Journal of Structural Geology, Vol. 12, No. 8, pp. 987 to 994, 1990
Printed in Great Britain

0191-8141/90 $03.00+0.00

Pressure solution and cementation stimulated by faulting in limestones

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(*Received* 23 *February*1989; *accepted in revised form* 15 *March* 1990)

Abstract—A close relationship exists between fault density and the intensity of pressure solution and cementation. The latter process is responsible for major changes in internal rock texture. A close examination, involving porosity measurements and matrix observations through scanning electron microscope, suggests that a fault, whatever its size, may stimulate the pressure-solution and cementation processes with transformation concentrated close to the fault plane. The observed mass transfer cannot be accounted for by simple percolation, but is considered to result from a mechanical effect in a closed system associated with faulting.

INTRODUCTION

CHANGES in pore volume can result from three major processes; mechanical compaction, pressure solution and cementation. The first one acts through crushing and rearrangement of the sedimentary particles by grain-boundary sliding. Pressure solution, associated with grain-boundary sliding (McClay 1977), induces a reduction of the grain size and a more compact arrangement. Cementation by deposition in the voids may intensify this transformation of the pore volume. This mass deposition may result either from local pressure solution (closed system) or from allochthonous inflows (open system). Basically the pressure-solution process results from differences in chemical potential between two faces of a particle: it is caused by a difference in stresses normal to the faces (Sorby 1865, Durney 1972, Paterson 1973, Gratier 1984, Jones & Preston 1987).

This condition is realized when stresses are applied to a rock. One expects to find the greatest amounts of dissolution and crystallization in the areas subjected to the highest stresses. The phenomenon may also proceed from local stress variations induced by displacements of the particles forming the rock aggregate. Any failure, across grains or in the cement bonds, provides an opportunity for grain sliding and rotation until locking occurs. So new local differences in normal stresses are created and consequently new conditions for pressure-solution processes exist.

Many authors have already emphasized the influence of the tectonic stresses on matrix transformation by such mass transfers (Mimran 1975, Sprunt & Nur 1977, Cros *et al.* 1981, Gratier 1984, Jones *et al.* 1984, Carrio-Schaffhauser & Gaviglio 1985). As a matter of fact, close to faults, rocks display pressure-solution features such as stylolites, cleavage and indentation or welding of grains. Geochemical and physical differentiations are a consequence of the migration of soluble minerals. The aim of this paper is to demonstrate that faulting can bring about matrix transformations through pressure solution and cementation.

GENERAL STRUCTURE AND ROCK MATRIX TRANSFORMATION

The investigated rocks are Campanian limestones from the Arc Syncline in Provence, southeastern France (Fig. 1). The northern and southern structural limits are overthrusts. In the syncline, faulting results from several tectonic events: compression, over the longest period (Eocene, Miocene and Pliocene), and extension during the Oligocene (Gaviglio 1985a, Nury & Raynaud 1986, Gaviglio & Gonzales 1987). The characteristics of the brittle deformation have been analysed through examination of fault-slip data, tension gashes and stylolites.

Brittle deformation is concentrated along two major faults, towards which the fracture frequency is found to

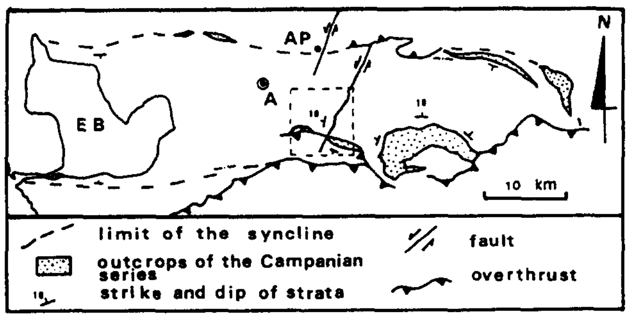

Fig. 1. Structural setting of the investigated zone. The box is the area shown in Fig. 2. The limit between the Upper Cretaceous and the Lower Cretaceous (or the Jurassic) is taken as the limit of the syncline. AP: Aix-en-Provence; EB: Etang de Berre. A is the location of the borehole selected for sampling the least faulted material, section A in Fig. 4 and the normal fault in Fig. 5.

regularly increase. The fracture frequency (F) was obtained by determination of the number of fractures per metre of core: a total of 7350 fractures were recorded in 2671 m of core from 14 boreholes. The orientation of the fractures, with respect to the vertical, was not taken into account, except in a few sections where the fracture pattern was regular enough to allow a determination of the linear frequency for each identified set and of the volumetric density (D) (Vialon *et al.* 1976). In the structural environment considered the ratio D/F is nearly constant (very close to 2). Therefore F may be regarded as a good estimation of the state of fracturing in the rock. This regular increase in fracture frequency towards the major faults is observed for all kinds of fractures: reverse, normal or strike-slip faults and tension gashes. Furthermore one finds that the higher the fracture frequency, the higher the percentage of calcite-filled fractures (Fig. 2).

The mesoscopic pressure-solution features follow the same distribution pattern. Their density was determined through core analysis: the ratio of the length displaying stylolites and solution cleavages to the total investigated length was used. This ratio ranges between 7 and 28%. This general pattern of deformation suggests a connection exists between faulting and matrix transformation through pressure solution and cementation.

This is corroborated by the rock density measurements. These were carried out by weighing dry samples and determining their bulk volume using caliper measurements; 161 samples were tested. The comparison between samples from the least and the most faulted zones indicates a significant increase in density (Table 1). The progressive increase in density was observed in each of the petrographic varieties of limestones. A clear linear relationship links density and porosity (Carrio-Schaffhauser & Gaviglio 1985, Gaviglio 1985b).

We propose to examine the relationship between tectonic features and textural characteristics, concentrating on two petrographic varieties, III and V, which are the most homogeneous micritic limestones of the series.

Table 1. Average density values of the limestones (after Gaviglio 1985b)

	Petrographic varieties			
	I	III	IV	V
Least faulted zone	2.19	2.40	2.21	2.02
Most faulted zone	2.40	2.57	2.45	2.41

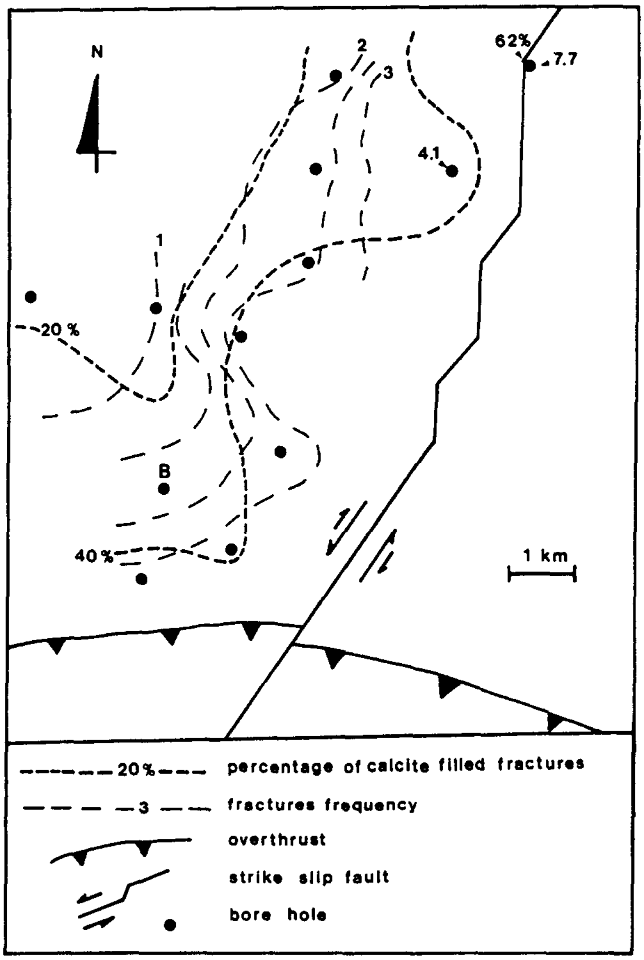

Fig. 2. Major faults: relationship between fracture density and percentage of calcite-filled fractures. B—location of section B shown in Fig. 4.

POROSITY AND TEXTURE MEASUREMENTS

The assessment of the phenomenon proceeds from a three-fold approach:
— porosity measurements, through mercury injection and alcohol absorption, correlated with distance from the major faults (kilometric scale);
— porosity measurements correlated with distance from minor discontinuities (centimetric scale);
— scanning electron microscope investigation of the rock textures (micrometric scale).

Porosity variations associated with major faults

The general relationship has been found (Carrio-Schaffhauser & Gaviglio 1985) that porosity of a homogeneous micritic limestone ($CaCO_3$ ranging from 98 to 100%) regularly decreases from the least faulted area in the basin to the most severely faulted zones. Close to the two major faults (a strike-slip fault and a reverse fault), the pore volume reduction reaches 65%. The study is based on the analysis, by mercury injection, of nearly 100 samples.

The decrease of total porosity near the major faults is associated with a severe pore diameter decrease as demonstrated by the mercury injection curves (Fig. 3): the largest spaces, mainly biogenic voids (with diameters ranging from 250 μm to 1 mm), are obliterated either by crushing or by sparite infilling. The only remaining voids are the intergranular spaces, which are also affected by the diminution (from 0.2 to 0.05 μm) (Fig. 3).

This change in texture brings about a lessening of the connection between the voids, as is clearly shown by the observed evolution of undrained porosity (from 35 to

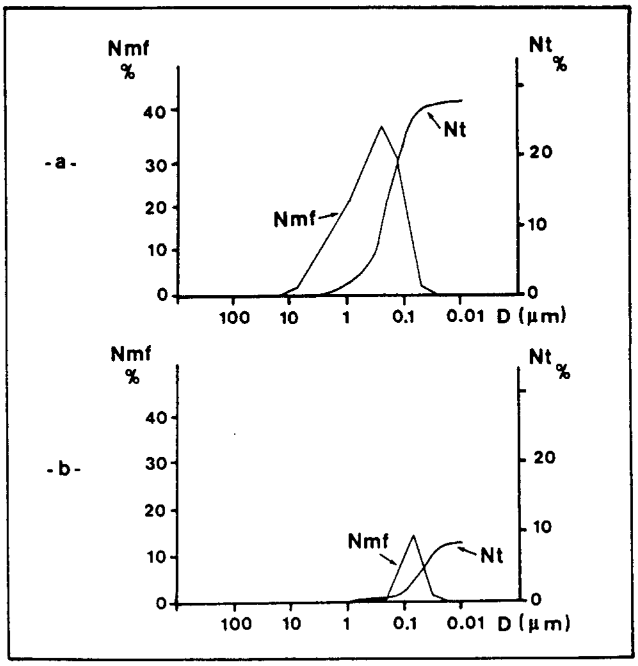

Fig. 3. Average characteristics (mercury injection technique) of (a) untransformed and (b) deformed material. The latter has a lower total porosity (Nt) and smaller pore diameters (*D*) as pointed out by the distribution of the main pore family (Nmf). Sampling of the deformed material took place within 500 m of the major faults in Fig. 2.

55% of the total porosity). The undrained porosity concerns voids with an access diameter considerably smaller than the internal diameter. Such contrasts in void aperture may restrict severely the fluid flow (Pellerin 1980, Carrio-Schaffhauser 1987).

The destruction of the largest pores is partly produced by mechanical compaction. This is supported by observations on thin sections: the closer the fault, the lower the degree of preservation of shells that shield the largest voids. However pressure solution and cementation seem to be most important in the transformation of the intergranular porous network (Carrio-Schaffhauser 1987). All the calcareous series is affected by similar changes, although the intensity depends on the original composition of the rocks (Gaviglio 1985b).

Porosity and minor discontinuities

The evaluation of the porosity, using the alcohol absorption method (Carrio-Schaffhauser & Gaviglio 1985) was carried out on hand samples and drill-cores. The average porosity increases with distance from the major faults. However, along continuous profiles there is much local variation, even in the least transformed sites which are always associated with the existence of tectonic discontinuities of various kinds and dimensions. The greater the number of faults, the lower the porosity of the rock section. There seems to be a cumulative effect of local transformations accounting for progressive changes in the rock matrix, as illustrated in Fig. 4, where sections A and B are representative of the least and most deformed areas.

The porosity variation is not simple: it shows two tendencies:

— a local decrease close to fractures, with a roughly symmetrical pattern;

— a general reduction of pore volume from the least to the most fractured zones. Nearer the major faults (where fracturing is greatest), the porosity of the whole section is lower and the porosity curves tend to be smoother.

A more detailed study of the phenomenon is provided by measurements of the variation in the footwall and the hanging wall of a small normal fault, with a centimetric throw (Fig. 5). The fault was observed in material with the lowest fracture density and the lowest degree of matrix transformation. The results were obtained using the mercury injection method. In this limited rock volume (20 cm between the extreme tested points), the following matrix changes were observed as the fault was approached (Fig. 5):

— a decrease in total porosity (Nt);

— a complete obliteration of the macropores (MN);

— a decrease in microporosity (μN);

— a decrease in pore size (from 0.1 to 0.03 μm).

A clear similarity exists in the effects of faulting on the matrix at different scales. The intensity is different and depends on the dimensions of the discontinuity concerned, but the process seems to be similar and, hence, it may be inferred that the described phenomena proceed from a unique mechanism.

Scanning electron microscope observations

Investigation with SEM provides an illustration of the modifications of the texture responsible for the porosity and pore size variations.

The undeformed material is a micritic rock; it has a point contact structure with anhedral to subhedral grains, ovoid or elongated in shape (classification after Loreau 1972). The average grain size is 0.2 μm. The transformation near the faults is depicted in Fig. 6 and consists of:

— agglomeration by interlocking and welding of grains;

— growth of the grains resulting in an increase in size (up to 1 μm) and a development of crystalline faces;

— closer packing of the micritic structure followed by a general coalescence.

An example of these transformation features is seen in rock fragments sampled on each side of the normal fault described above. Again one finds a symmetrical pattern with grain size increasing towards the fracture. Next to the shear plane, there are flat contact surfaces between the grains, and pore spaces are almost absent (Fig. 7). The abundance of interlocking grains, welding and recrystallization features points to the predominance of pressure-solution and cementation mechanisms in the process of transformation of the rock matrix. This typical evolution of the microstructures can be observed in the other rock types of the studied series, although with unequal intensities. This confirms how general the 'tectonic maturation' of the calcareous rocks is.

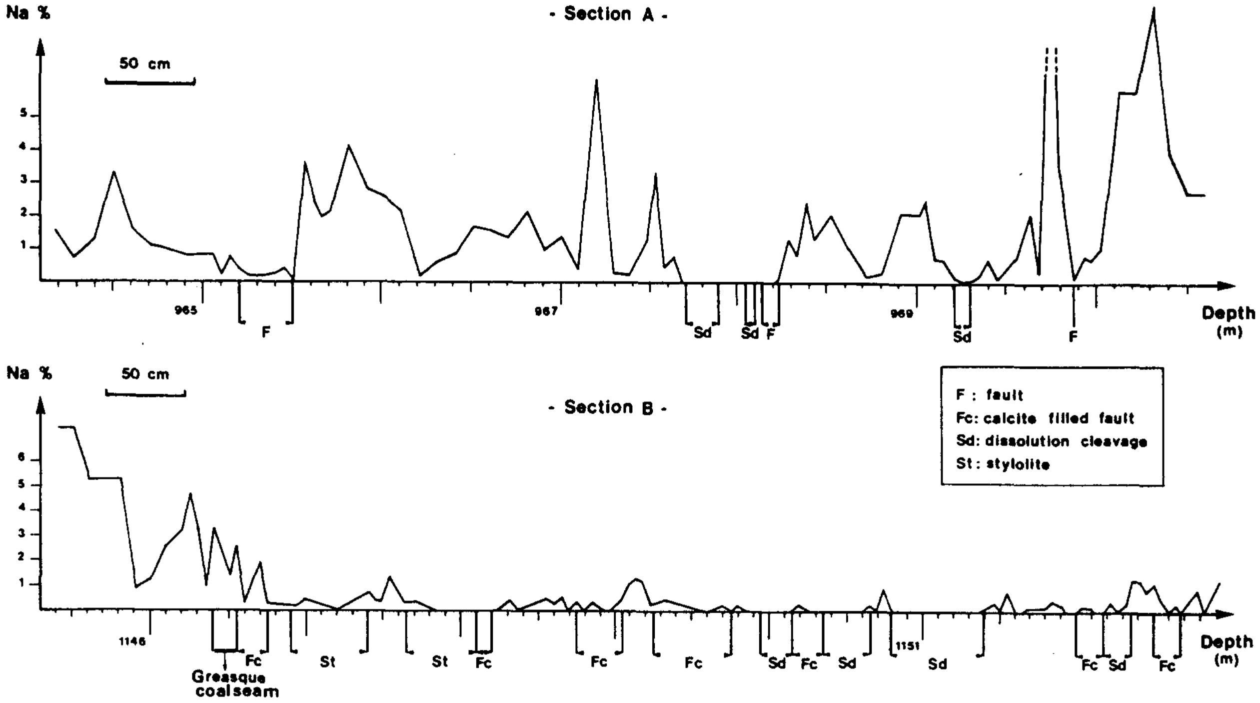

Fig. 4. Porosity profiles (alcohol absorption method) realized on a continuous core sampling. Section A: untransformed material (A in Fig. 1). Section B: deformed material (B in Fig. 2).

INTERPRETATION

Four findings of particular significance are:

— a change in texture takes place at the grain size level (SEM observations);

— a progressive spreading of this matrix change from faults is common (SEM observations, porosity profiles);

— there is a close correlation between faults, associated with stylolites or solution cleavages, and porosity reduction, ranging from kilometric to centimetric scales;

— because of the small pore size and high undrained porosity, the rock material is fairly impermeable; the permeability of the least transformed material reaches 10^{-10} m s^{-1}.

It is not possible to account for the observed transformations of the matrix, if only percolation is involved. Assuming a permeability coefficient equal to 10^{-10} m s^{-1}, a reduction of porosity from 25 to 9%, as recorded in the investigated area, would require 120 million years, more than the age of the rocks (70 million years). This estimation (after Gratier 1984) involves calculating the volume of dissolved mineral which is liable to be deposited per unit time, considering a cubic rock mass with a permanent fluid discharge. The calculation was carried out using the following basic data:

— gradient of fluid pressure = 30 MPa km^{-1};

— gradient of concentration (volumetric ratio) in dissolved calcium carbonate = 1.4×10^{-6} per MPa, assuming a temperature level reaching 100°C (Sharp & Kennedy 1965).

The assumed temperature level is realistic with respect to the maximum thickness of the overburden in the area (3000 m). The gradient of fluid pressure could be significantly higher in restricted rock volumes, in the most severely strained areas. However, we have to bear in mind that the transformation phenomenon extends over more than 10 km: if percolation is considered, the gradient has to be compatible with such a distance. For a 10 km distance the maximum possible difference in fluid pressure would be 300 MPa; 300 MPa is the maximum tectonic stress estimated in these limestones (Gaviglio 1985a).

The following deductions can be made:

— mass transfer, responsible for the matrix transformation, can be realized only by diffusion in a trapped fluid because of the impermeability of the medium. Consequently it occurs close to the dissolution sites localizing continuous deformation in a closed system. The mass is kept constant and the volume is reduced, thus density increases. A local mass exchange and redistribution is suggested: according to the intensity of the mechanical effort, the reduction and filling of the voids is more or less complete;

— each fault acts independently on the rock matrix. The more numerous the faults, the greater the rock volume transformed and the higher the intensity of the deformation: a broader change is produced by a cumulative effect.

Such a widespread and extensive phenomenon cannot be accounted for without considering the pressure-solution and cementation opportunities along the faces of the grains. Under a difference in chemical potential,

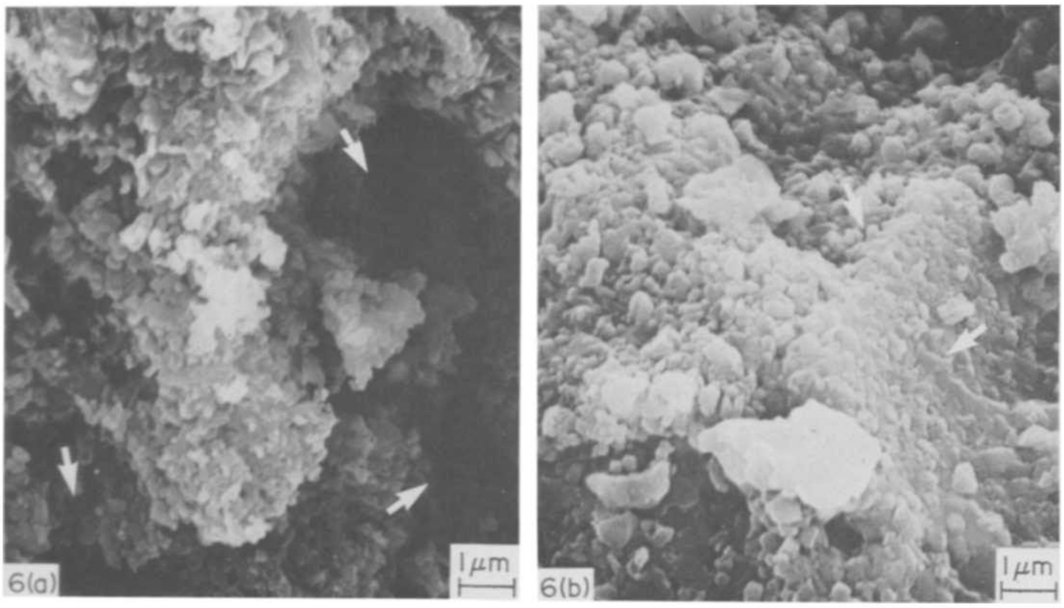

Fig. 6. SEM photographs illustrating the contrast in rock fabric of the micritic limestone between (a) the untransformed material and (b) the material deformed near a major fault. (a) Large pores (white arrows) located between aggregates made up of small particles with point contacts. (b) Very small pores: welding of the particles associated with a more compact arrangement (white arrows: plane contacts between the faces).

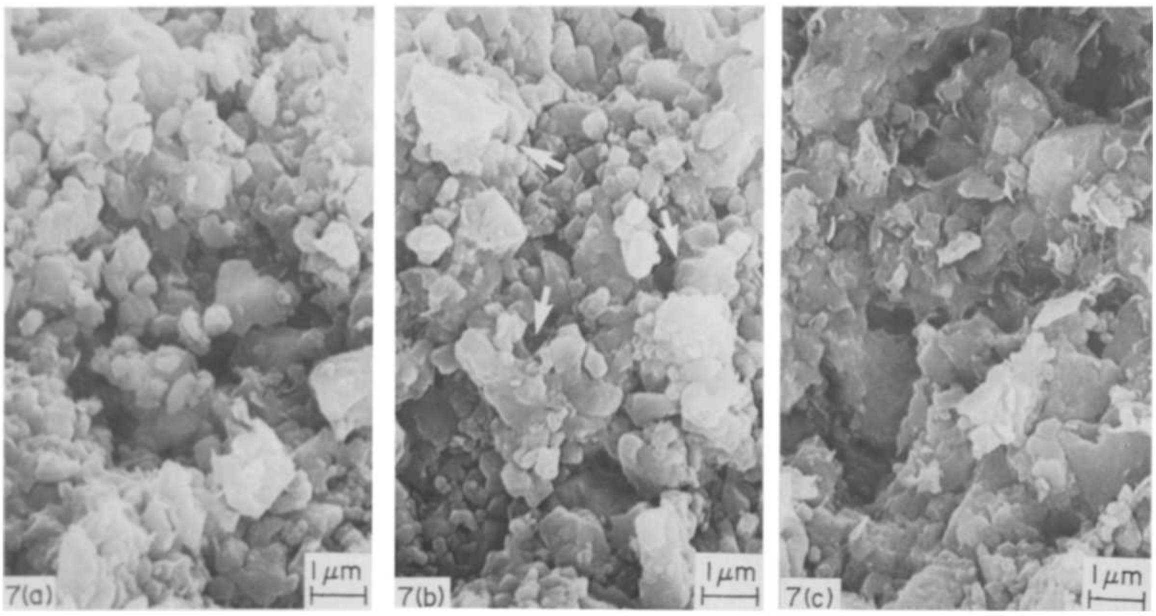

Fig. 7. SEM photographs illustrating the microstructures evolution near a minor normal fault (within a 10 cm thick band fringing the fault). (a) Untransformed matrix with loosely packed particles (point contacts). (b) The same matrix displaying patches with a tighter arrangement (white arrows) suggesting a progressive spreading of the transformation. (c) Latest stage in rock fabric modification through welding. Crystallization induces an increase of the particle sizes and the development of crystal faces leading to plane contacts (coalescent structure).

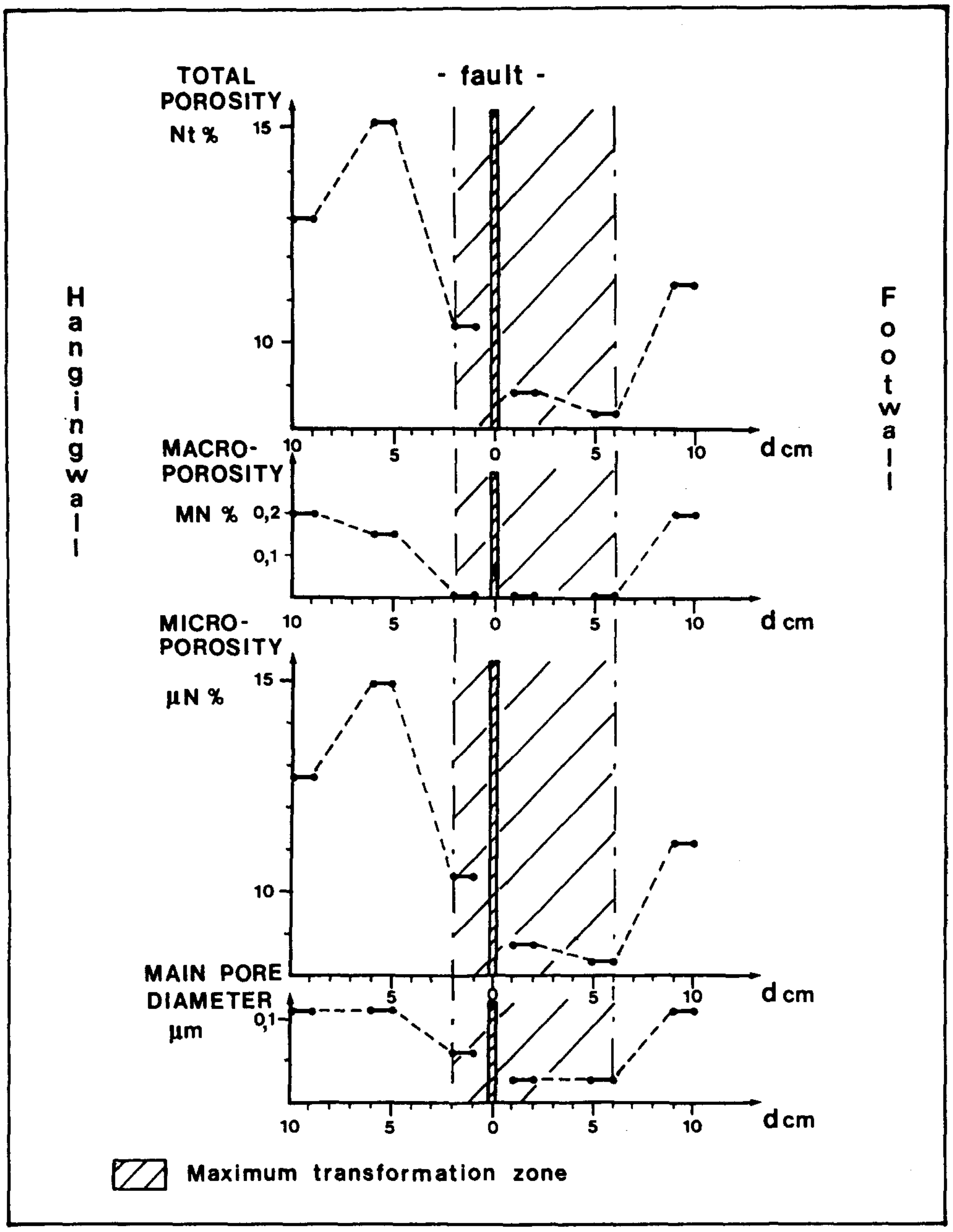

Fig. 5. Variation of porosity in the hangingwall and footwall of a small normal fault (data obtained using mercury injection). The macroporosity (pores with an access diameter greater than 1 μm) reaches 0% close to the fault. The location of the fault is shown by A in Fig. 1.

mass transfer occurs, involving dissolution along faces undergoing the highest normal stresses and crystallization along the faces subjected to the lowest normal stresses. The difference in chemical potential between two faces of a grain depends on several factors such as the internal or the surface energy differences, and the difference in stress normal to the faces; the latter has the greatest influence (Gratier 1987) and is the only factor considered here. This phenomenon cannot exist without a liquid phase supporting the exchange processes and material flow through diffusion or seepage.

When shearing is initiated, local stress variations may arise related to the movements between grains. In each grain such a variation brings about a heterogeneous load increase and therefore tends to increase the differences between the stresses normal to the faces. This change concerns every particle with stress levels depending on the shape and location of the particle. Therefore an increase in pressure-solution and cementation activity close to a fault does not necessarily result from higher stresses in this part of the rock.

As the movements get greater, failures of the cement bonds occur and a rearrangement of the rock grains is produced. Relative movements, involving sliding and rotation, create local variations of stress and, consequently, further opportunity for pressure solution and cementation. The pressure-solution sites are thought to be concentrated where these relative movements are the most numerous, adjacent to fault planes. Away from the fault plane the matrix transformation reduces because of a looser distribution of the pressure-solution and cementation sites. Such a mechanism develops by a progressive coalescence of the transformed particles, as suggested by the scanning electron microscope observations (Fig. 7b).

Particular attention has to be paid to the role of compaction. In high porosity materials, like chalk, a critical state behaviour can be reached: a breakdown of the initial sedimentary structure occurs, resulting in pore collapses and flow of the material (Jones *et al.* in press, Leddra & Jones in press). This critical state can be reached under tectonic deformation (Jones & Leddra 1989). Although pore collapse may have occurred to some extent, such a phenomenon cannot be considered as predominant in the change in rock texture described here. There are two reasons:

— no evidence of sediment flow has been observed in connection with faults;

— the pore filling evidences are always adjacent to the solution features. These solution features, such as stylolites or solution cleavages, are clearly associated, in orientation, with the brittle fractures, especially faults.

However, the influence of circulations of fluids cannot be ruled out in the case of coalescent fractures, especially in complex fault zones where mass transfer through a system of fractures is bound to occur, producing an opening of the system. The pressure-solution and cementation processes are controlled by permeability because the escape of pore fluids is a physical condition of cementation (Jones *et al.* 1984). The drainage may accelerate the process in major faults allowing the fluids to escape from the series, but not in minor faults.

CONCLUSIONS

In limestones the pressure-solution and cementation processes can extensively transform the rock matrix and this is commonly associated with faulting. This phenomenon may increase through the cumulative effect of individual faults forming either minor or major discontinuities, each fault stimulating pressure solution and cementation. The basic mechanism seems to result from local stress variations, induced by shearing, which bring about differences in stresses normal to the faces of the particles. The intensity of the phenomenon is probably proportional to the magnitude of the displacement. Where major faults are concerned, the effects of drainage may combine with the mechanical effects.

Cementation, progressing away from the fault, is the origin of the general transformation of the matrix. If brittle deformation is intense and concentrated, the reduction in pore volume is homogeneous. If it is scarce the matrix deformation is more heterogeneous because of a smaller density of pressure-solution and cementation sites. It seems that this phenomenon occurs in any kind of fault.

Acknowledgements—The authors are grateful to J.-P. Gratier (I.R.I.G.M. Grenoble), for very useful suggestions and comments. They wish to thank D. J. Sanderson, M. E. Jones and another referee whose detailed revisions of the manuscript, including corrections to the English, were of considerable help.

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