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Calcite fabrics in the hinge zones of experimentally folded single layers of marble and limestone

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Abstract—The preferred orientations of poles to (0006) and (10$\bar{1}$4) planes in calcite have been studied in the inner and outer arcs of experimentally produced single-layer buckle folds in Carrara marble and Solnhofen limestone. The textures produced in the medium-grained marble differ from that of the fine-grained limestone. Further, the pole figures from the inner fold arcs are characterized by a general orthorhombic symmetry and a strong preferred orientation of the crystallographic fabric elements, whereas that from the outer fold arcs generally exhibits a triclinic symmetry and a weak preferred orientation.

The difference in the pole figures in medium-grained marble and fine-grained limestone is attributed to the mechanism of internal deformation in calcite. The orthorhombic symmetry of the pole figures from the inner fold arc suggests a coaxial strain history in this zone, whereas the triclinic symmetry of the fabric diagrams from the outer fold arcs is attributed to a non-coaxial strain history.

INTRODUCTION

IN GENERAL it has been observed that naturally folded calcareous and quartzitic rocks do not exhibit a strong preferred orientation of the crystallographic fabric elements, though they may have a strong preferred dimensional grain orientation. The lack of a strong preferred orientation of the crystallographic axes and planes in calcite grains in natural rocks may be attributed to post-tectonic recrystallization or polyphase deformation. These rocks develop a strong preferred crystallographic orientation when deformed at moderate to high temperatures in laboratory experiments. Therefore, fabrics in marble and limestones have been studied in the homogeneous samples experimentally deformed under different stress conditions and varied temperatures (see references in Wagner *et al.* 1982). Considerable variations have been recorded in calcite fabrics under different conditions of temperature, pressure and strain rate (Wenk *et al.* 1973), which have been attributed to changes in the deformation mechanisms involved (Wagner *et al.* 1982). The fabrics, however, have not been studied in heterogeneous samples consisting of a combination of two or more rock types differing in rheological properties, and deformed in the laboratory. Such experimental studies would be closer to the natural conditions of deformation.

Experiments were carried out at raised temperatures under plane strain conditions for single-layer folding in rock salt (Gairola & Kern 1984a), and marble and limestone (Gairola & Kern 1984b). In these experiments the single layers embedded in a matrix of different physical properties, deformed in a heterogeneous system and provided samples for fabric study from the hinge zones of flow folds. The progressive changes in the textures developed in halite crystals from the hinges and limbs, have been discussed by Gairola & Kern (1984a). The pole figures for (1120) planes in calcite from the hinge zones of marble and limestone have been given earlier (Gairola & Kern 1984b). However, the pole figures have not been discussed in terms of symmetry and kinematics. In the present paper, therefore, the fabrics exhibited by poles to (0006) and (10$\bar{1}$4) planes in calcite from the inner and outer arcs of folded marble and limestone layers will be discussed.

EXPERIMENTAL TECHNIQUES

Thin layers of uniform thickness and dimensions (45 × 36 × 3 mm) of medium-grained Carrara marble and fine-grained Solnhofen limestone were cut from homogeneous rock masses. The marble layer was embedded in a matrix consisting of a homogeneous mixture of halite (60% by volume) and calcite (40% by volume). The total initial dimension of the sample in each experiment was 45 × 43 × 40 mm. The layers were deformed along their lengths under plane strain conditions at a temperature of 400°C in a triaxial press with six prismatic pistons. The average strain rate in the case of marble layer was $5.5 \times 10^{-7}\ s^{-1}$ (Fig. 1A), and in limestone layer was $6.8 \times 10^{-7}\ s^{-1}$ (Fig. 1B). The details of the apparatus and material, and the experimental methodology have been described in detail by Gairola & Kern (1984b). After the effects of layer parallel shortening the single-layers deformed by folding along one fold hinge. The geometrical features of the folds have already been discussed (Gairola & Kern 1984b).

TEXTURE AND MICROSTRUCTURE

The medium-grained marble layer is constituted of equidimensional pure calcite about 300 μm in size. The

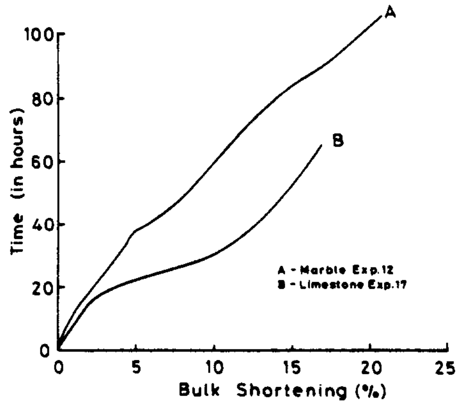

Fig. 1. Time–strain curve of the folded marble (A) and limestone (B) layers.

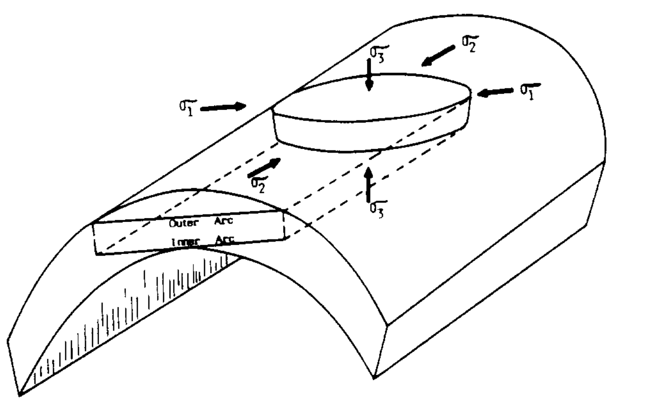

Fig. 2. Location of specimen from the fold hinge zone for the X-ray texture goniometer probe. σ denotes the bulk stress where $\sigma_1 > \sigma_2 > \sigma_3$.

grains do not exhibit any sign of anisotropy, are rarely twinned, and when twinned they exhibit wide twin lamellae (Kern 1979). After deformation the folded marble layer exhibits grains with two to three well developed sets of twin lamellae. The grains in the inner fold arc are flattened and fractured with sutured outline, and the most prominent twin lamellae along the length of the elongated grain are oriented perpendicularly to the layer surface. In the outer fold arc the grains are broader and larger than in the inner fold arc, do not exhibit flattening or compaction, and the twin lamellae are less pronounced and exhibit an oblique relationship with the layer surface. The details of the microstructures are discussed by Gairola & Kern (1984b).

The undeformed specimen of the fine-grained (size 10 μm) limestone exhibits a weak preferred orientation of calcite in contrast to the deformed specimen which develops a strong anisotropy that varies with the externally applied stresses (Kern 1977). The X-ray texture goniometer reveals well developed textures which differ in the inner and outer fold arcs.

FABRICS

The preferred orientation of the crystallographic fabric elements [poles to (0006) and (10$\bar{1}$4)] in calcite from the inner and outer fold arcs in the marble and limestone layers, have been determined in reflection mode by Phillips X-ray texture goniometer with Cu-radiation. A circular plate 12 mm in diameter, was cut from the hinge zone (Fig. 2) of each of the experimentally folded layers. The concave (inner arc) and the convex (outer arc) surfaces of the circular plate were ground to make them plane for the textural analysis. Thus, one surface of the plate was close to the inner arc, whereas the other surface was close to the outer arc. The intensities of the pole figures were corrected by the method described by Baker *et al.* (1969) by using the data obtained by Kern (1977) from the undeformed specimens.

In the pole figures (Figs. 3 and 4) the E–W axis denotes the direction of minimum bulk strain, i.e. the *Z*-axis (coinciding with σ_1 axis of bulk stress), the N–S axis represents the direction of fold hinge and also the intermediate bulk strain axis, i.e. the *Y*-axis (coinciding with the σ_2 axis of bulk stress). The centre of the diagram is coaxial with the direction of maximum bulk strain, i.e. the *X*-axis or the σ_3 axis of bulk stress, and is normal to the layer surface (Fig. 2).

Inner fold arc

In the pole figure from the inner fold arc of marble layer the poles to (0006) planes (Fig. 3A) occupy a small circle girdle with an opening angle of 20–30° around the *Z*-axis. The poles to (10$\bar{1}$4) planes (*r*-planes) also lie in a small circle girdle about the *Z*-axis (Fig. 3B), however, the opening angle is greater (30–40°). The fabric diagrams (Figs. 3A & B) exhibit an orthorhombic symmetry and the symmetry planes coincide with the symmetry planes of the macroscopic stresses. In limestone the poles to (0006) planes (Fig. 3C) exhibit a concentration along the axial plane in the form of a great circle girdle with a maximum along the *X*-axis of bulk strain, and another concentration forming a small circle girdle about the *X*-axis with an opening angle of 50°–60°. The diagram (Fig. 3C) exhibits an orthorhombic symmetry tending towards triclinic due to the partially developed small circle girdle. The poles to (10$\bar{1}$4) planes (Fig. 3D) lie along a great circle girdle parallel to the *XY* plane with a maximum along the *X*-axis, and a pair of symmetrical partial great circle girdles along the fold hinge with an opening angle of about 60° with respect to the *XY* plane. The fabric diagram (Fig. 3D) exhibits an orthorhombic symmetry.

Outer fold arc

In general the outer fold arc exhibits a weakly developed preferred orientation of the fabric elements. In the marble layer the poles to (0006) planes (Fig. 4A) lie along a broad peripheral cleft girdle pattern with several maxima. A few clusters of points are also observed showing a tendency of a small circle girdle about the *X*-axis. The monoclinic symmetry of the dia-

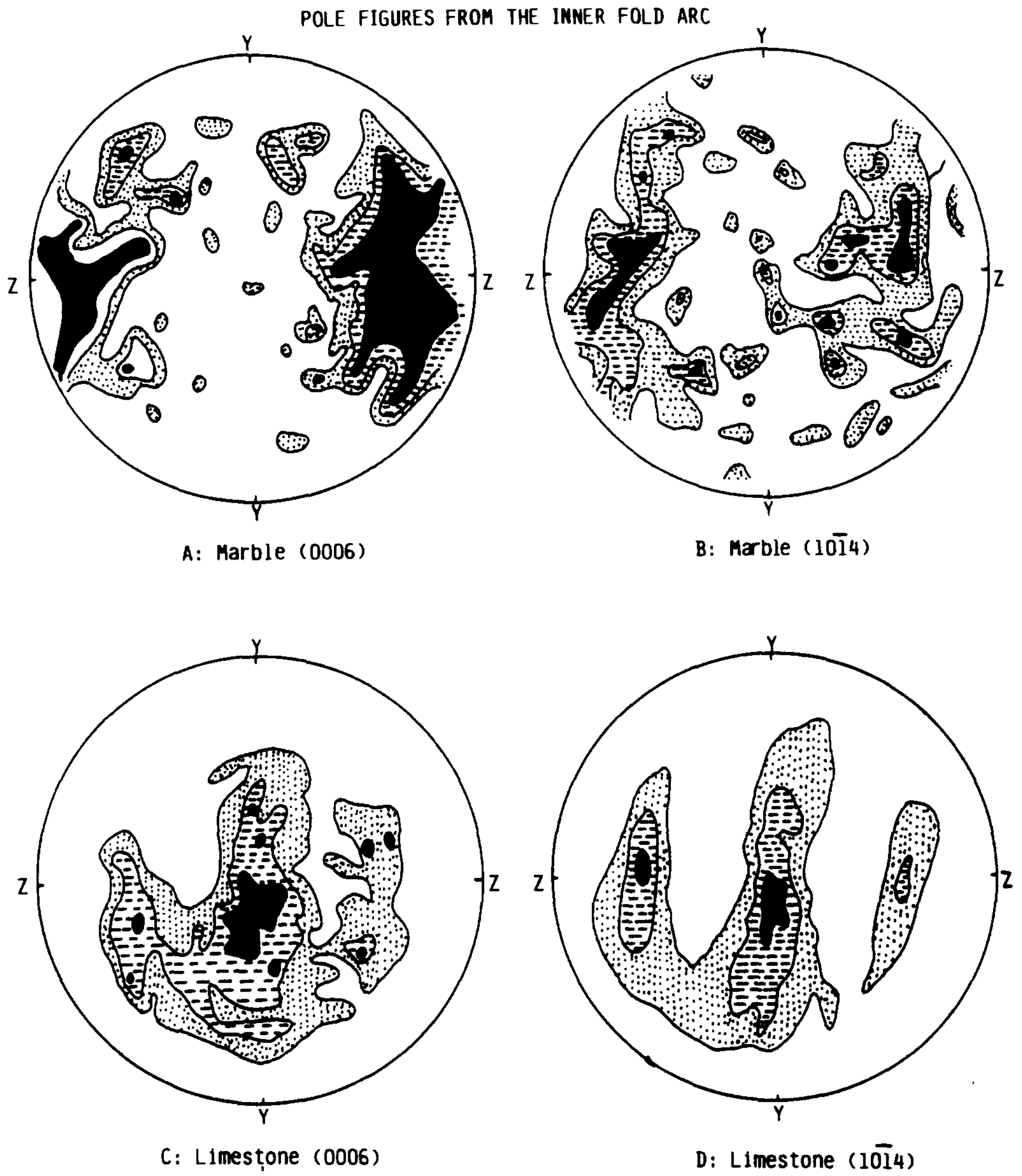

Fig. 3. Calcite pole figures from the inner arcs of the experimentally folded single layers. In the pole figures Z coincides with the maximum bulk stress axis (σ_1) and Y denotes the direction of fold hinge and coincides with the intermediate bulk stress axis (σ_2). (A) Poles to (0006) planes in marble layer. Contours: 1, 1.5 and >5% per unit area. (B) Poles to (10$\bar{1}$4) planes in marble layer. Contours: 1, 1.5 and >5% per unit area. (C) Poles to (0006) planes in limestone layer. Contours: 1, 1.5 and >2% per unit area. (D) Poles to (10$\bar{1}$4) planes in limestone. Contours: 1, 1.2 and >1.4% per unit area.

gram has become triclinic (Fig. 4A) due to the unequal distribution of the poles in the form of several maxima. The strongest concentration of poles, however, is along the Z-axis (Fig. 4A). The poles to (10$\bar{1}$4) planes in the marble layer show a very weak preferred orientation with several maxima which do not have any pattern. The fabric diagram (Fig. 4B) thus exhibits a triclinic symmetry.

In the limestone layer the pole figures (Figs. 4C & D) for both (0006) and (10$\bar{1}$4) planes in calcite from the outer fold arc show that two poles lie subparallel to the X-axis of the bulk strain. The concentration of the maximum exhibited by the poles to (10$\bar{1}$4) planes is weaker than for (0006) planes. Both the diagrams (Figs. 4C & D) exhibit a tendency for an orthorhombic symmetry.

DISCUSSION

In a single-layer buckle fold it has been shown that during the layer parallel shortening stage the strains are uniform throughout the layer and that the local strain axes x, y and z within the layer, coincide with the bulk strain axes X, Y and Z, respectively (Gairola 1977a, b, 1978). With the initiation of folding the values and directions of the local strain axes (x, y, and z) vary in different parts of the folded layer (Gairola 1977a, b, 1978). The fold hinges deform by tangential longitudinal strain and the outer fold arc experiences extension, whereas the inner fold arc undergoes compression along the layer surface (Ramsay 1967). Thus in the inner fold arc the orientation of the strain ellipsoid does not change at any stage of deformation and the local and bulk strains

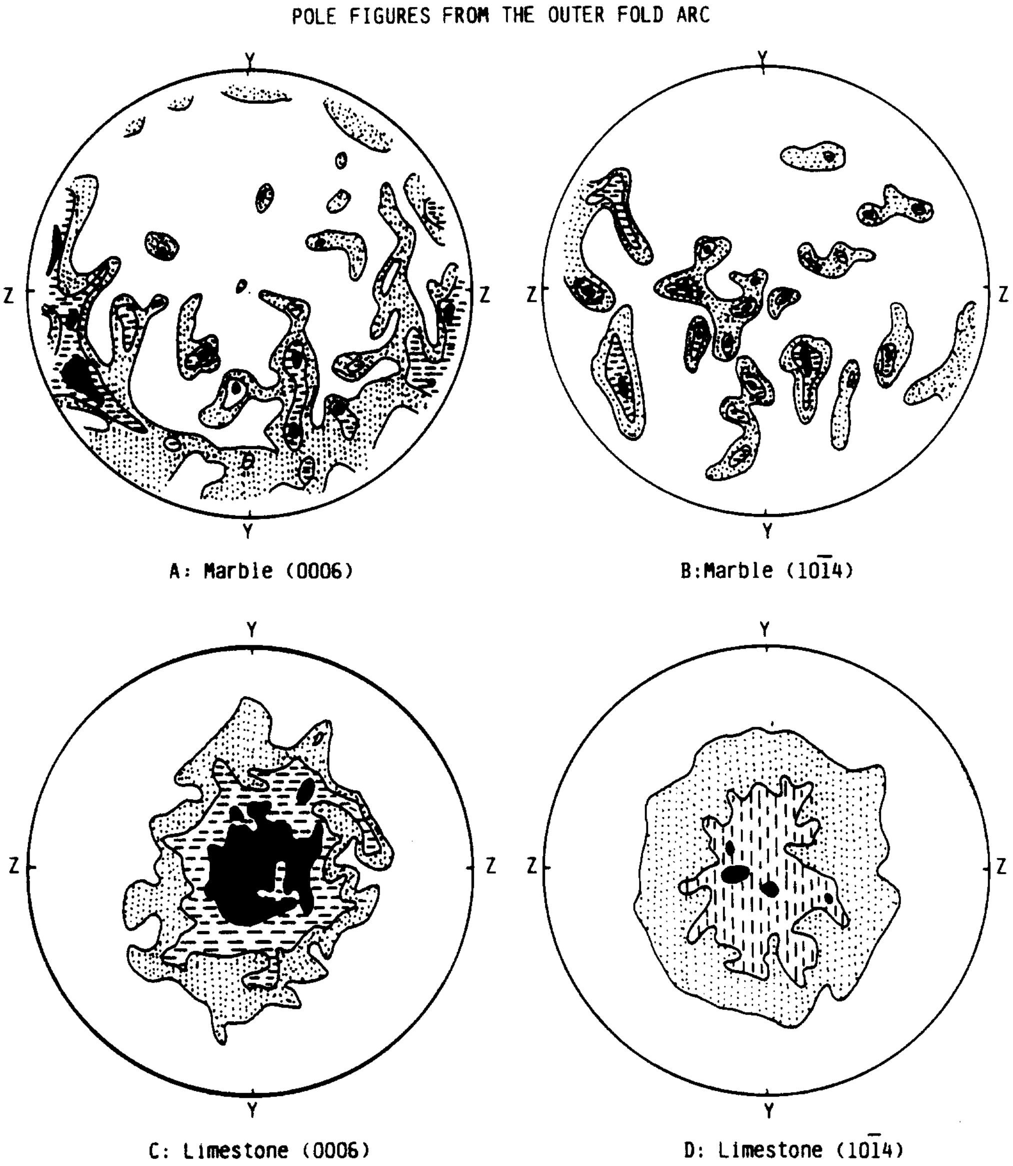

Fig. 4. Calcite pole figures from the outer arcs of the experimentally folded single layers. In the pole figures Z coincides with the maximum bulk stress axis (σ_1), and Y denotes the direction of fold hinge and coincides with the intermediate bulk stress axis (σ_2). (A) Poles to (0006) planes in the marble layer. Contours: 1, 1.5 and >5% per unit area. (B) Poles to (10$\bar{1}$4) planes in the marble layer. Contours: 1, 1.5 and >5% per unit area. (C) Poles to (0006) planes in the limestone layer. Contours: 1, 1.5 and >2% per unit area. (D) Poles to (10$\bar{1}$4) planes in the limestone layer. Contours: 1, 1.2 and >1.4% per unit area.

remain coaxial. However, in the outer fold arc, due to the local extensional strain with the initiation of folding, the local and bulk strain ellipsoids become non-coaxial. The x-axis of the local strain interchanges with the z-axis of the local strain, resulting in a complex strain history. Therefore, due to the different strain histories the inner fold arc has experienced greater total strains than the outer fold arc.

The pole figures (Figs. 3 and 4) from the inner fold arc zone exhibit a stronger preferred orientation than from the outer fold arc zone, and thus reveal that the former is more deformed than the latter zone. Further, a general orthorhombic symmetry of the pole figures in the inner arcs shows that the strain history was coaxial, whereas in the outer fold arc the symmetry is generally triclinic indicating that this zone underwent a non-coaxial strain history.

The pole figure (Fig. 3A) for the (0006) planes in calcite from the inner fold arc of the medium-grained marble layer, is consistent with the observations made on experimentally deformed marble and limestones (Griggs 1953, 1960, Turner *et al.* 1956, Heard & Turner 1965) where the c-axis concentrations in calcite occupy a small circle girdle about the Z-axis of strain (σ_1 axis of bulk stress) with an opening angle of 20–30°. In contrast, in the fine-grained limestone the maxima of poles to (0006) planes lying in a cleft girdle pattern (Fig. 3C) about X-axis (σ_3 axis of bulk stress) is consistent with the pole figures observed in axially symmetric extension parallel to the elongation direction (Turner & Weiss 1963). Sander (1930) has also observed a prevalent tendency for c-axis maxima to fall on a small circle girdle about the σ_3 axis with a wide angular radius. In earlier work the pattern of pole figures to (10$\bar{1}$4) planes in calcite has not been described. From the present observations (Fig. 3B) it may be inferred that the poles to $(10\bar{1}4)$ planes in calcite in medium-grained marble layer also occupy a small circle girdle about the σ_1 axis with an angular radius of 30–40°. The poles to (1120) planes in calcite from the inner fold arc (Gairola & Kern 1984b, fig. 9B) shows that the fine-grained calcite crystals deform by *r*- and *f*-slip mechanisms. Hence, it may be concluded that the present pole figure (Fig. 3D) for $(10\bar{1}4)$ planes may also be indicating deformation within the calcite grains by *r*- and *f*-slip.

In the outer fold arc the weak preferred orientation and a general triclinic symmetry exhibited by the pole figures in the medium-grained calcite (Figs. 4A & B) is due to the changes in the orientation of the local infinitesimal strain ellipsoids. Kern (1979) has suggested that besides *r*- and *f*-slip, not fully understood intracrystalline slip also imparts preferred orientation in fine-grained limestone. Therefore, in the fine-grained calcite the orthorhombic symmetry of the pole figures (Figs. 4C & D) may be attributed to this different mechanism of deformation.

CONCLUSION

In flow folds the fabrics in the hinge zones are controlled by the strain histories in different parts of the hinge during fold development. The outer fold arcs are characterized by a very weak fabric as compared to the inner fold arcs. The fabrics that develop in calcite are influenced by the grain size, and reflect the mechanism of internal deformation in the crystals.

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