

Rock matrix structures in a zone influenced by a stylolite

SUZANNE RAYNAUD

Laboratoire de Géologie Structurale et Appliquée, Université de Provence, 13331 Marseille Cédex 3, France

and

ELISABETH CARRIO-SCHAFFHAUSER

Laboratoire de Géophysique Interne et Tectonophysique, IRIGM, Université J. Fourier, BP 53 X,
38041 Grenoble Cédex, France

(Received 3 October 1991; accepted in revised form 27 May 1992)

Abstract—A stylolitic structure is one of the visible manifestations of the pressure-solution process in a rock. The stylolitic 'process' zone (as defined in previous studies) on both sides of a stylolite, is studied by SEM. The chosen samples concern tectonic stylolites within a high porosity limestone (16%) without tension gashes. This zone corresponds to a local increase of porosity and comprises a large number of stylolitic joints showing a decreasing size from the macroscopic structure to simple contact between two grains. Two hypotheses are presented for the stylolite formation: (1) the macroscopic stylolite is the result of the coalescence of earlier minor pressure-solution structures; (2) small stylolites nucleate gradually from a major stylolite joint.

The mass transfer can be realized either by diffusion between particles or by seepage through previously undescribed process zone fractures. The mass deposition can be localized in the porous volume and the microcracks, without requiring any additional tectonic openings including tension gashes. The rock deformation is therefore limited to shortening parallel to σ_1 , without normal extension.

INTRODUCTION—PREVIOUS WORK

RECENT studies (Carrio-Schaffhauser *et al.* 1990, Raynaud *et al.* 1990) have shown the existence of a matrix structure around a stylolite joint. A general scheme of stylolitic structures was provided by the analysis of vertical tectonic stylolites sampled from drill core (1000 m in average depth) in limestones located in south-eastern France (Provence). These pressure-solution joints which caused a bulk shortening of 20%, are several centimetres long and show one or two terminations in the core plugs. They are outlined by insoluble residue concentrations. These stylolites are not associated with tension gashes. The host rock is an homogeneous micritic limestone (98–100% CaCO_3), made up of grains a few microns in diameter, with random orientation. The original porosity of the rock is 16% and the permeability is very low, less than $10^{-10} \text{ m s}^{-1}$ (Carrio-Schaffhauser & Gaviglio 1990).

The investigation methods used here were chosen to allow the description and interpretation of the internal structure of the material. In particular the distribution of the porosity within the samples has been studied using computer-assisted tomography (CAT), a non-destructive method used recently to study the deformation of rock (Raynaud *et al.* 1989, 1990, Carrio-Schaffhauser *et al.* 1990). The morphology of the grains and voids and the size of the grains were examined by SEM. Also, the porosity has been quantified, and the distribution of pore sizes measured, using mercury injection. Using these methods several distinct zones are detected in the stylolite (Figs. 1 and 2).

The undeformed zone (A)

In zone A, remote from the stylolite, the porosity is 15%. The micropores are $0.2 \mu\text{m}$ wide. SEM images show a tight or interlocking structure of ovoid to elongated micritic particles $0.6\text{--}1 \mu\text{m}$ wide. The computer-assisted tomography images (Fig. 2) indicate small variations in the radiological densities due to minor local sediment changes. This area can be taken as a reference state for the quantification of petrophysical variations near the stylolite (Carrio-Schaffhauser & Gaviglio 1990).

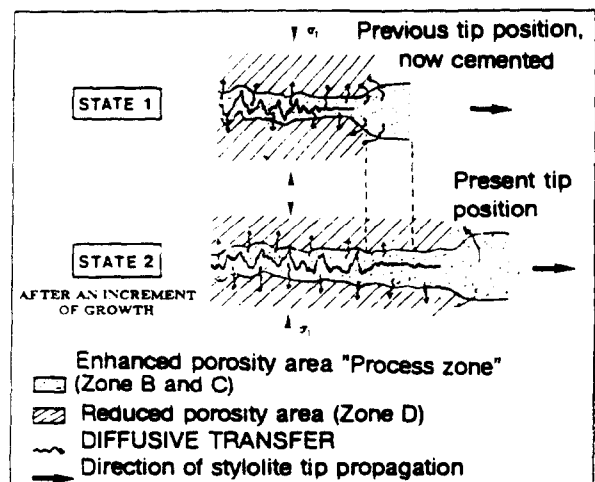


Fig. 1. Processes in stylolite tip propagation and diffusive transfer, after Carrio-Schaffhauser *et al.* (1990, fig. 4). Features of zones B, C and D are illustrated in Fig. 2.

The stylolite end zone or transition zone (B)

In zone B the porosity is higher than in A (18%), but the width of the micropores is unchanged ($0.2\ \mu\text{m}$). SEM images show a growth of the porous network by a micritic structure made up of smaller spheroidal particles $0.4\text{--}0.6\ \mu\text{m}$ with weak to tight contacts. The lower radiological density in B corresponds to an increase in porosity. Partial dissolution of calcite is considered to be the cause of development of the porous network between particles. As a result of dissolution, particle sizes decrease, contact areas are reduced and grain shapes become more spheroidal.

The stylolite (C)

Within zone C, the same matrix structures are revealed as in B (by SEM, CAT and porosimetry) with local accentuations in the characteristics described above. So, zones B and C are called the 'process zone' (Figs. 1 and 2).

Recrystallized matrix (D)

The recrystallized matrix on both sides of the stylolite (D) has an increased density compared to the other zones. The porosity is low (12%) and the micropores have an average diameter of $0.1\ \mu\text{m}$. The SEM images show an interlocking to coalesced structure. Micritic grain size growth of $1\text{--}1.5\ \mu\text{m}$ by micro-deposition and the development of crystalline faces has resulted from accentuated interlocking and welding of particles. A higher radiological density confirms the porosity reduction. Area D seems to be the cementation zone of solute diffusing from the process zone by mass transfer, probably over very short distances, and in a closed system probably owing to a low permeability of the sides of the stylolite.

Thus at the stylolite tip, porosity enhancement occurs in a process zone (Fig. 1). The growth of the porous network seems to be due to a pressure-solution mechanism, characterized by the formation of smaller and more ovoid grain shapes in the matrix zone. This process induces a diffusive transfer towards both sides of the stylolite where the porosity reduces. This reduced porosity area must be the site of crystallization of the soluble species generated in the process zone. A similar transfer must occur on the fringe of the stylolite.

In a later state, after an increment of stylolite growth, the stylolite tip process zone has migrated into undisturbed material ahead of the stylolite tip. The previously enhanced porosity zone has now become cemented. The diffusive transfer process provides mass deposits in the host rock, on either side of the seam.

Several problems appear to have been posed by the work of Carrio-Schaffhauser *et al.* (1990) including the quantity of mass loss, nature and dynamics of fluid in the system and the behaviour of process zone. In this paper, further investigations are carried out on the process zone to improve the understanding of the dynamics of the

process. This analysis has been carried out using the same samples as in Carrio-Schaffhauser *et al.* (*op. cit.*) and so, certain petrophysical characteristics are known in advance from analysis of the SEM images and the porosity, radiological and permeability data. Other techniques have been employed in the process zone, in particular semi-quantitative chemical analysis has been carried out by EDS (energy dispersive spectrometry) with the SEM and chemical back-scattered electron images. In this paper, only chemical back-scattered electron images are presented, but the conclusions, especially concerning the porous network, are controlled by topographic secondary electron images.

RESULTS

Structural description of the process zone

The process zone is complex. The results of the analysis of the process zone are compiled in Figs. 3 and 4.

Figures 3(a) and 4(a) are a generalized SEM view of the stylolitic structure. The other views are successively greater magnifications of the stylolitic structure. Images in Fig. 3(a) and 4(a) confirm the increased porosity in the process zone. The grey colour, which is darker in this area, is due to a greater number of pores of various sizes, each black in colour.

At different observational scales, the presence of a high volume of voids is evident within the process zone: intergranular spaces, joint openings, voids were all probably occupied by fluids during the functioning of the process zone. In Figs. 3(a) and 4(a), 3(b) and 4(b), and 3(c) and 4(c), the stylolite interface is sinuous and is positioned near the centre of the process zone.

When viewed macroscopically, the stylolite joint is seen to be composed of stylolites with different dimensions which become more apparent at greater magnifications (Figs. 3b–e and 4b–e). The amplitude of the macroscopic joint has a mean value of $0.2\ \text{mm}$; it is $0.4\ \mu\text{m}$ for the smallest. In this case, the amplitude of the macroscopic stylolite is larger than the grain size, contrary to the hypothesis of Gratier (1987).

Insoluble elements such as pyrites, can be clearly seen in the stylolite opening and within the rock matrix at greater magnifications (Figs. 3d, f & g and 4d, f & g).

On both sides of the stylolite joint, but within the process zone, sinuous discontinuities are present which are oblique or perpendicular to the stylolite. These structures, named here 'process zone fractures', are previously undescribed and their possible role will be discussed below.

Chemical composition in the process zone

For the chemical study, a semi-quantitative and punctual analysis has been made along profiles perpendicular to the stylolite joint. This detailed analysis at different

Rock matrix structures associated with stylolites

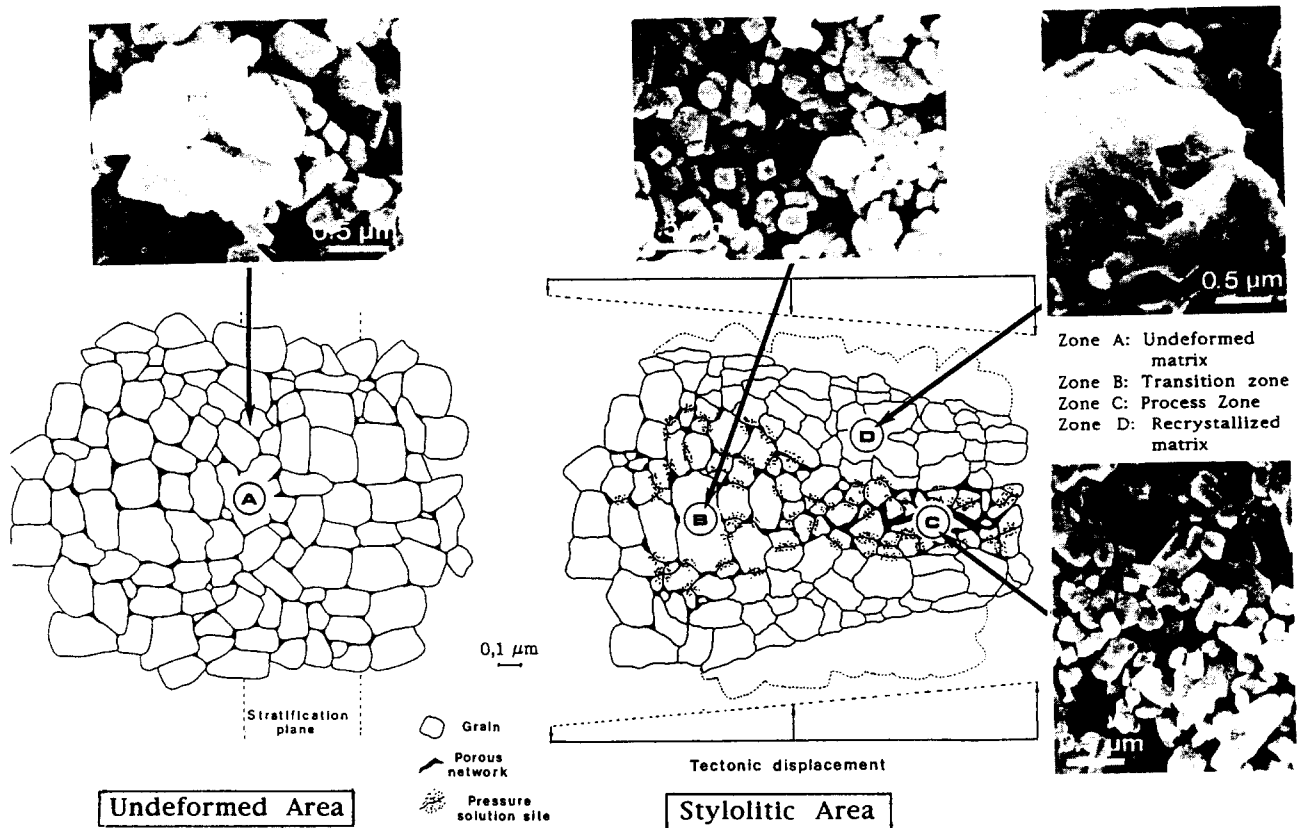


Fig. 2. Tomography, porosity and SEM data for undeformed and stylolitized rock, modified from Carrio-Schaffhauser *et al.* (1990, fig. 3). SEM views illustrate stages in the transformation from a tightly interlocking structure in the undeformed state (zone A), transitional through to the stylolite 'process zone' (zone C), to a recrystallized matrix with coalescent structure (zone D). Variations in grain size, grain shapes, contacts and pores can be distinguished.

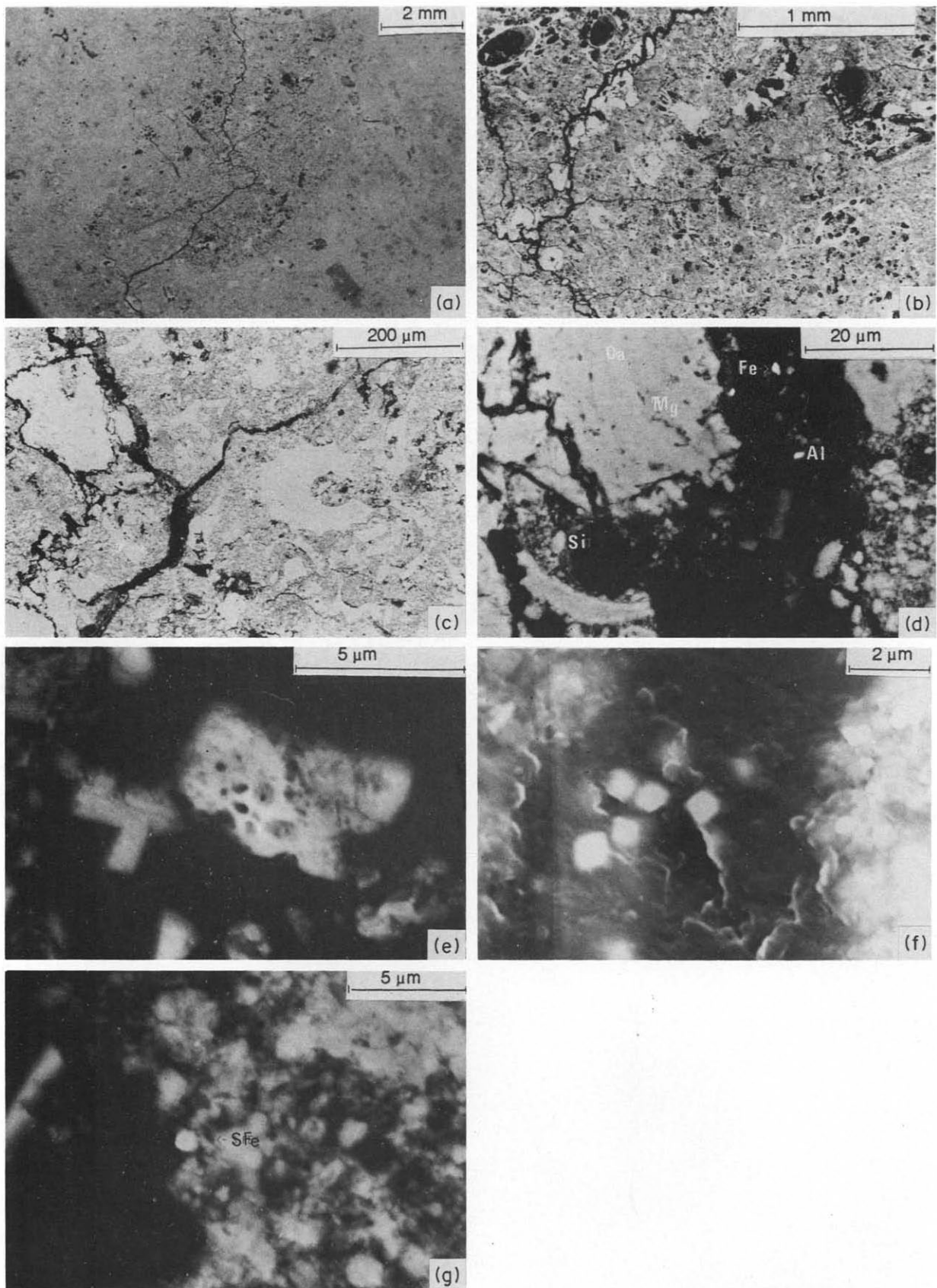


Fig. 3. SEM results at different scales. (a) High porosity in the process zone. (b) Process zone fractures. (c) & (d) Different sizes of stylolite structure, with geochemical analysis points shown in (d). (e) Calcite scale pressure solution. (f) & (g) Concentration of pyrites on stylolite rims, due to calcite solution.

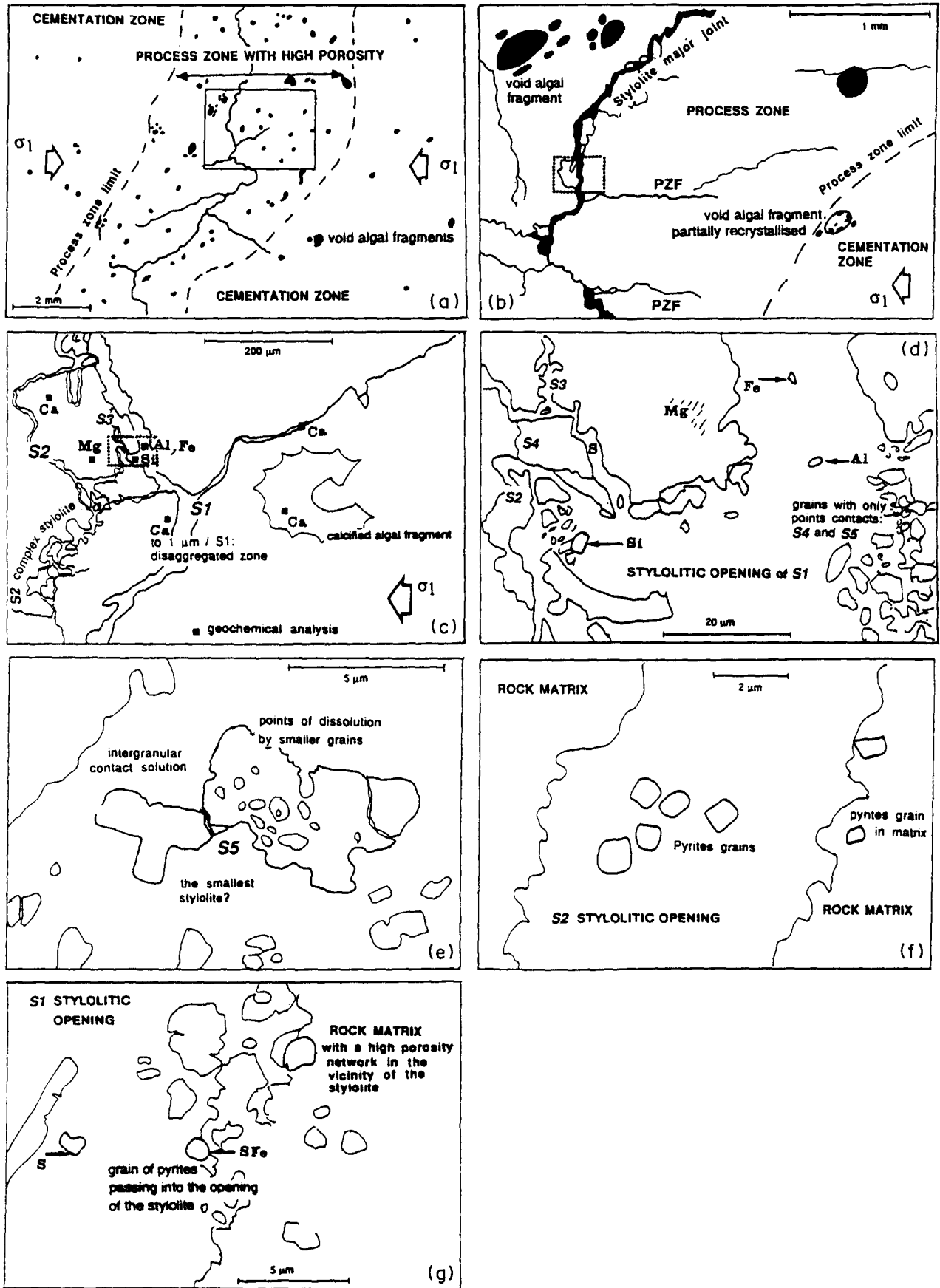


Fig. 4. (a)–(g) Structural interpretations of the SEM images in Figs. 3 (a)–(g). Fields of view and figure numbers are equivalent. See caption to Fig. 3 for details.

positions has been carried out with a step interval of 2 mm, towards 2 cm of the stylolite. To obtain the chemical characteristics of the undeformed matrix, and so provide a reference state, other analyses were made on a surface of several square millimetres.

In most of the undeformed rock mass, only Ca appears (CaCO_3 in each case). In places, algal fragments in the limestone matrix are present and occasionally contain Mg (Figs. 3d and 4d). Only in one place are Fe and S detected in matrix, indicating the presence of a grain of pyrites. Along the profile, towards the stylolite, and even very close to the joint, the same results are obtained. However, at a micrometric scale, occasional pyrite grains are revealed (Figs. 3g and 4g).

Other materials were detected mainly in the opening of the stylolite. They are either isolated elements such as sulphur, aluminium, silicon and iron, or minerals. Grains of pyrite were more often seen in the opening of the stylolite than in the rock, thus indicating a concentration. Otherwise, the punctual analysis indicates that the rock matrix appears to have very few insoluble chemical compounds. Si and Al could be the components of a decalcified clay present in insufficient quantity to be identified using this method.

The insolubles present could have two origins. Either they could have been introduced hydrothermally from outside (i.e. the system was open), or they were concentrated by the pressure-solution phenomenon. Figures 3(g) and 4(g) show a pyrite grain passing from the matrix to the opening of the stylolite, which supports the second hypothesis.

The process zone fractures

The process zone fractures can be described by comparison with the stylolite. A stylolite joint typically extends through the whole rock, is perpendicular to σ_1 , appears with a sinuous aspect and contains insoluble matter. By contrast, a process zone fracture is limited to the process zone, appears with a sinuous aspect oblique to, or parallel to σ_1 , and does not contain insoluble matter.

Although the process zone fractures seem to contain some material in their opening (Figs. 3c and 4c), chemi-

cal analysis reveals only Ca and no insoluble matter. The process zone fractures therefore do not seem to be minor stylolites.

MECHANISMS

Stylolite formation and evolution

Two hypotheses can be suggested concerning the different orders in the size of the stylolites observed in the process zone. In the first hypothesis, very small stylolites appear, at a scale of a few micrometers, and coalesce to produce larger stylolites (Fig. 5). In the second hypothesis a major stylolite or a pre-existing joint enhances the circulation of fluids in its vicinity which dissolves the calcite and induces, after a certain time, stylolites of several dimensions in the matrix around the joint through the first mechanism.

In the example studied these two processes may be considered. It appears that the first hypothesis can explain the initiation of the process zone (zone B; Figs. 1 and 2) in the matrix where no macroscopic joints exist, but where the porosity increases by pressure solution at grain scale and mass transfer (Fig. 5). In an impermeable rock the existence of fluids trapped in certain zones, in a closed system, which are otherwise identical to the rest of the rock, could explain the localization of the appearances of the stylolites.

Later when the stylolitic joint is formed, the second proposed process could start to produce the stylolites of different sizes observed on both sides of the main stylolite (Fig. 5). As stylolites are created, according to the above hypothesis, their evolution can be illustrated as follows (Fig. 6).

- (i) Pressure solution acts across the three stylolites and the zone between them decreases.
- (ii) With time the material between S2-S3 and S3-S1 is dissolved and S3 disappears.
- (iii) Eventually the material between S2 and S1 is dissolved and S2 ceases to exist.

The rock deformation is only a shortening parallel to σ_1 without perpendicular extension, because there are no tension gashes.

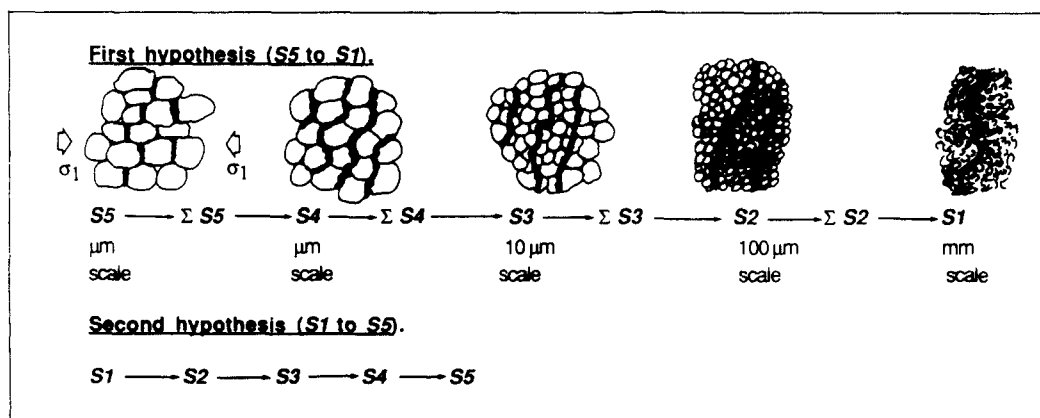


Fig. 5. Alternative hypotheses for stylolite formation. See text for details.

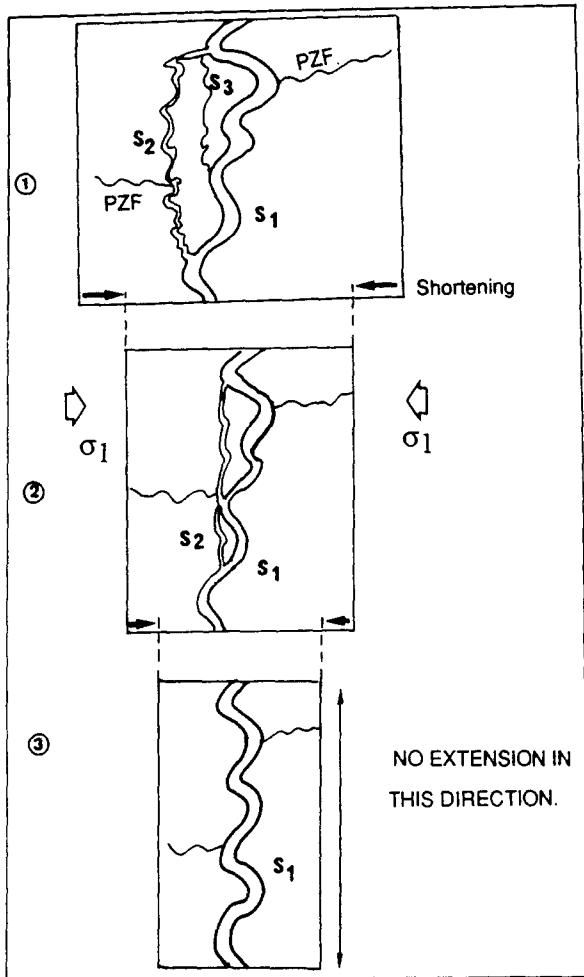


Fig. 6. Association of rock shortening and stylolite formation.

The behaviour of the process zone

Several features of the process zone must be recalled (Fig. 7). First, the process zone reduces in width from the tip of the seam to the maximum development of the joint. Secondly, on both sides of the porous process zone a cementation zone is present (Fig. 2) where porosity is strongly decreased by calcite deposition. Thirdly, the process zone fractures exist only in the process zone.

During the evolution of the stylolite, the width of the process zone tends to decrease and settle. The size of the stylolitic process zone could be reduced by shortening and pore cementation (Fig. 7). The shortening is due to pressure solution. The pore cementation is due to crystallization in pore and process zone fracture spaces. The crystallization front migrates inwards as the stylolite develops (the reverse is impossible).

The stable distance between stylolite joint and crystallization front could confirm the progressive and continuous aspect of the solution–deposition process along the structure, due to a diffusive transfer (Figs. 3 and 7) in a closed system.

In an open system, the ‘process zone fracture’ could have a drainage function and could induce a higher crystallization around the PZF tips. Therefore, the inhomogeneous distribution of PZF might probably induce an irregular cementation front. This is not observed, so

diffusive transfer is probably the major mechanism and infiltration transfer along PZF the minor mechanism. In the open system, part of the crystallized matter could have an allochthonous origin, and some soluble species could migrate outside the system, along the stylolite joint.

Experimental hydraulic fractures, with the morphology of process zone fractures, were obtained at a low velocity by Gratier (1984). PZF could be interpreted in the same way. However, in the light of his studies on cleavage seams (Fueten & Robin 1991) Robin has suggested (personal communication 1992) that the process zone fractures are not hydraulic fractures but, independently of whether the system is open or closed, the fractures form to accommodate the relative displacement between the transition zone and the intact rock. If we consider that the amplitude of the macroscopic stylolite joint (0.2 mm) is the minimum amount of shortening, the minimum displacement is 0.2 mm between the intact rock and the deformed rock in the process zone. It cannot be accommodated by elastic processes alone and results in localized fracture in the process zone, more or less parallel to σ_1 . Part of this non-elastic strain may also be accommodated by grain-to-grain pressure solution such as shown in the stages S5 and S4 (Fig. 5).

In this model, a stylolite can be considered as an anti-crack as defined by Fletcher & Pollard (1981). The stress concentration at the tip of the stylolite could result not only in pressure-dissolution phenomena but also in PZF formation and could provide the motor for the propagation of the process zone.

So, whatever the initial heterogeneity, the initiation

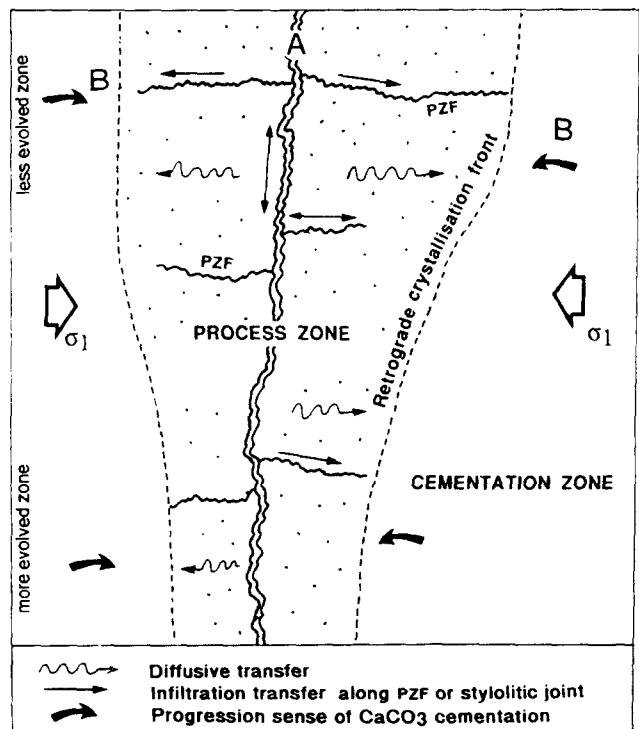


Fig. 7. Model for the variation in width of the process zone. A is site of shortening by solution; B is area of shortening by displacement of the retrograde crystallization front.

and propagation of a stylolite seems to correspond to an evolution in space and time of a self-organized system, as proposed by Merino (1987).

DISCUSSION AND CONCLUSIONS

This study provides evidence for an unknown aspect of stylolites that has been discovered using computed tomography and SEM. The pressure-dissolution phenomena, as in the example used of a rock with an initial high porosity (16%), and no tension veins, resulted in the following conclusions.

The dissolution is effective within a process zone, and not just between two grains along a macroscopic joint. This results in the individual nature of macroscopic stylolitic seams. The amplitude of the stylolite macroscopic peaks is larger than the grain size of the rock. Process zone fractures are observed approximately perpendicular to the main stylolitic plane and limited to the process zone. The transfer of material could depend on two mechanisms related to the fluid pressure: a transfer by intergranular diffusion, and a transfer by intergranular infiltration in the process zone fractures. The distance of transfer could not be evaluated in the samples studied. In this example with a high porosity and an absence of tension veins, the recrystallization occurs in pores in the proximity of the process zone and moves inwards towards the stylolite. Evolution of the stylolitic systems does not produce extension parallel to the stylolites since cementation takes place within pre-existing voids, and the process zone fractures are of only limited extent. The existence of these voids allows the process of pressure-solution-crystallization to function without a requirement for tension gashes. From this perspective, it can be suggested that stages S5 and S4 apply to the large volumes of rock undergoing diagenesis with recrystallization in the neighbouring pores, and the absence of extension. In the case of rocks with a very low

original porosity, tension gashes are probably essential for the process to continue.

Several problems are therefore evoked by this work.

(1) What is the origin and the role of the PZF?

(2) Is there coexistence or alternation in space and time of the closed/open system?

(3) If the closed/open system coexists in space-time, what is the mass transfer balance?

(4) What is the driving force that leads the fluid flow in the open system case?

REFERENCES

- Carrio-Schaffhauser, E. & Gaviglio, P. 1990. Pressure solution and cementation stimulated by faulting in limestones. *J. Struct. Geol.* **12**, 987–994.
- Carrio-Schaffhauser, E., Raynaud, S., Latiere, H. J. & Mazerolle, F. 1990. Propagation and localization of stylolites in limestones. In: *Deformation Mechanisms, Rheology and Tectonics* (edited by Knipe, R. J. & Rutter, E. H.). *Spec. Publ. geol. Soc. Lond.* **54**, 193–199.
- Fletcher, R. & Pollard, D. D. 1981. Anticrack model for pressure solution surfaces. *Geology* **9**, 419–424.
- Fueten, F. & Robin P.-Y. F. 1991. Finite element modelling of the propagation of a pressure solution cleavage seam. *Terra Nova Abs. Suppl.* **45**.
- Gratier, J.-P. 1984. La déformation des roches par dissolution-cristallisation: aspects naturels et expérimentaux de ce fluage avec transfert de matière dans la croûte supérieure. Unpublished thèse d'état, Université de Grenoble.
- Gratier, J.-P. 1987. Pressure-solution-deposition creep and associated tectonic differentiation in sedimentary rocks. In: *Deformation of Sediments and Sedimentary Rocks* (edited by Jones, M. E. & Preston, R. M.). *Spec. Publ. geol. Soc. Lond.* **29**, 25–38.
- Merino, E. 1987. Textures of low temperature self organization. In: *Geochemistry of the Earth's Surface* (edited by Godriguez, C. & Tardy, F.). Cons. Sup. Investigaciones científicas (Spain) and CNRS (France), Madrid, 597–610.
- Raynaud, S., Fabre, D., Mazerolle, F., Géraud, Y. & Latière, H. J. 1989. Analysis of the internal structure of rocks and characterization of mechanical deformation by a non-destructive method: X-ray tomodensitometry. *Tectonophysics* **159**, 149–159.
- Raynaud, S., Carrio, E., Mazerolle, F. & Latière, H. J. 1990. Computed tomography, a tool for measuring porosity in millimetric rock volumes around a stylolitic joint. *C.r. Acad. Sci., Paris, Sér.* **2** **310**, 271–276.