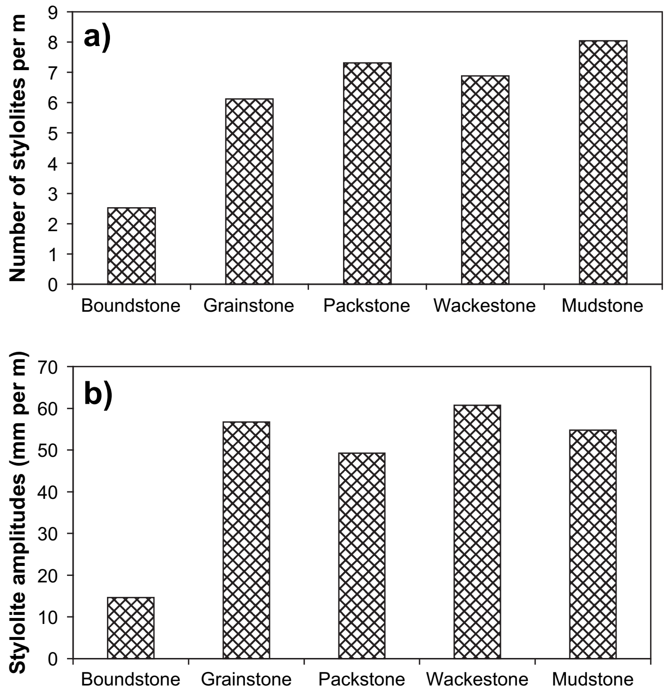

Fig. 4. Stylolite characteristics in different texture carbonates in well B. (a) Numbers of stylolites per metre. There is a tendency for more stylolites in finer rocks, so boundstones have fewer stylolites than wackestones. (b) Stylolite amplitudes (millimetres per metre of core). There is no tendency for more pressure solution in finer rock, although pressure solution has been suppressed in the porous boundstones.

there is no tendency for more pressure solution in finer rocks, as indicated by cumulative stylolite amplitudes (Fig. 4b). Qualitative inspection of core suggests that fewer stylolites tend occur in more porous rocks, and that pressure solution is suppressed in the more shaley and muddy rocks, possibly because there is less carbonate material to be dissolved. The rate of pressure solution is controlled by the slowest of the dissolution, transport and reprecipitation of material (Knipe, 1989), so it is also possible that transport of material is slow in mud-rich rocks.

4.4. Reservoir and dense zones

Fewer stylolites per metre (Fig. 5a) and less pressure solution (Fig. 5b) tend to occur within the dense zones. This may be because pressure solution is inhibited by the anhydrite and the related low porosities and permeabilities within the dense zones.

5. Stylolite scaling relationships

Stylolite amplitudes appear to obey a single power-law scaling relationship over the 20 mm to 150 mm range (Fig. 6a). It is possible that stylolites with amplitudes of less than 20 mm are under-sampled because they are harder to see. It is probable, however, that there are proportionally fewer small stylolites because they merge into braided zones and become merged to form a bigger stylolite (Fig. 1c). Insoluble residue thicknesses also appear to obey a power-law scaling relationship, over the 1 mm to 10 mm range (Fig. 6b).

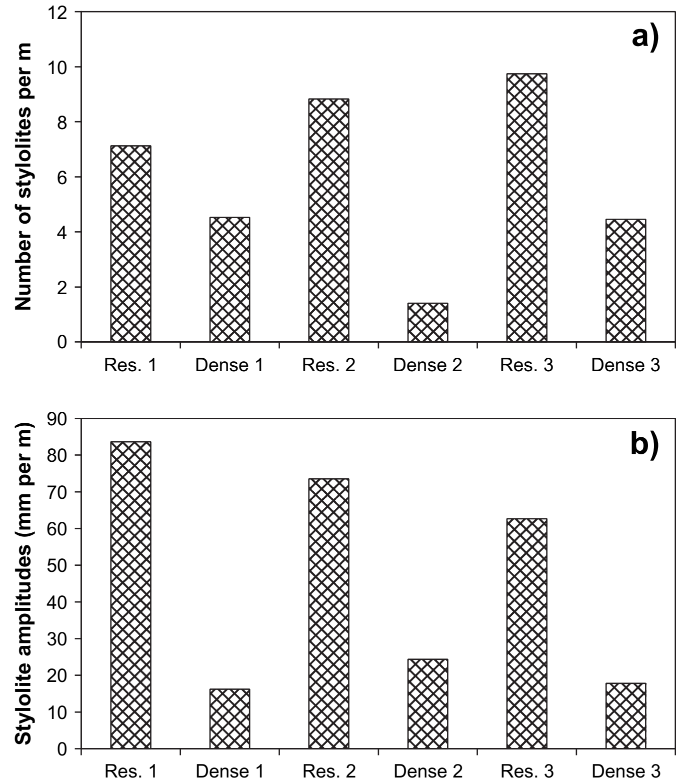

Fig. 5. Stylolite characteristics in the reservoir and dense zones of the Khuff Formation of well B. (a) Number of stylolites per metre. There is a tendency for fewer stylolites in the anhydrite-rich, low permeability dense zones. (b) Stylolite amplitudes (millimetres per metre of core). There is a tendency for lower stylolite amplitudes in the dense zones, indicating pressure solution is inhibited by the anhydrite and low porosity in the dense zones.

Limestones and dolomites show similar scaling relationships (Fig. 6a and b), although the graph of stylolite amplitudes for the dolomites is slightly steeper. This may be because stylolites are less developed and therefore less merged in the dolomites than in the limestones. This is also indicated by the stylolite amplitudes in the dolomites having a power-law scaling relationship down to about 10 mm, while stylolite amplitudes in the limestone have a power-law scaling relationship down at about 20 mm.

Fig. 6c shows the scaling relationships of stylolite amplitudes in wells A and D. The slightly gentler slope of the graph for well D may be because it is on the limbs of the fold, where there is more intense pressure solution and therefore greater merger between stylolites than in the hinge region of the fold (as at well A). The difference between wells A and D may have been caused, however, by the small number of stylolites with large amplitudes in well D.

There is a weak correlation between the thicknesses of the insoluble residues and the amplitudes of the stylolites (Fig. 6d). This indicates that either stylolite amplitudes or thicknesses of insoluble residues are not proportional to displacement. The mean values of stylolite amplitude divided by insoluble residue thickness is 34.4 (standard deviation of 36.1) for limestones and 42 (standard deviation of 42.4) for dolomites.

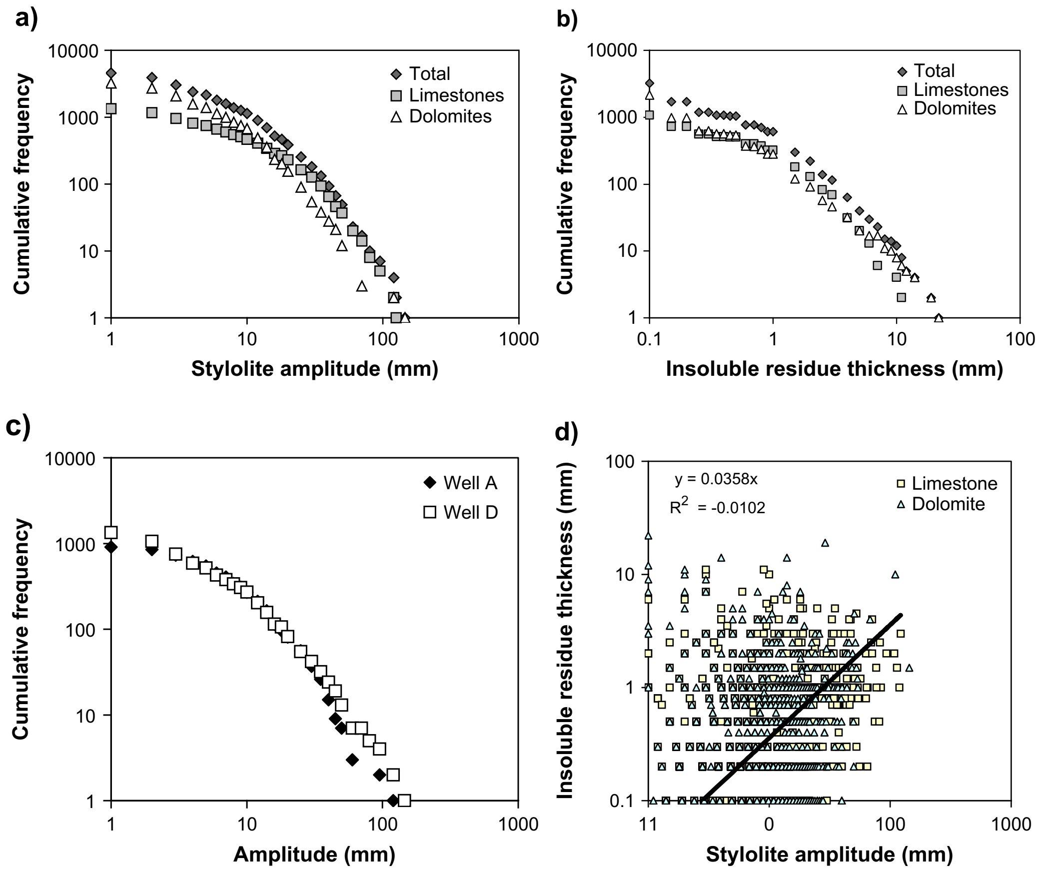

Fig. 6. Scaling characteristics of the population of stylolites ($n = 4639$ from four vertical wells). (a) Cumulative frequency against stylolite amplitude. (b) Insoluble residue thickness of stylolites against cumulative frequency. The stylolites appear to obey power-law scaling relationships for both amplitude and insoluble residue thickness. (c) Scaling of stylolite amplitudes for wells A and D. Well A appears to have a slightly steeper slope. This may be because it is in the hinge region of the fold, so shows fewer mergers of smaller stylolites to form bigger stylolites than does well D, where hydrocarbons were probably emplaced later. (d) Graph of insoluble residue thickness against stylolite amplitudes, which show a weak correlation.

6. Conclusions

Pressure solution, as indicated by stylolite frequencies, amplitudes and insoluble residue thicknesses, is controlled by the following factors:

1. Pressure solution is about 50% more intense in well D than in wells A and C. This is probably because stylolite development was suppressed progressively by gas emplacement, starting in the hinge region and later into limbs of the fold.
2. There is twice as much pressure solution in limestones as in dolomites, because rates of pressure solution are lower in dolomites. Lucia (2004) shows that dolomites are less susceptible to compaction than limestones, although does not mention different rates of pressure solution as a factor in controlling this compaction. Zhang et al. (2002) show that increased magnesium reduces the rate of pressure solution. Well B may have less pressure solution than well D, which is also on the limb of the fold, because it has a higher proportion of dolomite.
3. There is a tendency for more stylolites in finer rocks, so boundstones have fewer stylolites than wackestones. There is, however, no tendency for more pressure solution (as indicated by stylolite amplitudes) in finer rocks.
4. Anhydrite and the related low porosities and permeabilities appear to have inhibited pressure solution within the dense zones.

Stylolite amplitudes and insoluble residue thicknesses appear to obey power-law scaling relationships. The steeper power-law exponent for stylolite amplitudes in the limestones and the possibly steeper power-law exponent for the limbs of the fold indicate more pressure solution and more merger between stylolites than in dolomites and in the hinge region of the fold. The rocks with the least pressure solution are dolomites in the hinge region of the fold, so these have the highest porosities and form the best reservoirs.

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