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Three-dimensional morphology and connectivity of stylolites hyperactivated during veining

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Abstract

The limestone of the Palaeozoic Jack Formation in north Queensland, Australia, contains bedding-parallel stylolites that locally increase in amplitude adjacent to calcite veins. The veins formed in response to inhomogeneous strain locally superposed on the tightly folded strata. Stylolites were locally hyperactivated during vein formation and provided calcite for vein filling. Three-dimensional reconstructions of the morphology of the stylolites, based on detailed serial profiles, demonstrate that the side-faces of columnar stylolites form an interconnected fluid pathway through the rock. The connective morphology defines a drainage network comprising highly tortuous major trunks of high amplitude side-faces linked locally by minor pathways of variable amplitude. The permeability pathway anastomoses in three dimensions making it impossible to image in two dimensions alone.

1. Introduction

Stylolites are common features in carbonate rocks, form throughout diagenesis (Moss and Tucker, 1995; Clari and Martire, 1996), and form or reactivate during tectonic activity (Newman and Mitra, 1994). Stylolite formation is intimately related to changes in rock (Carrio-Schaffhauser et al., 1990). Stylolites influence fluid flow in limestones on a basin-wide scale (Ortoleva et al., 1995), petroleum generation (Leythaeuser et al., 1995), dolomitization (Srinivasan et al., 1994) and the formation of veins (Ramsay, 1982). Stylolite-vein systems can accommodate large bulk strain through the process of fluid transfer (Mullenax and Gray, 1984; De Paor et al., 1991).

Generally, "in three-dimensions the stylolite surface is characterized by a complex interfingering of material" (Drummond and Sexton, 1998, p. 8). However, investigations of stylolite morphology have been based on the two-dimensional morphology normal to the stylolitic surface (Park and Schot, 1968; Tada and Siever, 1989; Andrews and Railsback, 1997). The progress of investigations into the processes of stylolite initiation and growth (Gal and Nur, 1998; Railsback, 1998) requires an understanding of the three-dimensional connectivity of stylolites, which is presently lacking.

This paper establishes the structural setting of stylolites locally hyperactivated during the formation of veins. Detailed serial sections through the stylolitized and veined limestone illustrate the three-dimensional morphology and connectivity of these columnar stylolites. The implications of the morphology of stylolites for fluid flow during the formation of stylolites are considered.

2. Field locality

Calcite veins and stylolites are well developed in limestone of the Jack Formation in north Queensland, Australia. The Jack Formation is a carbonate-rich unit at the top of the clastic-dominated Graveyard Creek Group of the Broken River Province (Fielding et al., 1993). The Broken River Province forms part of the northern section of the Palaeozoic Tasman Fold Belt of eastern Australia. The Jack Formation has a Late

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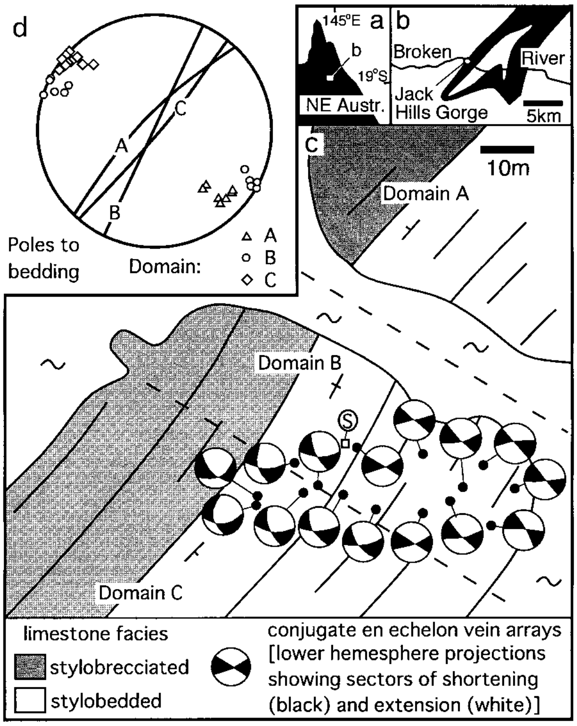

Fig. 1. (a, b) Location maps of the Jack Hills Gorge on Broken River, north Queensland, Australia. The dominant structure is an elongate dome of Palaeozoic strata (Silurian strata shown in black). (c) Geological map of outcrop of the lower Jack Limestone in the bed of Broken River (alluvium and standing water shown by wave marks). The beds young toward the NW. Three-dimensional stylolite morphology in sample (S) is illustrated in Figs. 6 and 7. Three structural domains (A, B and C, separated by dashed lines) are based on (d) the equal angle stereographic representation of the orientation of bedding. Great circles representing the mean orientation in each domain are shown.

Silurian age and the upper parts may be earliest Devonian (Fielding et al., 1993). The formation is composed of lower and upper fine-grained, locally muddy, fossiliferous limestone units separated by bedded arenites and mudrocks with abundant fossils. During the Early Carboniferous, the strata were folded into tight to open folds (Lang, 1993).

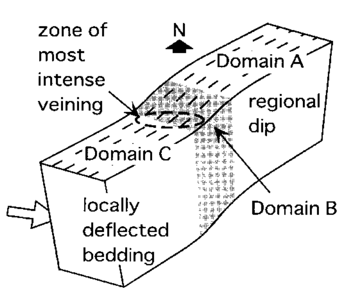

Fig. 2. (a) Three-dimensional schematic representation of structural domains A, B and C. Deflection (open arrow) of domain C is interpreted to be responsible for the zone of veining near the domain B–C boundary and the local hyperactivation of stylolites.

Exposure of the lower Jack Limestone member in Broken River shows NE–SW striking limestone with stylolites developed on bedding and fracture surfaces. The lower part of the exposure is stylobedded and the upper part is stylobrecciated (Flugel, 1982; Fig. 1). Three structural domains are recognised. Domain A is steeply NW-dipping and conforms to the regional orientation of strata around the field locality. Domain B has NNE–SSW strike with vertical dip and Domain C is steeply SE-dipping. This structural configuration indicates that the strata in Domain C have been deflected toward the southeast with respect to the orientation of regional bedding dip, and Domain B is a transition zone for this change in bedding dip (Fig. 2).

3. Vein systems

Veins are widely distributed throughout the lower limestone member of the Jack Formation (Smith, 1997). White calcite veins, with up to 20-mm aperture widths, occur in arrays with widths up to 25 cm. Well developed vein arrays are concentrated in an east–west-trending band within the bedded limestone facies (Fig. 1c). The concentration of veins near the Domain B–C boundary is interpreted to mean that the vein arrays formed during the development of the structural domains. Arrays with left-stepping and right-stepping en échelon arrangements are inferred to form by dextral shear displacement and sinistral shear displacement, respectively. Where dextral and sinistral vein arrays occur in close proximity, and their zone of intersection contains evidence of simultaneous formation such as fractures parallel to the acute bisector, they are interpreted to be a conjugate pair of vein arrays.

To determine the strain pattern recorded by the vein arrays, the orientations of 15 conjugate vein systems were measured. The maximum principal shortening axes inferred from the acute bisectors for the arrays cluster around a horizontal WNW–ESE trend (Fig. 1c). The maximum principal extension axes inferred from the obtuse bisectors of the arrays mainly trend NNE but the angle of plunge progressively increases from sub-horizontal at the base of the exposed unit to a moderate plunge about 50 m above the base of the exposure (Fig. 1c).

4. Stylolites

Stylolites are developed on fractures and bedding surfaces. The lower (eastern) part of the exposure contains predominantly bedding-parallel stylolites (stylobedded facies). The stylolites are continuous through vein arrays and their orientation is deflected in the directions expected from the inferred sense of shear of

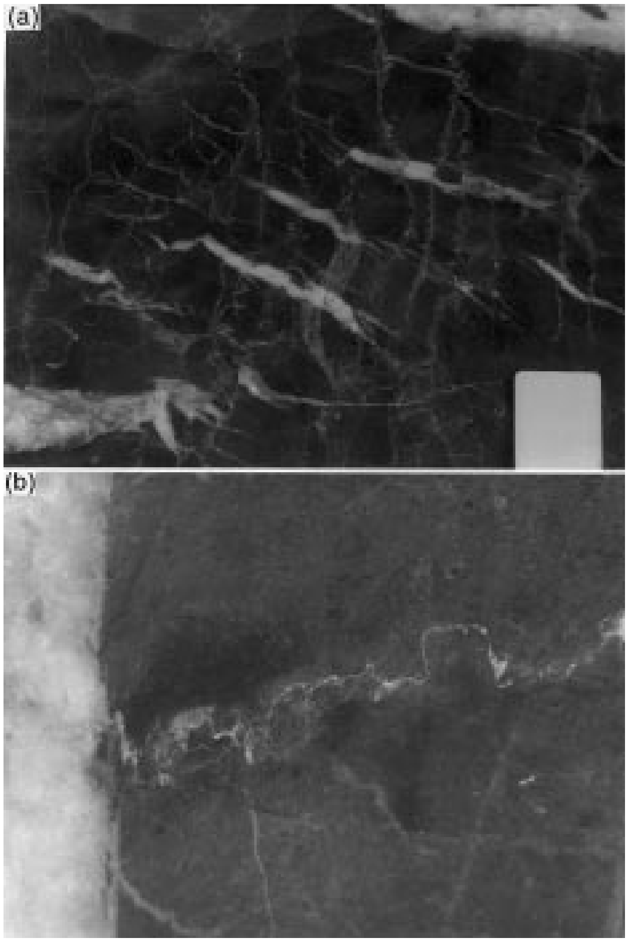

Fig. 3. (a) Photograph of a dextral array of calcite veins (white). Stylolites (top to bottom) are deflected across vein arrays. Scale bar is 30 mm across. (b) Profile of a stylolite showing a calcite vein on the left. Field of view 32 mm across. This face is opposite to the face at the front of Fig. 6(a).

the arrays. Veins typically continue through stylolites, but they are disrupted by dissolution at stylolites indicating that veining and stylolite activity overlapped in time (Ramsay and Huber, 1987, p. 627).

Field measurements of maximum stylolite amplitudes in the lower Jack Formation range from 1.7 mm (standard deviation, $\sigma = 0.9$; number of measurements, $n = 63$) at sites more than 1 m distant from veins, to 2.0 mm ($\sigma = 0.7$, $n = 23$) between 5 and 20 cm distant from veins, to 4.7 mm ($\sigma = 1.5$, $n = 22$) at less than 2 cm from veins. The change in stylolite amplitude is accompanied by sigmoidal curvature across vein arrays (Figs. 3a and 4). Because the low-amplitude bedding-parallel stylolites and the high-amplitude stylolites associated with veins are continuous and both compatible with NW–SE compression, the stylolites are referred to as hyperactivated rather than reactivated.

To facilitate a discussion of three-dimensional stylolite morphology appropriate terminology is introduced (Fig. 5). Columnar stylolites have two main morphological

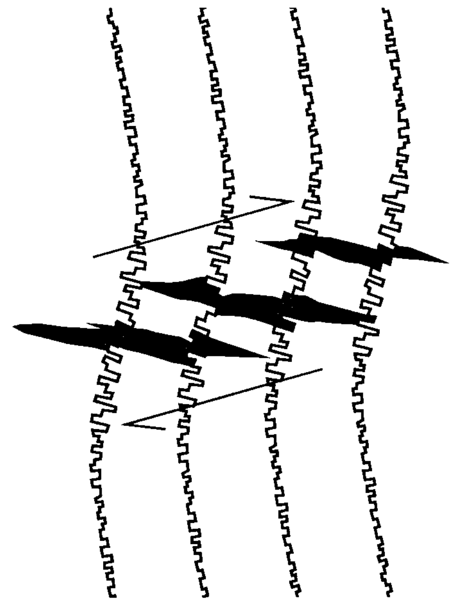

Fig. 4. Schematic diagram of hyperactivated stylolites in a vein array. Stylolite amplitude is greater within arrays and sigmoidal curvature of stylolites is consistent with sense of shear of array (arrows). Veins (shaded) and stylolites are in a similar orientation to that shown in Fig. 3(a).

components: (1) end-faces, which are commonly enriched in low solubility components of the rock, and (2) side-faces, which are generally perpendicular to end-faces. End-faces are subdivided into: (1) terminal end-faces, which are bound by side-faces projecting in the same direction (both up or both down) and (2) intermediate end-faces, which are bound by side-faces projecting in opposite directions (up and down). Terminal end-faces are either upper or lower as a function of orientation. A purpose of this paper is to use serial sections to make the geometric interpretation that side-faces have complex continuous traces that wrap around end-faces.

5. Serial sections

To investigate the three-dimensional morphology of

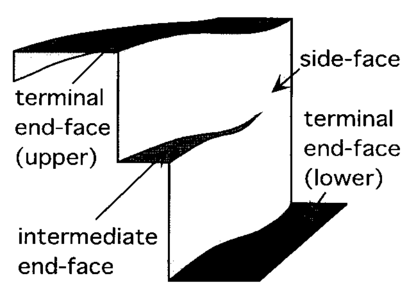

Fig. 5. Terminology for the three-dimensional morphological elements of stylolites as used in text.

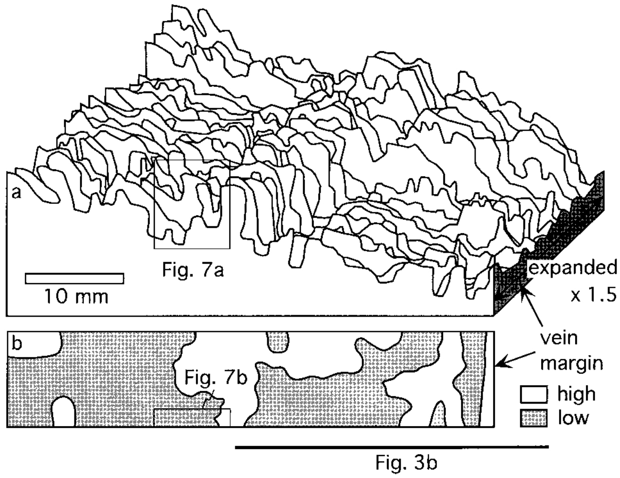

Fig. 6. (a) Twenty-one stacked profiles at a 0.5-mm interval through 10 mm of stylolitized limestone adjacent to a vein. (b) Plan view of stylolite relative to a datum surface showing zones which are predominantly above (light shading) and below (dark shading) an average datum surface. Zones are separated by continuous side-faces. Fig. 3(b) is a photograph of the face opposite the front of the block from which the profiles were generated.

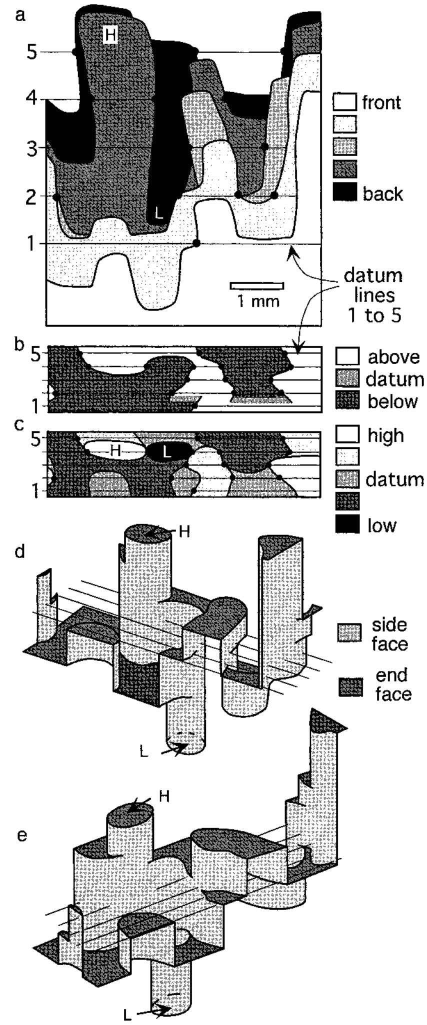

Fig. 7. (a) Detailed stacked profiles obtained at an interval of 0.25 mm through 1 mm of limestone. Dots indicate intersections of profiles and the datum surface (fine lines). (b) Datum-parallel section showing only side-faces (lines) which intersect the datum. End-faces above, below and intersecting the datum are also shown (shading). Dots show intersections of side-faces and datum as in (a). (c) Datum plan view of stylolite showing all side-faces (lines) projected onto the datum and end-faces in five depth bands relative to the datum (shading). (d and e) Isometric diagrams (from front right and front left, respectively) of the stylolite showing the three-dimensional geometry of the stylolite columns. H and L mark adjacent high and low points on the stylolite to assist comparison of figure parts.

the stylolites near the veins, sections were cut perpendicular and parallel to stylolites in one sample (Fig. 1c, S). Sections perpendicular to stylolites confirmed the columnar pattern observed in the field (Fig. 3). To determine the three-dimensional geometry of stylolites, serial perpendicular profiles were used. The serial profiles were created in a rectangular block ($55 \times 50 \times 20$ mm^3) of limestone containing a prominent stylolite and vein by progressively grinding with corundum grit on a glass plate. Photographic images were taken at an interval of 0.25 mm for the first 1 mm and 0.5 mm for a further 9 mm (measured by micrometer), producing five profiles with a 0.25-mm spacing and a total of 21 profiles with a 0.5-mm spacing.

The profiles show the complex three-dimensional morphology of the stylolite surface (Fig. 6a). The height of side-faces is extremely variable but continuous zones of high amplitude can be identified in the profiles. Continuous side-faces in excess of 3-mm high are shown in plan view (Fig. 6b), defining areas of upward and downward penetration. Side-faces become more regularly spaced and vein-parallel approaching the vein.

A set of five stacked profiles (0.25-mm-spaced sections) shows the morphology of the stylolite relative to a datum surface (Fig. 7a). The locations of side-faces intersecting the datum on a plan view section (Fig. 7b) shows the limitations of a two-dimensional image parallel to a stylolite since it fails to show how the side-faces are interconnected. The locations of all side-faces were projected onto plan view (Fig. 7c). Fig. 7(c) shows that side-faces at different levels relative to the datum are interconnected. To illustrate the three-dimensional morphology, isometric projections for the interpreted linked side-faces were constructed (Fig.7d, e). The side-faces anastomose by splitting into branches separated by intermediate end-faces. All end-faces are also linked by the anastomosing scroll of side-faces. The three-dimensional reconstruction shown in Fig. 7(d) and (e) have been simplified by maintaining side-faces at a constant height. In reality, the height of side-faces is variable adding further complexity and difficulty in graphical representation.

The effects of dissolution are evidenced by the presence of insoluble components including clay and iron oxide at end-faces. The side-faces of the hyperactivated stylolites host calcite deposits (Fig. 3) which supports the interpretation of their role as fluid pathways. Some end-faces appear to host calcite also, but three-dimensional investigation showed that these 'pseudo-end-faces' were formed by two-dimensional surfaces intersecting side-faces at an acute angle.

Network geometric characteristics such as connectivity for the stylolites are determined from the three-dimensional morphology of side-faces and their ability to link end-faces. In the example investigated here high amplitude side-faces form a continuous but highly tortuous surface.

6. Discussion

The zone of most intense veining occurs in the stylo-bedded limestone facies and does not continue into the brecciated limestone facies (Fig. 1) indicating the latter lithology was unsuitable to form the same style of mesoscale fractures. The concentration of veining near the Domain B–C boundary suggests that the vein systems formed in response to the deformation recorded by the structural domains. Therefore, the veins formed by localised deformation at the end or after the main phase of folding. The high-amplitude parts of stylolites observed in vein arrays are therefore hyperactivated parts of the previously formed bedding-parallel stylolites.

The side-faces of stylolites form an interconnected network around the end-faces, which occur at various heights relative to the datum surface. Between the major high-amplitude side-faces there is an interconnected network of side-faces of lower amplitude down to the sub-millimetre level. The side-faces make a highly tortuous but continuous network throughout the rock. The side-faces decrease in tortuousity and become vein-parallel within about 10 mm of the vein. This geometric change is interpreted to mean that vein formation locally influenced stylolite growth.

The morphological description of stylolites presented here indicates that they are geometrically analogous to a drainage network with a hierarchy of channel sizes as defined by the height of side-faces. Based on this geometry, fluid flow through a stylolite could potentially be modelled as a three-dimensional network of paths with variable permeability related to the variation in amplitude of side-faces.

7. Conclusions

Sub-millimetre serial sections through stylolites in limestone illustrate the three-dimensional morphology of the structure. Stylolites form a connected 'anastomosing continuous scroll' with a hierarchy of column heights. This morphology, and in particular the interconnectedness of its parts, cannot be observed in two-dimensional images normal or parallel to stylolite surfaces. The high amplitude of stylolites in the vicinity of vein arrays indicates they were hyperactivated during vein formation. The close association of veins and stylolites is evidenced in three-dimensions by stylolite morphology changing from sub-circular columns to vein-parallel ridges within millimetres of veins.

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