

Calcite c-axis textures along the Gavarnie thrust zone, central Pyrenees

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Abstract

Orientations of calcite c-axes have been measured in limestones from the eastern part of the Gavarnie thrust zone, central Pyrenees. They show preferred orientations (textures) with one or more maxima. By comparing the textures with existing experimental and theoretical data, it was possible a) to confirm the regional sense of movement along the thrust, b) to interpret a significant contribution of pure shear to the total strain in the thrust zone, and c) to recognize natural patterns which have not been reported before.

It is suggested that the studied limestone samples were deformed at a temperature of about 200° C in a transitional regime with textures ranging from low to high temperature types. Specific rock properties may have governed the local predominance of a high or conversely of a low temperature type. The data, however, appear to exclude grain size as a controlling factor.

Introduction

Intracrystalline slip is an important mechanism in ductile deformation of rocks. During slip, crystal lattices are bound to rotate with respect to an external reference frame due to constraints imposed by neighbouring grains. As a consequence, preferred orientations of crystallographic directions, also referred to as textures or fabrics, develop. Crystallographic preferred orientations may contain information on active slip systems, deformation conditions, type of strain and strain path. They can thus be of importance in structural analyses. A comprehensive review on texture analysis is given by Wenk (1985).

Investigations of textures in deformed quartzites have proved to be very useful in gaining insight into deformation processes and conditions (e.g. Lister & Williams, 1979; Law et al., 1984; Schmid & Casey, 1986). Natural calcite textures reported so far seem less informative because they generally

display little variation, in spite of a variety of experimentally and theoretically produced textures.

In this paper, c-axis textures are presented of calcite-rocks from a thrust zone in the central Pyrenees. It will be shown that these textures:

- a) exhibit patterns which differ from the well known monotonous ones, and
- b) contain new information on the deformation conditions and strain history of this particular thrust zone.

Calcite textures: A brief review

Mechanisms of intracrystalline slip in calcite have been determined in detail by deformation experiments on single crystals (Turner et al., 1954; Griggs et al., 1960). Slip on the crystallographic r- and f-planes and twinning on e-planes appeared to be the most important deformation systems. Experimental axial compression and extension of Yule

marble (Turner et al., 1956) confirmed these observations, producing concentrations of c-axes around the compression axis or at a high angle to the extension axis. Information about the full nature of textures is obtained by X-ray analysis of experimentally deformed samples (e.g. Casey et al., 1978 for axi-symmetric tests). Pure shear and simple shear experiments by Wagner et al. (1982), Kern & Wenk (1983) and recently by Schmid et al. (1987) produced a variety of textures as a function of conditions of deformation and type of material.

Computer simulations of texture development were carried out by Lister (1978), Wenk et al. (1986) and Takeshita et al. (1987). They used Taylor theory and explored the so-called Single Crystal Yield Surface, which is calculated on the basis of fundamental knowledge of all potential slip- and twinning systems. Low strain rate sensitivity of yield strength (e.g. Heard & Raleigh, 1972 for marble, and De Bresser, 1988 for single crystals) supports the applicability of Taylor theory for texture modelling in calcite rocks. The results match reasonably well with experimentally produced textures. Wenk et al. (1987) compare experimental and theoretical data and their overview is adopted here.

Fig. 1 shows calcite c-axes pole figures that were produced experimentally and by computer simulation. A texture transition separates low temperature (LT) and high temperature (HT) preferred orientations. For LT pure shear the c-axes are concentrated in a broad maximum parallel to the main compression direction. At higher temperature, this maximum is split into two maxima that are symmetrically oriented at an angle of about 30° to the compression axis. LT simple shear pole figures show the same broad maximum as the pure shear equivalents, but its orientation is rotated against the sense of shear. Taylor calculations for simple shear predict that the angle between the c-axis maximum and the pole of the shear plane will be 36° for all values of shear strain. In a combination of simple shear and pure shear, this angle is modified by the pure shear contribution to the total deformation (Wenk et al., 1987).

The theoretical and experimental HT simple shear textures correspond less well with each other.

However, they show (Fig. 1) a slightly asymmetric pattern with respect to the shear plane, and a split maximum comparable with the HT pure shear texture.

The temperature at which the texture transition from a single to a double maximum pattern occurs is documented as $200\text{--}300^\circ\text{C}$ (at strain rate $10^{-4}\text{--}10^{-5}\text{ s}^{-1}$) for both the theoretical predictions and the experimental data on fine-grained Solnhofen limestone (Wenk et al., 1987). It is $\sim 600^\circ\text{C}$ for coarse-grained Carrara marble in experiments at the same strain rates (Schmid et al., 1987). Thus, the transition temperature depends on the material, probably on the grain size. Particularly deformation twinning, which is an active mechanism in texture development at lower temperature, is a grain size dependent process (Spiers, 1982; Rowe & Rutter, in press).

Natural calcite textures reported so far (e.g. Trommsdorff, 1964; Schmid et al., 1981; Behrmann, 1983) in general only show a single point-maximum, comparable with the LT-texture type. The sense of shear inferred from the asymmetry of the pattern corresponded with the known shear direction in most cases.

It is emphasized here that c-axis pole figures do not give a complete description of textures. However, they appear suitable to distinguish pure shear from simple shear history and low-temperature from high-temperature deformation.

Geological setting

The Gavarnie thrust is a distinct feature of the central Pyrenees. It is exposed at Gavarnie, near Gedre (France), and can be traced eastward along the northern side of the Lys-Caillauas massif. Triassic and Mesozoic rocks along the fault indicate an Alpine age (Zwart, 1986).

Near Gavarnie, the thrust forms part of series of duplexes, described by Parish (1984). Such a complex sequence has not been demonstrated along its eastern continuation (Roddaz, 1977; Majesté-Menjoulas, 1979). Here, the thrust is not a discrete fault but a zone of strongly sheared Silurian black slates and Silurian and Devonian mylonitic lime-

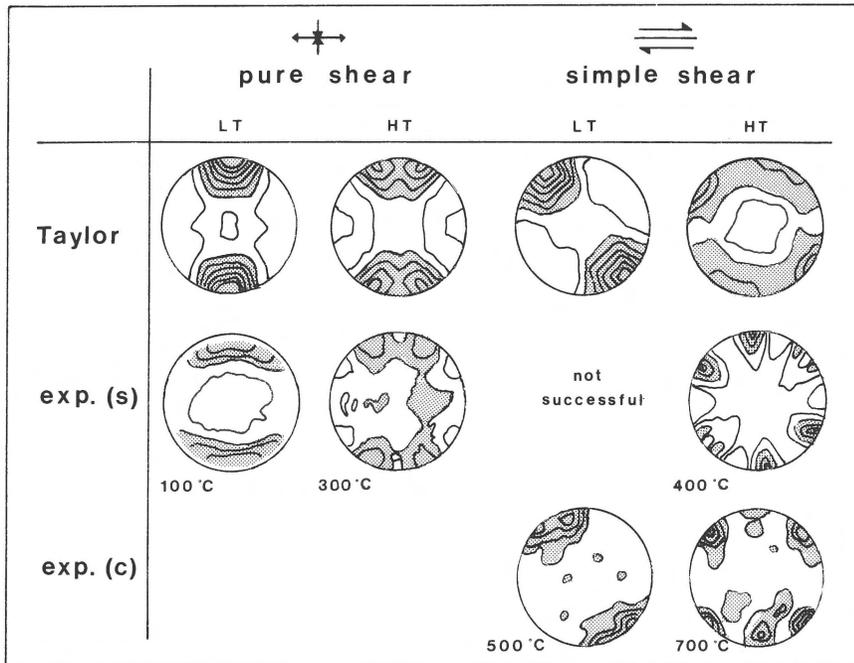


Fig. 1. Calculated (Taylor) and experimentally produced c-axis pole figures for calcite rocks. Equal area projections. Taylor and experimental data on Solnhofen limestone (s) after Wenk et al. (1987). Contour interval 0.5 of a uniform distribution, shaded above 1. Experimental data on Carrara marble (c) after Schmid et al. (1987), contour interval 2.0 of a uniform distribution, lowest contour 1.0.

stones that overly Cambro-Ordovician basement. The regional tectonic transport direction is to the south.

In the western part of the Lys-Caillauas massif, the Gavarnie thrust has a steep orientation and is locally affected by upright folds and steep faults (De Bresser et al., 1986). Axial traces of the folds are slightly oblique to the strike of the thrust zone.

Thickness of the overburden during Alpine thrusting was probably of the order of 6 km, which is estimated from the balanced cross-sections for the Gavarnie area from Parish (1984). This result is in general agreement with estimates from balanced and restored cross-sections for the south central Pyrenees (Williams, 1985) and from descriptions of stratigraphy (Zwart, 1979 and Majesté-Menjoulas, 1979), including a correction for pre-Alpine thickening (Van den Eeckhout, 1986). Using a 'normal' thermal gradient of 30°/km (e.g. Ranalli, 1987), the pressure-temperature conditions during thrusting then were approximately 1.6 kbar and 200° C.

Sample description and method of study

The rock samples used for this study were collected at four localities (Fig. 2) along the eastern part of the Gavarnie thrust zone, in the area described by De Bresser et al. (1986). The rocks are Silurian and Devonian limestones with a cm-scale compositional and grain size layering. Rotated porphyroclasts, displaced broken objects, small scale isoclinal folds and a distinct extension lineation indicate a mylonitic nature of these rocks. On a micro-scale, this is confirmed by evidence for intracrystalline deformation and dynamic recrystallization (Fig. 3a). All samples show only minor deformation twinning. In some rocks, elongate grain shapes and alignment of grain boundary segments (Fig. 3b) define a foliation oblique to the compositional layering. This geometry is similar to that of the microstructure in so-called S-C mylonites (Lister & Snoke, 1984), and can be used as a shear sense indicator. The S-C geometry yields the correct southward movement direction, with the compositional layering parallel to the shear- or C-plane. The sense of shear and the

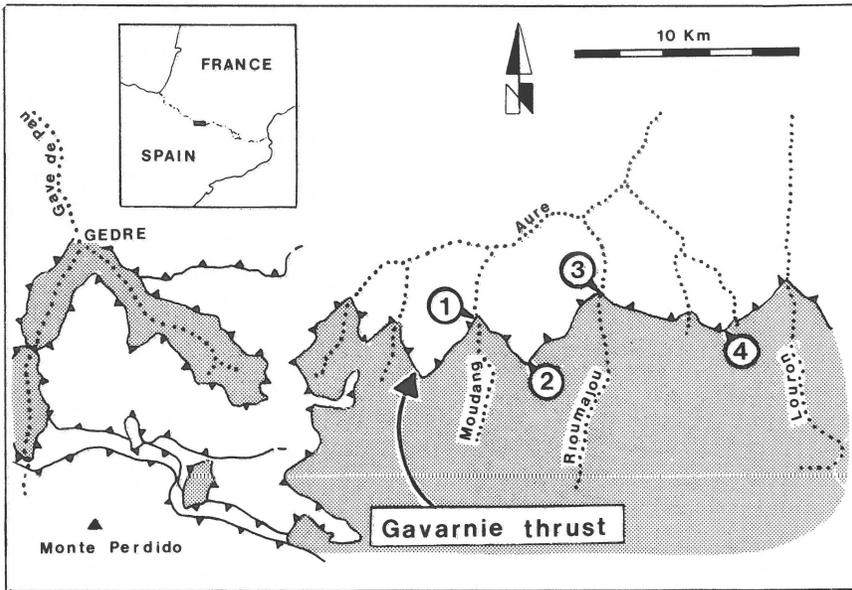


Fig. 2. Simplified geological map of the Gavarnie thrust (after Majesté-Menjoules 1979). Triangles in upper block. Cambro-Ordovician basement is shaded. Sample localities are Moudang Valley (1), Crête d'Escalet (2), Rioumajou Valley (3) and Crête de Bassiouente (4).

orientation of the shear plane are further evidenced by the orientation of shear bands in nearby slates (cf. Simpson & Schmid, 1983), and the geometry of the porphyroclast systems (cf. Passchier & Simpson, 1986), and displaced broken objects.

Crystallographic orientations of calcite *c*-axes have been determined optically in ultrathin ($5\ \mu\text{m}$) sections, oriented parallel to the extension lineation and perpendicular to the compositional layering. The measurements were carried out on a universal stage, mounted on a Leitz microscope and connected with a computer for automatic data collection. Reproducibility of measurements was within 3° and 5° for azimuth and plunge respectively. In two samples different types of grains have been distinguished and measured separately.

Results

The results of the *c*-axis measurements are presented in pole figures and contoured plots in Fig. 4.

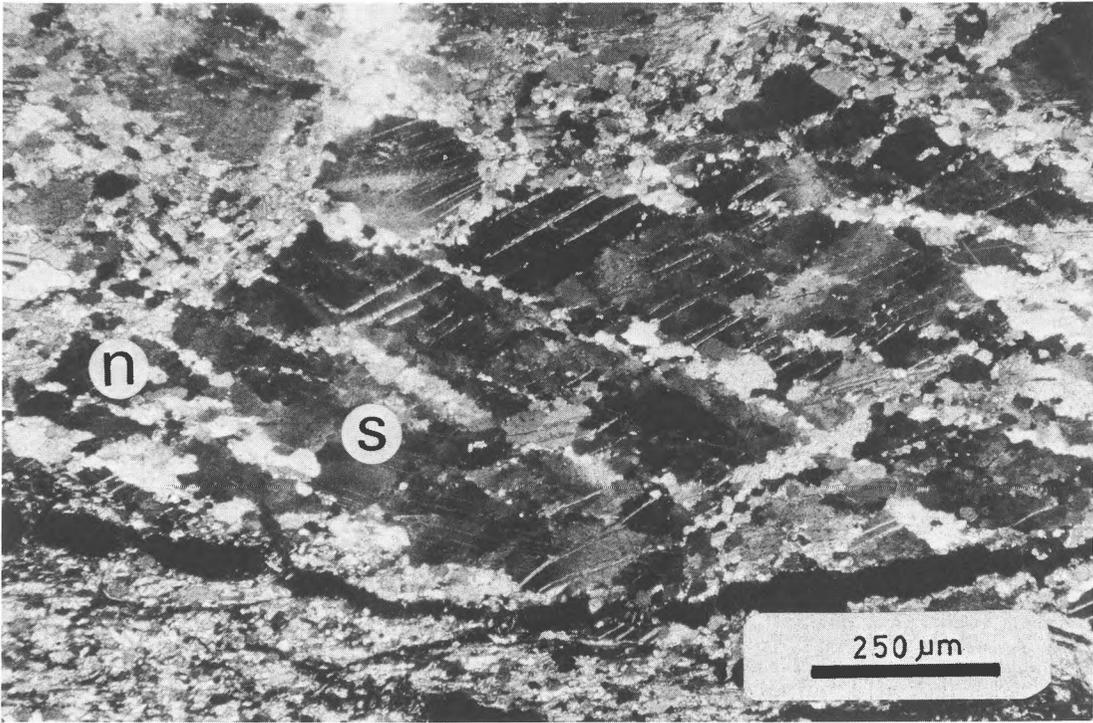
A distinct point-maximum can be seen in pole diagrams 4a and 4g. The maximum is oriented oblique to the shear plane as well as to the grain-

shape foliation (Fig. 4a). *C*-axes are also concentrated at a high angle to the shear plane in pole diagram 4d, with a tendency towards a small-circle distribution. All other pole diagrams show more than one *c*-axis maximum and a pole free area around the shear plane. They are not clearly asymmetric and can be grouped in pole diagrams with three maxima at a high angle to the shear plane (Figs 4b, 4c and 4e) and pole diagrams with less defined maxima and a tendency towards a distribution along the perimeter of the projection (Figs 4f, 4h and 4i).

Discussion

The single maxima in pole diagrams 4a and 4g are comparable with the well known LT-textures (Fig. 1). The orientation oblique to the shear plane confirms the known (dextral) sense of shear, but the small angle with the shear plane normal ($10\text{--}20^\circ$) suggests an additional pure shear component to the total strain up to 60% (cf. Wenk et al., 1987). The almost symmetrical nature of the other pole diagrams supports the contribution of a pure shear

a



b

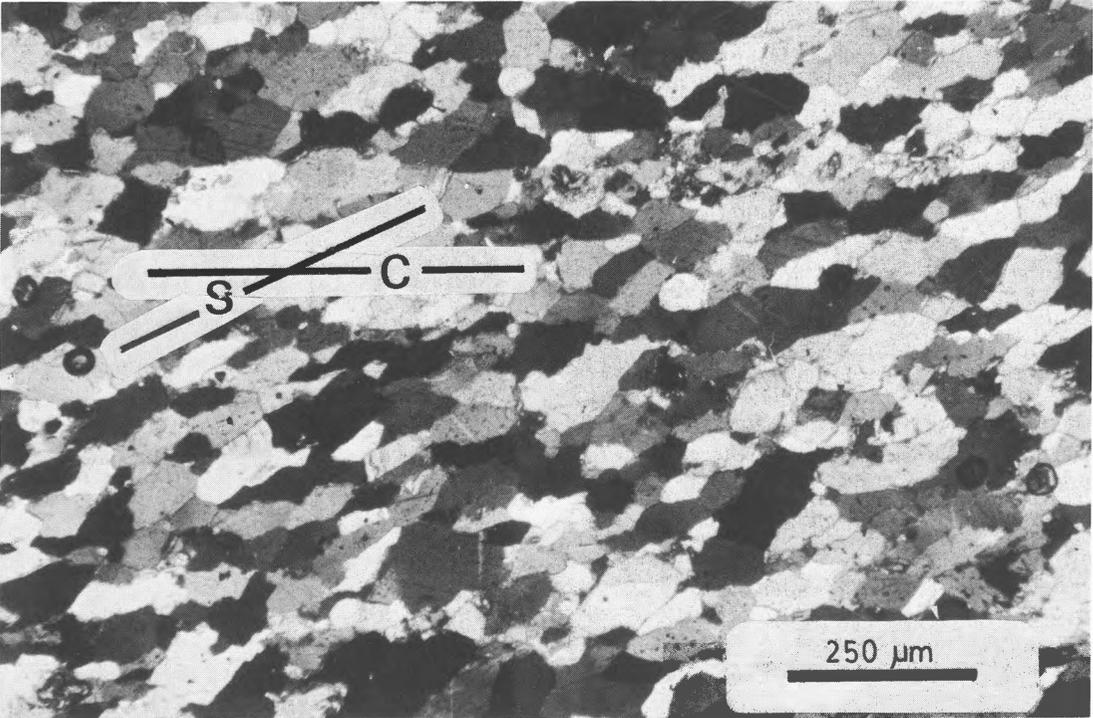
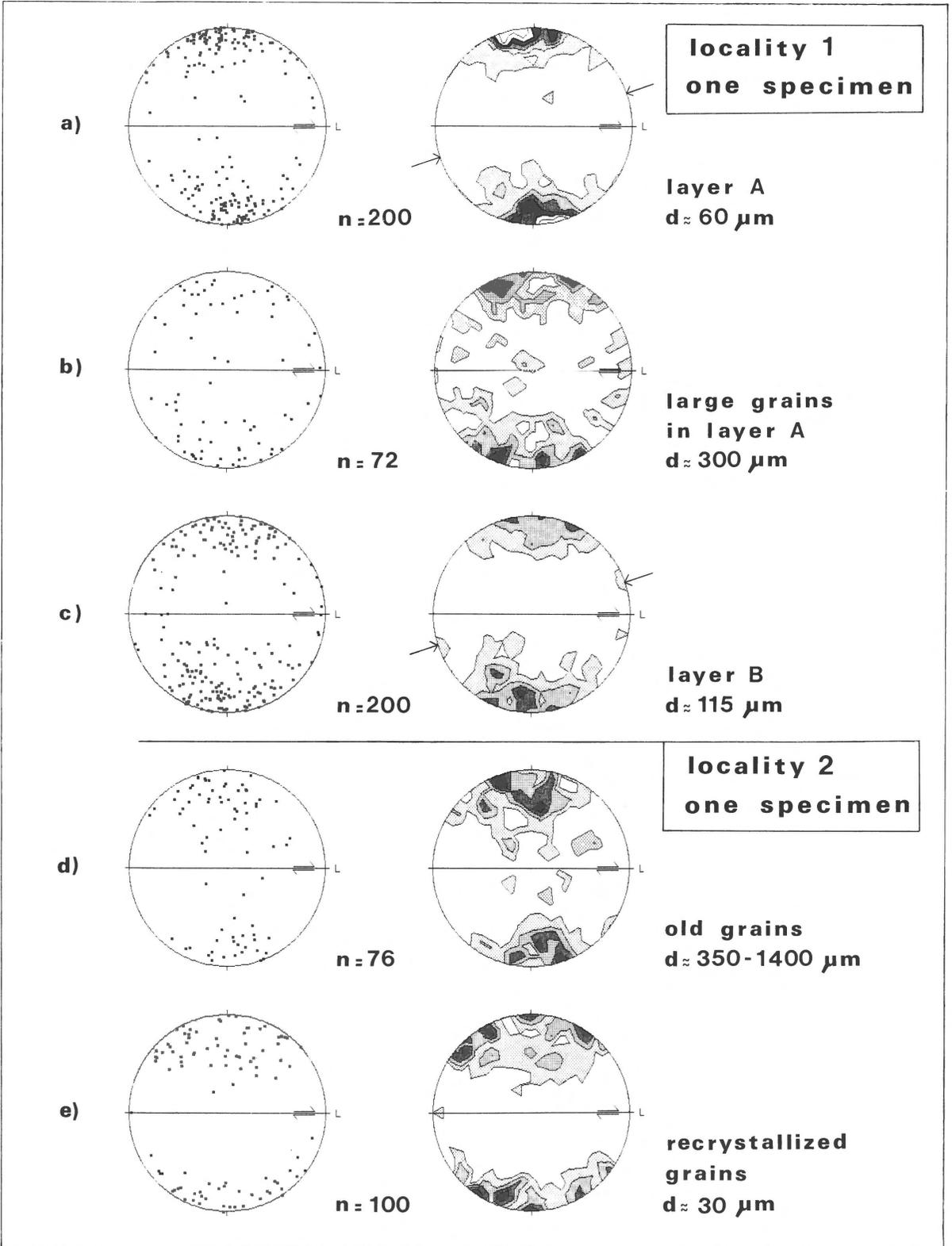


Fig. 3. Photomicrographs.

a) Old calcite grain with subgrains (s) and recrystallized, new grains (n). Intracrystalline deformation is indicated by undulatory extinction under crossed nicols of both old and new grains (locality 2). b) Microstructure of a calcite SC-mylonite (locality 1). Elongate grains and alignment of grain boundaries define a foliation (S) oblique to the shear plane/compositional layering (C). Dextral sense of shear. Crossed nicols.



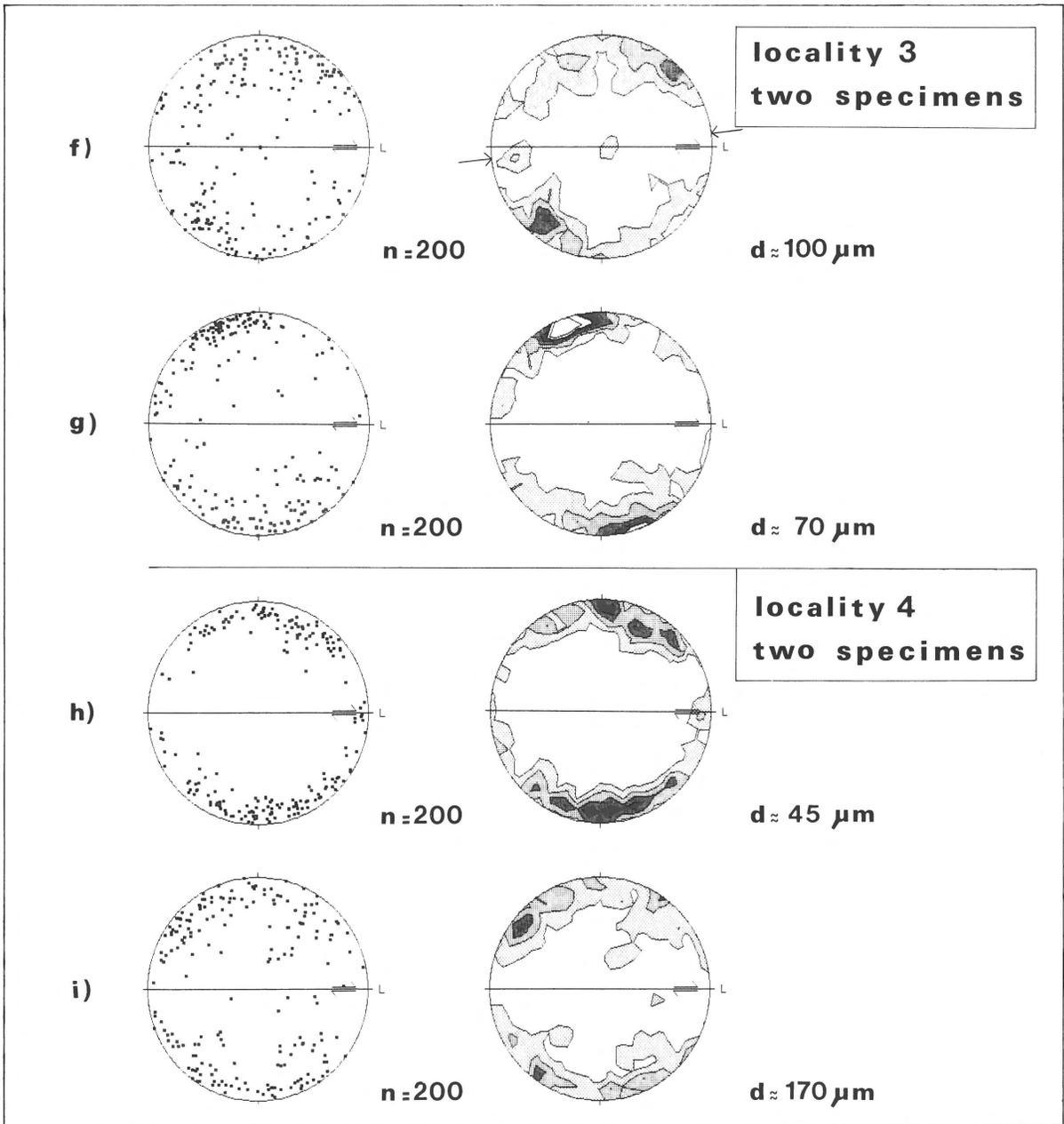


Fig. 4. C-axis pole diagrams and contoured plots for samples from localities 1 to 4 (Fig. 2). All plots looking east; horizontal line in all plots represents the shear plane, with dextral sense of movement. Equal area, upper hemisphere projections. For contouring 1% counting circles have been used. Contour levels are 1, 2.5, 4, 5.5, 7 and 8.5 times uniform distribution; first four intervals shaded. L denotes the extension lineation, N is the number of measurements, d is grain size and arrows at the perimeter indicate the grainshape foliation.

component. Different pole diagrams for thin layers from the same sample (Figs 4a and 4c) suggest heterogeneous deformation at the scale of a hand-specimen.

The c-axis distribution of old grains and of recrystallized new grains (Figs 4d and 4e) are slightly different, but show virtually no change in symmetry. Thus, they do not give direct information on the strain path, but may be interpreted to indicate a change in dominant slip mechanism, possibly related to the change in grain size during recrystallization. Alternatively, a host grain control on the c-axis orientation of the recrystallized grain is possible, as the new grains appear to have been developed by progressive rotation of subgrains of the host grain (Fig. 3a).

The separate maxima of pole diagrams 4b, 4c and 4e, and the spreading of c-axes along the perimeter of the plots in Figs 4f, 4h and 4i deviate from the LT single maximum textures (cf. Fig. 1). They show better agreement with the HT-textures, notably the experimental pure shear and theoretical simple shear ones, respectively. Detailed comparison is complicated by the limited correspondence of theoretical and experimental textures (Fig. 1; see Wenk et al., 1987 for discussion). However, it appears that LT- and HT-type textures occur close to each other in the limestones from the Gavarnie thrust zone (localities 1 and 3, Fig. 4). The estimated temperature of 200°C during thrusting is in good agreement with the documented temperature of 200–300°C for the experimental LT- to HT-texture transition for fine-grained calcite-rock. It is therefore suggested that the studied limestones were deformed in the regime of LT-HT texture transition. Local predominance of LT- or HT-type of texture was probably governed by changes in dominant intracrystalline twinning or slip mechanism, related to variations in rock properties. Grain size, however, was not likely a controlling factor, as there is no obvious correlation between the grain size and the type of texture (Fig. 4). The correspondence between the temperature of texture transition for the (slow) natural deformation and the (fast) experimental deformation implies a low strain rate sensitivity of this transition temperature.

The symmetrical textures in several specimens suggest that pure shear was important in the deformation history of the Gavarnie thrust zone. A significant contribution of coaxial bulk shortening approaching pure shear during mylonitization has been observed in other thrust belts, e.g. in the Moine thrust zone in Scotland (Law et al., 1984) and in the Betic movement zone in Spain (Platt & Behrmann, 1986). This is attributed to a partitioning of the bulk flow into domains of approximately simple shear deformation and domains of a lower degree of non-coaxiality than simple shear, approaching pure shear. Flow partitioning may have accounted for the pure shear type of textures in the Gavarnie thrust zone. More detailed work is needed in order to actually distinguish domains of different types of strain history.

Conclusions

C-axis textures of calcite rocks from the Pyrenean Gavarnie thrust zone:

- confirm the known sense of shear along the zone,
- indicate a considerable contribution of pure shear to the total strain, and
- show characteristics of both low-temperature and high-temperature textures.

The latter indicates that deformation in the thrust zone may have occurred in a regime of texture transition, at a temperature of about 200°C.

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