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A PETROFABRIC ANALYSIS OF A FOLD

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ABSTRACT. A petrofabric method whereby polygenetic folds can be analyzed is described. The method has been applied to the study of the tectonic history of a fold from the Grampian Highlands of Scotland. An earlier deformation was produced by shearing, followed by accordion folding, utilizing the same S-planes.

SUMMARY OF PREVIOUS WORK

Detailed analyses of folds have been made by various workers, following the classic description by Sander (1930) of a folded quartzite from Brenner, Tyrol. This fold was a flexure fold, and similar structures have been described by Turner (1948), Ingerson (1940), and others.

Ladurner (1954) described a method by which a polygenetic fold (in this case shear, followed by flexure) could be analyzed, and also described the analysis of such a fold. Jones (1959) first described the method in English, and also attempted the analysis of polygenetic folds, but came to the conclusion that possibly later movements had obliterated the earlier fabric.

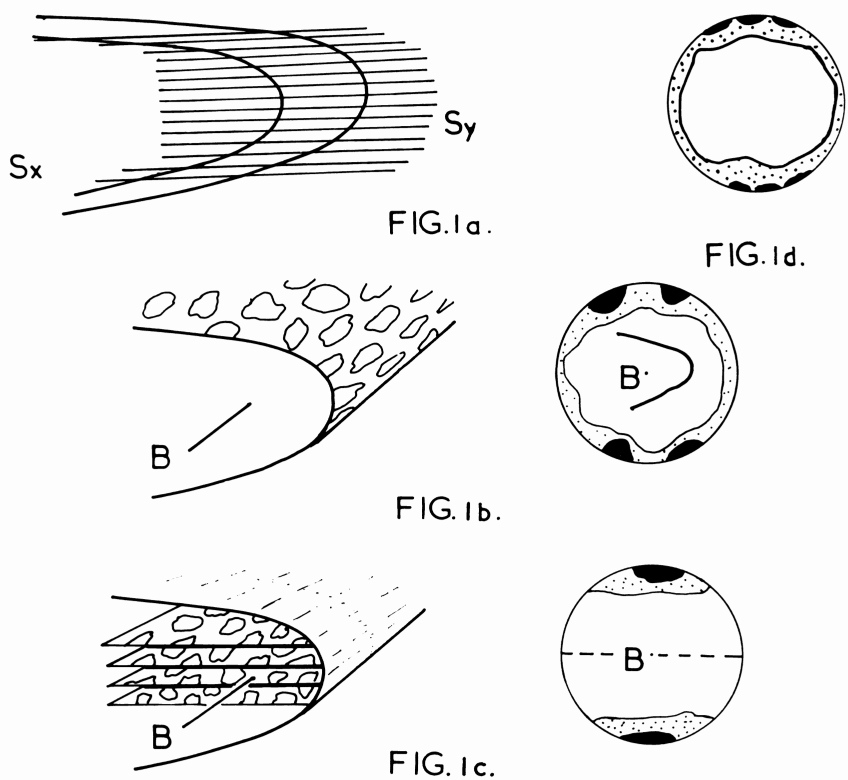

Fig. 1. (a) Relation of S_x & S_y to fold, (b) Mica Orientation for flexure fold, (c) Mica Orientation for shear fold, (d) collective mica diagram.

MONOGENETIC FOLDS

Folds of this type may originate through (a) pure shear, (b) pure flexure, (c) flow, and, (d) any combination of these processes.

The common orientation rule for micas is that in which the (001) cleavage plane lies in an S-plane, with the "c" crystallographic axis normal to the S-plane. The orientation of the quartz will be considered subsequently.

(a) *Fold formed by pure shear.*—The fold is formed by deformation along an infinite or finite number of shear planes (S_y), usually parallel to the axial plane of the fold (fig. 1a). The micas will become oriented, either by syntectonic crystallization or by subsequent growth along S-planes. They will be oriented, firstly, by deformation of the original S-plane (S_x), and will produce a girdle developed about the fold axis as axis of symmetry, with maxima corresponding to the limbs (fig. 1b and Ingerson, 1940). Secondly they will be

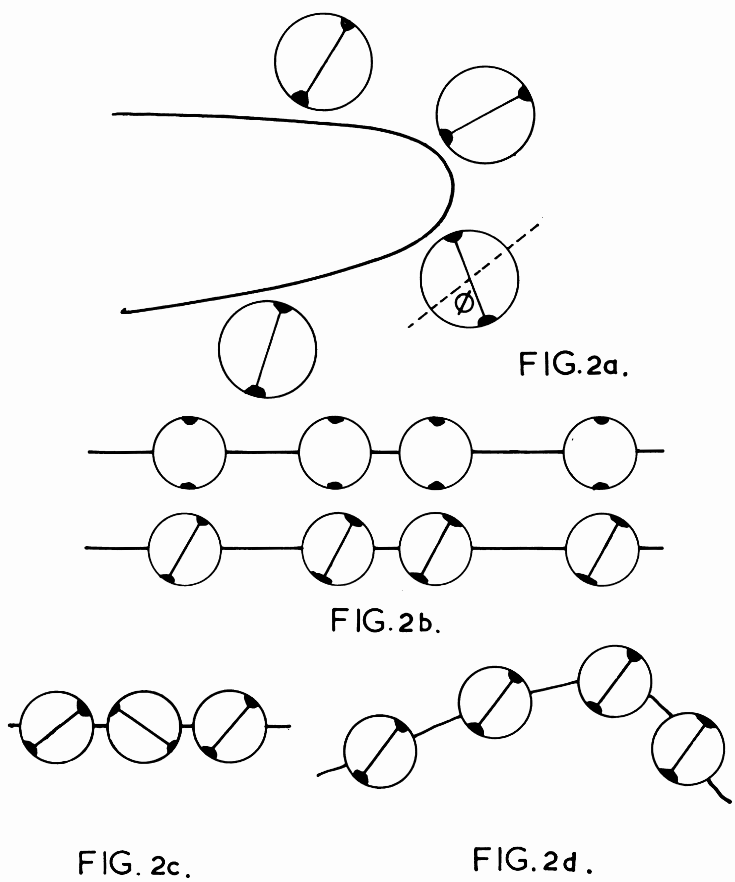

Fig. 2. (a) Relation of q-richtungen to fold, (b) Parallel alignment of q-richtungen on unfolding 2a. Mica diagram, above; Quartz diagrams below. (c) Relation of q-richtungen on complete unrolling of a polygenetic fold. (d) Polygenetic fold partly unfolded so that q-richtungen are parallel.

oriented parallel to the shear planes (S_y) in the fold, giving a preferred orientation of the "c" axes perpendicular to the shear direction (fig. 1c). In practice, however, it will be found difficult or impossible to distinguish between the two types of micas, and the fabric diagrams will be superimposed (fig. 1d).

The fabric of the quartz grains will be identical in all parts of the fold, no matter which orientation rule the quartz follows, and the main sets of maxima will be in the same relative positions (Ladurner, 1954).

(b) *Fold formed by pure flexure.*—The fold is formed by pure flexure, or flexural slip, whereby the fold develops by rotation about the axis (B) with attendant slip upon the primary S-plane (S_x), in order to accommodate the core without rupture. In this case the mica orientation will form a girdle about "B", with maxima corresponding to the limbs (fig. 1b).

Provided that the quartz grains in the fold had an originally anisotropic fabric, then the quartz orientation diagrams, at all points on the fold, will each have an identical relationship with the tangent to the fold. For example, assuming that the initial quartz orientation was such that it made an angle of ϕ° with S_x in the plane of section, then as S_x is folded about "B", the relationship of the quartz axes to the fold will appear as in figure 2a. The S-planes, as defined by the mica maxima, can then be brought into alignment and the fold "unrolled", with the q-richtungen[1] for the quartz diagrams lying parallel to each other (fig. 2b).

(c) *Fold formed by flow.*—The fold is formed by flow, in which there is no relation between the planes of deformation and the stress direction. The quartz fabric will tend to be markedly heterogeneous, and the symmetry of the fabric will not correspond to the symmetry of the fold. The layers in the fold will become stretched and thickened, and it will be impossible to estimate the shortening involved (Hills, 1951; De Sitter, 1956).

POLYGENETIC FOLDS

This group includes folds which have been formed, or modified, by one type of deformation followed by another (e.g. shear followed by flexure, or vice versa).

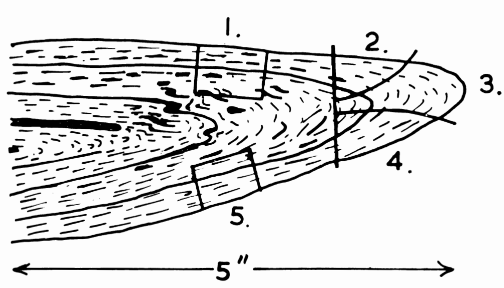

FIG. 3

Fig. 3. Diagram of fold showing position of sectors. The sections were cut normal to the fold axis (120°N).

[1] q-richtungen are lines joining maxima to the center of projection (Ladurner, 1954).

Shear followed by flexure.—Such a structure may be defined by referring to the description of the folds analyzed by Ladurner (1954) and Jones (1959).

Ladurner, on completely "unrolling" a fold, found that the angle ϕ was not the same for each sector (fig. 2c). He overcame this difficulty by *partially* unfolding the fold until the q-richtungen were aligned parallel to each other (fig. 2d). The fold was thus initiated by shear, to give the shallow fold in figure 2d, and the fold was subsequently tightened by flexure of S. In the fold discussed by Ladurner $\phi = 68\text{-}78°$, and it retained its original fabric axis and a-c symmetry plane.

Flexure followed by shear.—With this type of deformation, the analysis is more complex. There will be an original mineral orientation, related to the folded S-plane (S_x), upon which is superimposed an orientation induced by shearing. It is possible that this later shear will completely obliterate the fabric of the earlier flexure. Where there are more than two modes of deformation, it will probably be impossible to detect the first unlss the later dformations have been much less intense.

APPLICATION TO A FOLD

In order to illustrate these principles an analysis of a fold from the Grampian Highlands of Scotland will be described (see fig. 3). The fold was located 2¾ miles west of Balquhidder (British Nat. Grid. Ref. NN/490207). The reversal of direction of curvature in small quartz veins in the core of the fold indicates that a certain amount of flexure has occurred during the evolution of the fold (Sander, 1930; Turner, 1948). The fold was divided up into a number of segments, the nose of the fold being subdivided into as many sectors as possible (fig. 3).

The sectors 1 and 5 give mica diagrams which can be related to the primary S-plane (S_x) (fig. 4). Sectors 2 and 4 give orientation patterns which define a statistical S-plane sub-parallel to the axial plane of the fold (S_y). Sector 3 gives a more complete girdle, with maxima that can be related to S_y and the limbs of the fold (see also fig. 1d). The mica diagrams in the nose of the fold define slightly divergent S-planes (fig. 7c).

On the basis of the mica fabric, the limbs of the fold have been affected by flexural slip, the nose and the region bordering the axial plane having been affected by shear acting parallel or sub-parallel to the axial plane of the fold. The relation of the q-richtungen to the quartz diagrams and the diagrams to the fold are shown in figure 6b, the pattern of the q-richtungen being similar in each case. In sector 2 the q-richtungen that can be drawn are greater in number, but directions can be found which correspond to the pattern constructed for other diagrams. The fabric diagrams for the nose of the fold give, in general, much sharper and more clearly defined orientation patterns than on the limbs. The patterns are identical in the sectors 1 and 5, but one diagram is the mirror image of the other. Use could not be made of the mica diagrams in unrolling the fold (Ladurner, 1954), but only of tangents to the S_x plane which could be determined in the hand specimen.

In the completely unfolded state, the quartz diagrams will be related as in figure 7a. The measure of the flexure of the fold can now be obtained by

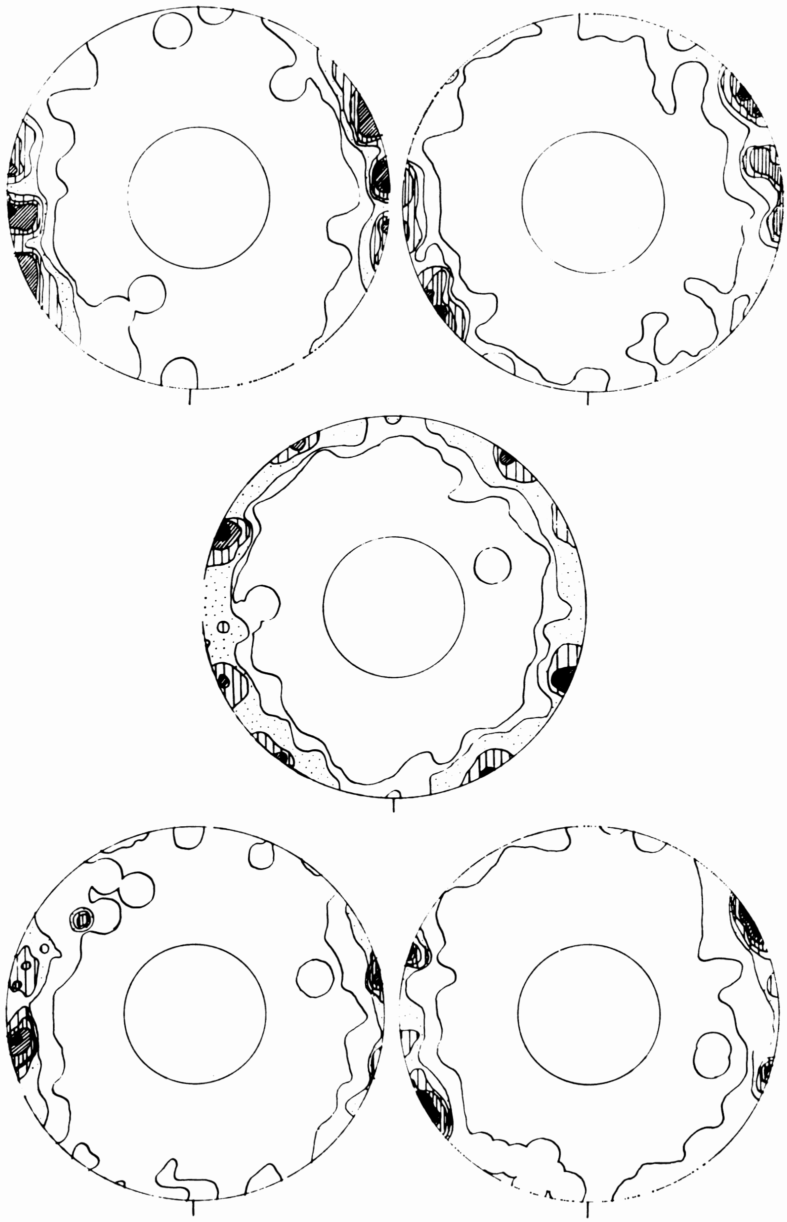

Fig. 4. Mica & Chlorite diagrams, poles to (001) cleavage.

Sector 1: 100 micas; contours at 15, 12, 10, 8, 5, 1% per 1% area.
Sector 2: 105 micas; contours at 12.6, 10.5, 7.3, 5.7, 3.6, 0.91% per 1% area.
Sector 3: 130 micas; contours at 10, 8, 6.1, 4.6, 2.4, 0.8% per 1% area.
Sector 4: 100 micas; contours at 12, 10, 8, 6, 4, 1% per 1% area.
Sector 5: 100 micas; contours at 16, 12, 10, 8, 5, 1% per 1% area.

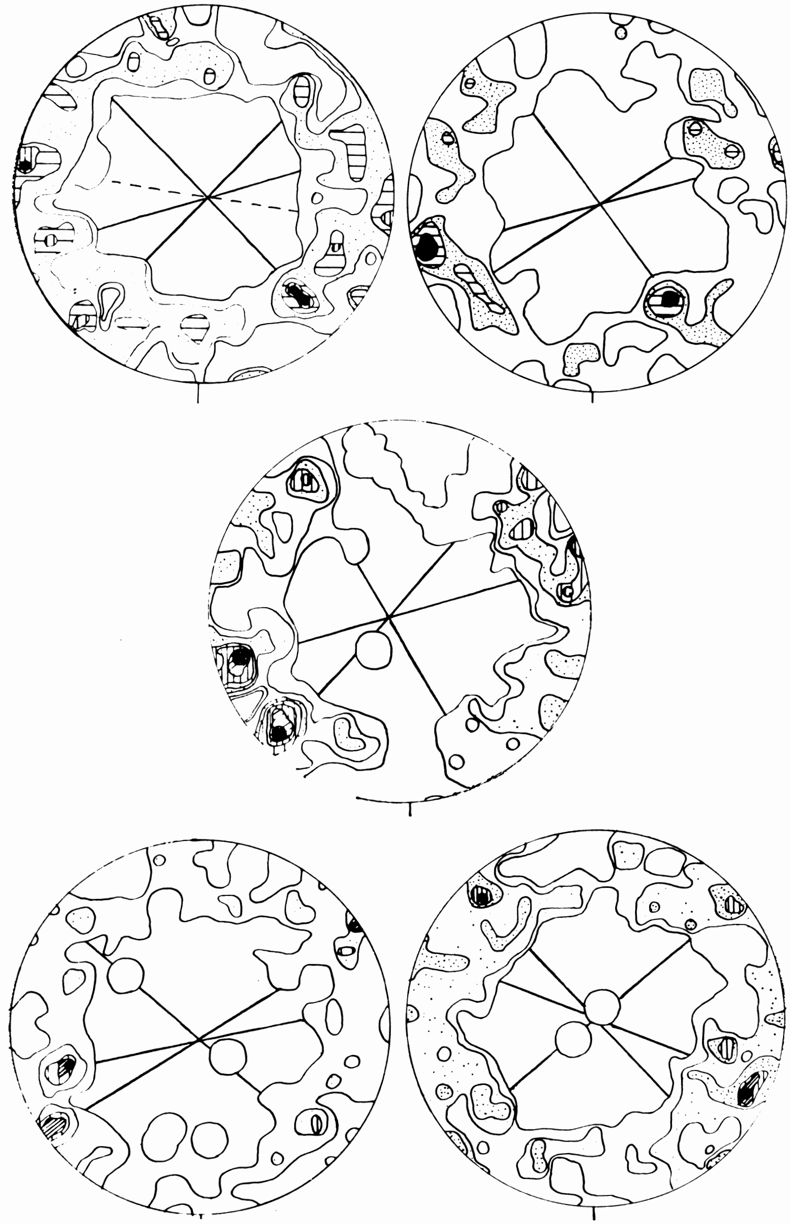

Fig. 5. "c" axes diagrams of small rounded quartz grains.
Sector 1: 110 grains; contours at 7.4, 5.5, 4.5, 2.7, 0.9% per 1% area.
Sector 2: 150 grains; contours at 4.7, 4, 2.7, 1.3, 0.7% per 1% area.
Sector 3: 154 grains; contours at 5.3, 4, 2.7, 1.3, 0.7% per 1% area.
Sector 4: 136 grains; contours at 5.6, 5, 3.6, 2.1, 0.7% per 1% area.
Sector 5: 154 grains; contours at 5.3, 4.7, 4, 2.8, 1.3, 0.7% per 1% area.

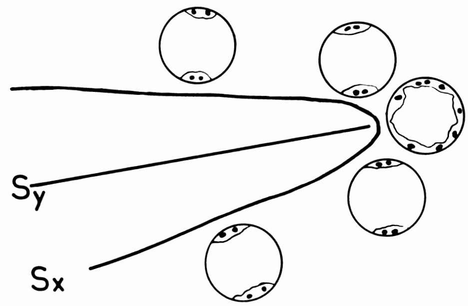

FIG.6a

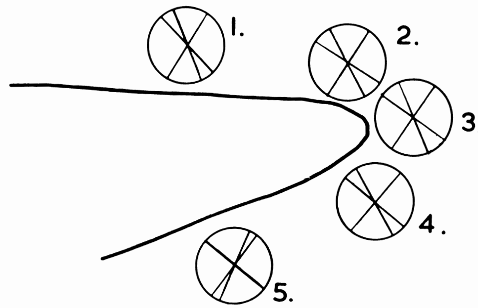

FIG.6b

Fig. 6. (a) Idealized relationship of mica diagrams to the fold.
(b) Relationship of q-richtungen to the fold.

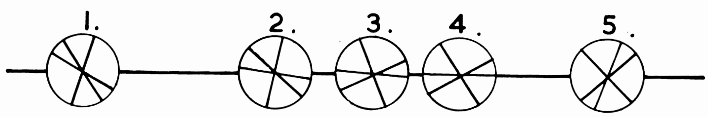

FIG. 7a.

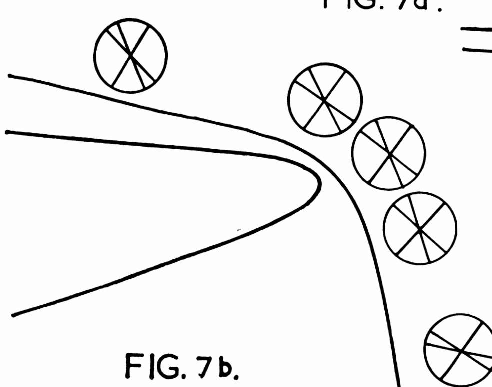

FIG. 7b.

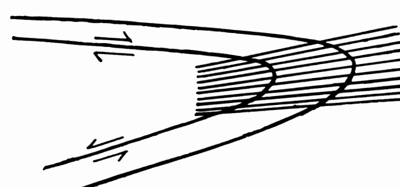

FIG. 7c.

Fig. 7. (a) Fold completely unfolded. (b) Fold partly unfolded with q-richtungen patern roughly parallel. (c) Accordion folding.

unfolding the fold so that the q-richtungen lie parallel to each other (fig. 7b). The symmetrical relations of the q-richtungen to the limbs of the fold, indicates that the fabric was impressed upon the rock prior to the later folding (Ladurner, 1954).

The origin of such a structure may therefore be summarized:

(1) Shear folding produced the open fold form in figure 7b, and impressed an appropriate quartz fabric on the rock.

(2) Flexural slip folding with concomitant axial plane shearing (accordion folding) utilized the same shear planes and directions (S_x), resulting in the mica orientation patterns and sharpening the quartz fabric in the core of the fold (fig. 7c).

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