Schistosity in Deformed Anhydrite—A Reinterpretation

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ABSTRACT

Schistosity (mineral foliation) is a common feature of anhydrite rocks in evaporite domes, and appears to have the same kinematic significance as schistosity in mica schists, hornblende gneisses, and other metamorphic tectonites. It develops perpendicular to the minor axis of the local strain ellipsoid, and becomes conspicuous after compressive strains of 20–30 per cent. Subsequent increments of deformation tend to alter the orientation of schistosity in the finite-strain ellipsoid. This re-orientation may involve slip on regularly spaced discrete foliation surfaces, or crenulation of the schistosity. Thus the plane of schistosity tends to become oblique to the minor axis of the total-strain ellipsoid.

In an earlier paper on the same subject, this author suggested that schistosity develops parallel to pre-existing planar discontinuities in anhydrite rocks. He wrongly concluded that the schistosity normal is a direction of tensile total strain in some tectonic structures, notably in certain bending folds. Contrary to conclusions drawn in the earlier paper, schistosity proves to be a reliable indicator of the maximum-shortening direction, at least for the early stages of progressive deformation in evaporite domes.

INTRODUCTION

Schistosity (mineral foliation) is a conspicuous feature of severely deformed anhydrite rocks, whose origin is comparatively unknown (Lamcke, 1936; Schwerdtner, 1961, 1970a). Regardless of the dominant orienting mechanism(s) of the anhydrite grains, however, one may attempt to establish the paleokinematic significance of schistosity by comparison with co-existing deformational structures. This method was used in an earlier study (Schwerdtner, 1970b), with special emphasis on anhydrite lineation. The following conclusions were drawn with regard to schistosity: (1) schistosity develops parallel to pre-existing planar discontinuities (bedding or fracture cleavage), and (2) the schistosity normal can be a direction of tensile total strain, i. e. it need not correspond with a local direction of total finite shortening. The latter conclusion was mainly based on evidence from the Benther Salzstock, northwestern Germany, which will be re-interpreted in this paper.

The salt stocks of northwestern Germany are characterized by internal diapiric movements between a thick lower unit of laminated "pure" salt (Na 2) and the overlying evaporites (Z3 and Z4), which are chiefly comprised of "impure" rock salt, anhydrite and saline shale (Schwerdtner, 1970b, p. 322). This second-order diapirism of the pure salt gave rise to bending folds in the younger evaporites (Z3 and Z4), which have been analyzed by Lotze (1957, Fig. 171) and Schwerdtner (1961). A thorough understanding of this general type of folding is prerequisite for the following re-interpretation of schistosity.

STRAIN DISTRIBUTION IN CYLINDRICAL BENDING FOLDS

Unlike the classical flexural folds or buckle folds, which are discussed in all texts of structural geology, bending folds involve no overall tangential shortening, and are generally due to transverse differential displacement (Ramberg, 1963). In most diapiric structures, there is no gross longtitudinal strain normal to the direction of the overall diapiric movement (Fig. 1; Schwerdtner, 1970c, Fig. 6). This leads to a close interrelationship between the cross-sectional fold geometry and the finite strain distribution.

There are two fundamentally different types of bending-fold geometry, (1) a quasi-parallel type, and (2) a more similar type in which the degree of fold curvature de-

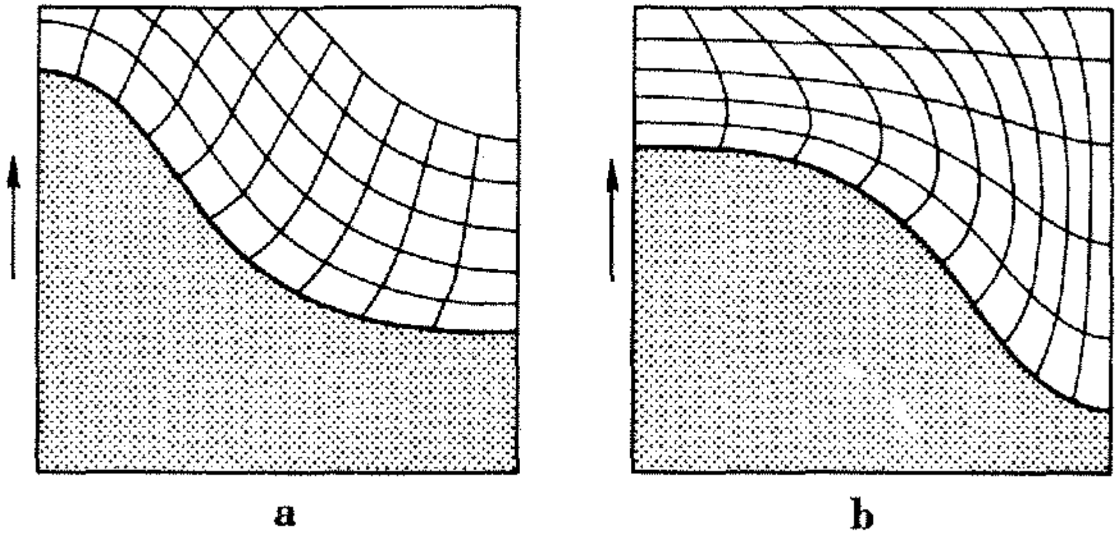

Figure 1. Distorted square grids due to two-dimensional bending, (a) fold type 1, (b) fold type 2. Note that the horizontal sides of the models remain undeformed (after Fletcher, 1972).

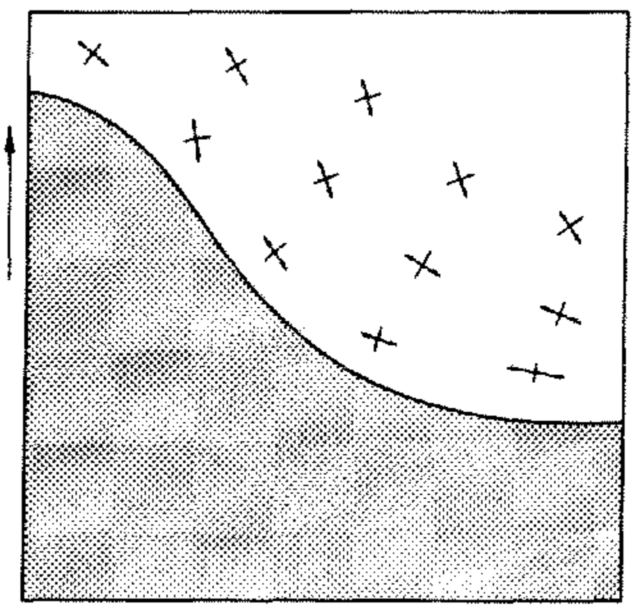

Figure 2. Strain distribution in a bending fold of type 1. The crosses represent principal axes of finite-strain ellipsoids for plane deformation (after Fletcher, 1972).

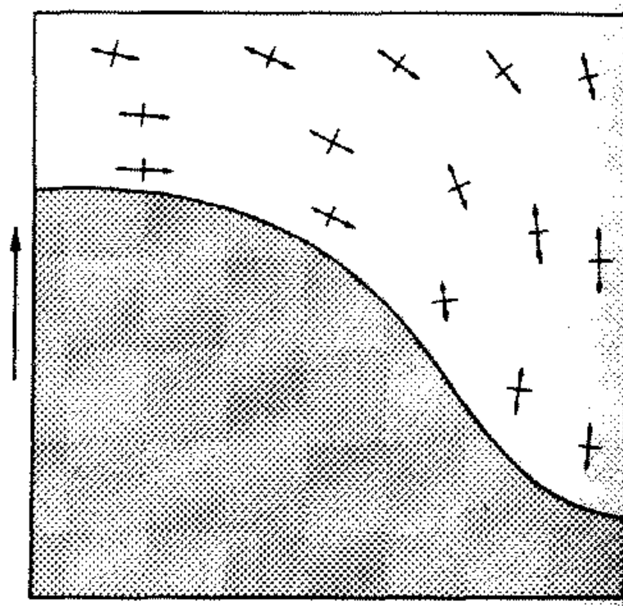

Figure 3. Strain distribution in a bending fold of type 2 (after Fletcher, 1972).

creases away from the contact between the diapiric material and the passive "overburden." The strain distribution for both fold types has recently been studied in computer-simulated folds (Fletcher, 1972), and has been reproduced in Figures 1–3.

The cross-sectional longitudinal strain of the folded surface for (1) is tensile throughout the entire bending structure. This type of fold geometry is rarely observed in the Benther Salzstock, and may be confined to individual thin units of competent anhydrite and/or shale. The cross-sectional strain distribution for (2) is characterized by compressive longitudinal strain in the synclinal hinge zone and tensile longitudinal strain in the anticlinal hinge zone (Fig. 3). If the axial longitudinal strain of a fold is zero (as assumed in Fig. 3), then the layer thinning at the anticlinal hinge must be accommodated in the cross-sectional plane, and leads to flow from the anticlinal crest into the synclinal trough.

This flow becomes unnecessary if the restriction of no axial longitudinal strain is relaxed, i.e. the strain markers can be stretched normal to the cross-sectional plane. Figure 4 represents a qualitative attempt of analysing the resulting strain distribution. The model is composed of porous rubber, in which the necessary decrease in cross-sectional area is achieved by dilatation rather than axial extension. Thus there is no significant tensile strain in the cross-sectional plane, in which folding results from heterogeneous finite flattening of the layers. Owing to the areal variation in magnitude of compressive strain, there must also be variations in axial tensile strain (maximal at the concave anticlinal crests). This variation does not affect the cylindrical geometry of the folds (cf. Schwerdtner, 1970c).

PALEO-STRAIN WITHIN A MAJOR SYNCLINE

Within the Benther Salzstock, most exposures of schistose anhydrite are situated in the limbs of major bending folds (Schwerdtner, 1961, 1970b). In one instance, however, the closure of a thin anhydrite unit is adjacent to a crosscut (Schwerdtner, 1970b, Fig. 10). It was this structure (Fig. 5), on which the earlier conclusions with regard to schistosity were largely based. Let us re-examine the available structural evidence in order to find the most appropriate model of bending for the folded anhydrite unit. Owing to limited exposure, it is impossible to determine the fold geometry of the distorted unit. Nevertheless one may assess the applicability of the three principle models of bending (Figs. 1 to 4) after estimating the finite strain near the hinge.

The maximum thickness of the anhydrite unit in the hinge zone of the syncline is approximately 6 per cent greater than the stratigraphic thickness, as quoted for the Benther Salzstock by Hofrichter (1960). This rules out the first bending model (Fig. 1a and 2). As shown in the earlier paper (Schwerdtner, 1970b), the anhydrite mineral lineation is oblique to the synformal hinge. If the anhydrite

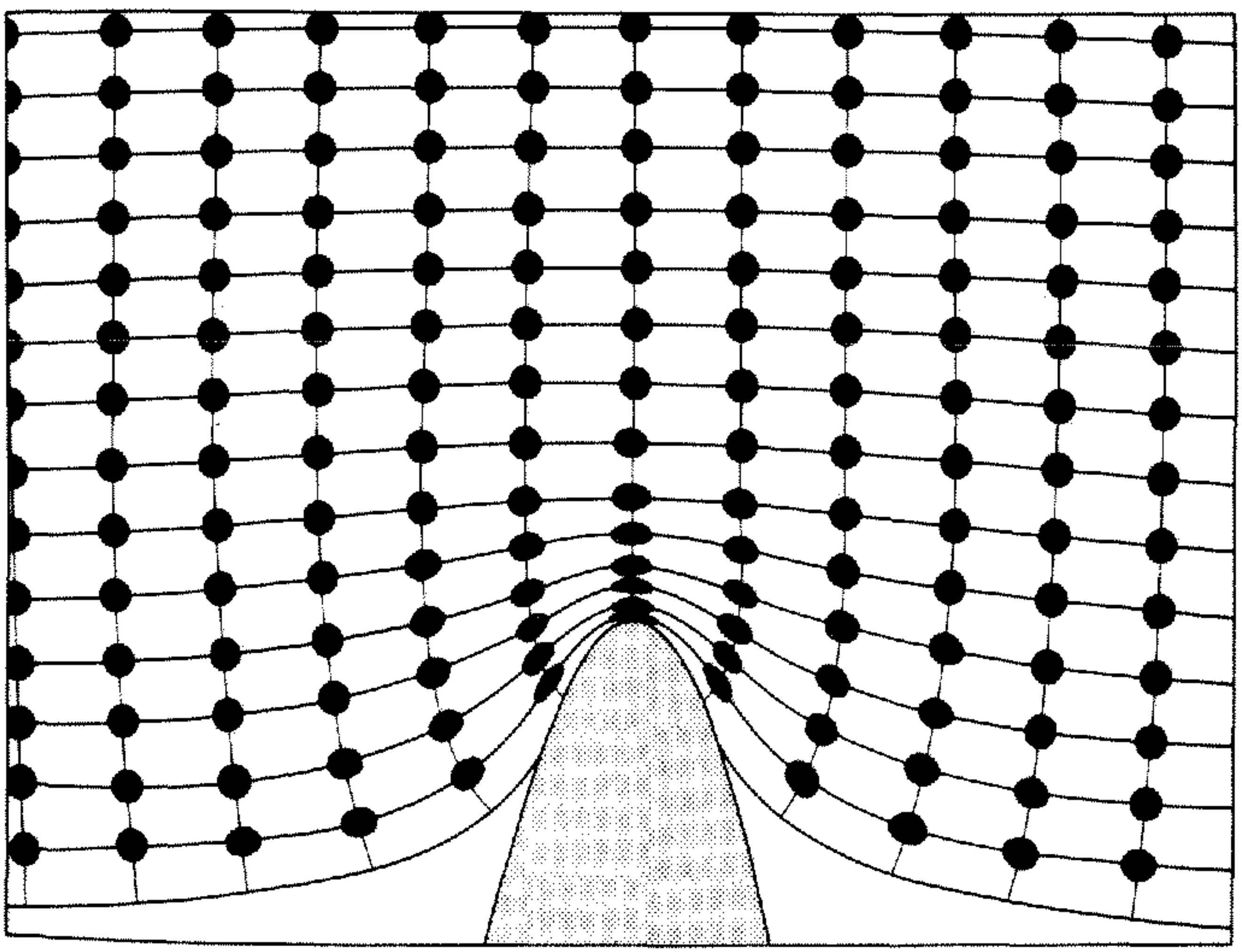

Figure 4. Bending folding in a sheet of porous rubber, confined between two glass plates. The diapiric body is a rounded wooden wedge.

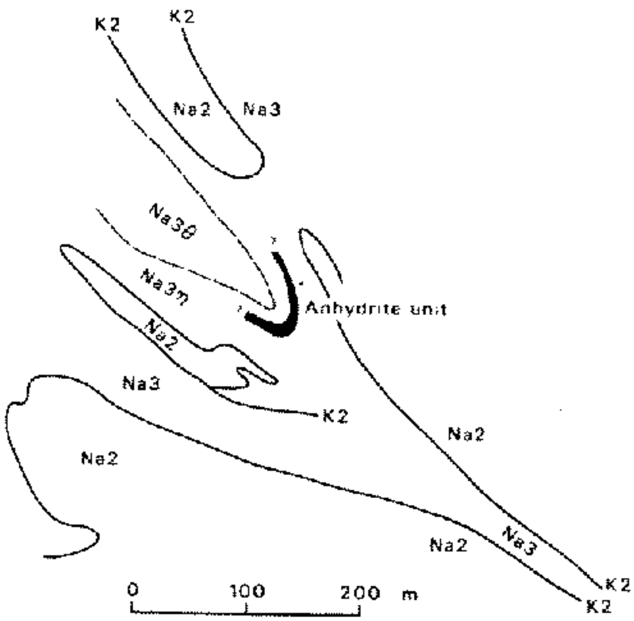

Figure 5. Horizontal section (653 meter level) through noncylindrical bending folds in the Benther Salzstock (Benthe Field) (Ronneberg Mine). Synclinally folded anhydrite bed shown in black (thickness exaggerated). Greek letters denote stratigraphic units (after Richter-Bernburg (1955)).

lineation is parallel to the local direction of maximum total extension, then we must also exclude the second bending model (Fig. 1b and 3). This might have been expected in view of the low amounts of tectonic thickening in the hinge zone. Finally one may rule out the third ideal model (Fig. 4) on the grounds that there is finite deformation near the synclinal hinge. The structural evidence suggests that the process of natural bending involved a compromise between the ideal cases of the second and third models.

Let us now compare the attitudes of schistosity in the hinge region of the syncline with the local strain directions in the bending models. Schistosity forms a marked fan about the hinge surface, which opens toward the convex boundary of folded anhydrite unit (Schwerdtner, 1970b, Fig. 10). An identical pattern of fanning is displayed by the axes of maximum finite extension in the second and third models. Note, however, that the first model (Fig. 2) shows a fanning in the opposite direction. This evidence suggests that schistosity is generated normal to the local axis of maximum finite shortening.

Closer inspection of the exposures reveals that selected schistosity surfaces have been activated as discrete slip planes. Thus the upper boundary of the anhydrite unit assumed a step-like configuration, which is conspicuous on the walls of the crosscut. The lower stratigraphic boundary, which is marked by a thin layer of massive argillaceous anhydrite (called Tonfuss), does not show any offsets (see Schwerdtner, 1973, Fig. 4A). This indicates that the slight offsets of the upper boundary are not solely due to rigid-body displacement but also involve some differential longitudinal strain parallel to the slip planes, whose average magnitude is rather small. The translational slip parallel to schistosity may be regarded as a component of simple shear on the scale of the major folding. This shearing guarantees that the principle axis of progressive finite shortening becomes oblique to schistosity, and that the axis of total maximum extension will be nonparallel to schistosity (Schwerdtner, in press).

Ignoring the strain increments during the phase of slip, it is possible to estimate the maximum magnitude of finite strain that generated the schistosity. This is most readily done where schistosity is perpendicular to bedding, i. e. the orthogonal thickness is measured in a principal plane of deformation and perpendicular to the minor axis of the strain ellipsoid. The major axis of the strain ellipsoid is parallel to lineation.

If the state of finite distortion could be represented by an oblate spheroid, then the magnitude of extension would be equal to the proportional increase in thickness of the anhydrite unit (approximately 6 per cent), in all directions on the schistosity plane. This would amount to 11 per cent shortening perpendicular to schistosity. A prominent mineral lineation on the schistosity suggests, however, that the distortion was nearly biaxial. Under this assumption the magnitude of shortening becomes 18 per cent (Fig. 6). The actual strain value must lie between these extreme figures, and should be closer to 18 per cent (Schwerdtner, in press).

Hofrichter's (1960) stratigraphic thicknesses for the Benther Salzstock represent rough estimates, and it is possible that the tectonic thickening of the above anhydrite unit is somewhat greater, say 10 per cent. This would give

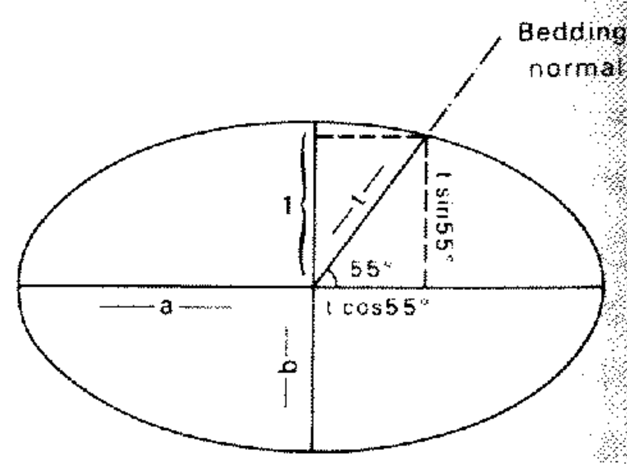

Figure 6. Strain calculation for anhydrite bed, sectioned parallel to schistosity and perpendicular to bedding. a>b>c are the principal semi-axes of a biaxial-strain ellipsoid, and t is the deformed thickness of the anhydrite bed. The angle between a and the lineation direction is 55 degrees.

rise to magnitudes of finite shortening between 17 and 31 per cent, depending on the actual state of distortion. These estimates suggest that a prominent schistosity results from shortening of 20 to 30 per cent. Incipient schistosity is probably generated by significantly lower magnitudes of distortion.

BOUDINAGE STRUCTURES AND MINOR FOLDS

Incipient lenticular boudins of anhydrite in the South Fiord Dome, Canadian Arctic Archipelago, exhibit a weak schistosity parallel to bedding (Schwerdtner, 1970b, p. 321). The trajectories of greatest finite extension, however, are generally oblique to bedding, so that schistosity must be oblique to the local directions of greatest finite shortening for boudinage.

Ramsay (1967, p. 106) has pointed out that ductile necking is generally preceded by uniform stretching of the competent layers. This longitudinal strain could easily produce a bedding schistosity, which would be deformed together with bedding during subsequent boudinage.

Salt "seismograms" tend to involve minor folding of thin layers or laminae of anhydrite (Schwerdtner, 1966). The tightly folded anhydrite layers are characterized by a prominent schistosity parallel to the hinge plane (Fig. 7). These similar type folds are probably due to buckling and subsequent overall flattening (Ramsay, 1967, p. 434), during which any transverse foliation would become subparallel to the hinge plane. Whether a prominent schistosity is formed in an early phase of uniform shortening (Ramsay, 1967, p. 403), or during subsequent buckling, cannot be decided.

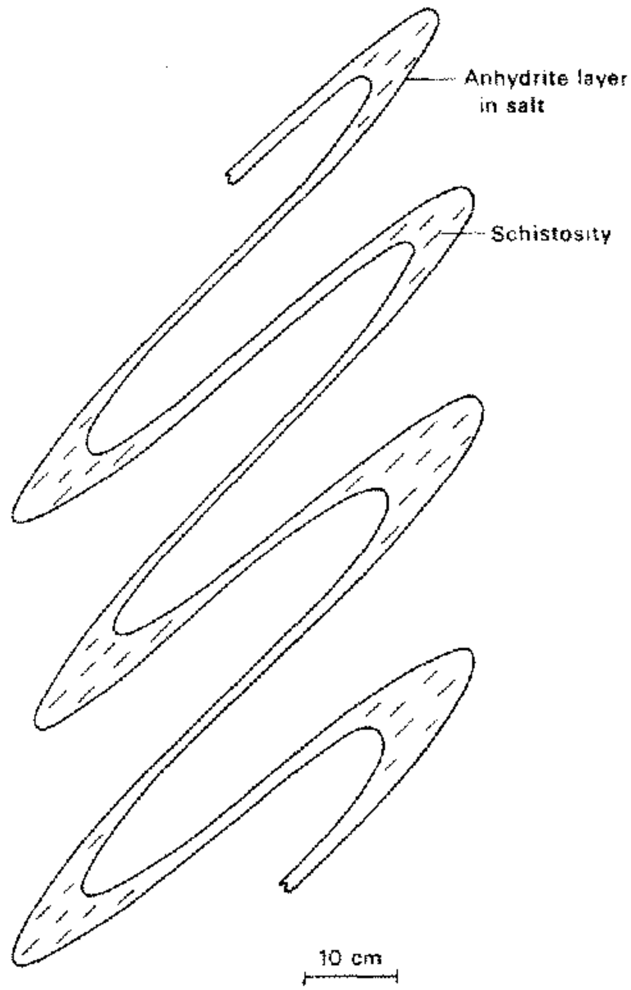

Figure 7. Minor buckling folds with superimposed flattening strain (Ramsay, 1967, p. 411). Outer hinge zone of bending syncline, just north of schematically shown anhydrite unit in Figure 5. Geometry of minor folds is schematic.

CONCLUDING DISCUSSION

In an earlier paper on schistosity in deformed anhydrite (Schwerdtner, 1970b), the writer wrongly assumed that the longitudinal finite strain is tensile throughout all bending folds, and that all structural discontinuities in anhydrite rocks predate the schistosity. Contrary to erroneous conclusions drawn in this earlier paper, schistosity proves to be a consistent indicator of the direction of early maximum shortening in progressive deformation. Thus it tends to be non-parallel to pre-existing planar discontinuities (such as bedding surfaces or early fractures) unless they are perpendicular to the local direction of early maximum shortening. Once developed, schistosity is prone to competent deformation, such as bending during boudinage or flexural slip (gently crenulation). Here schistosity can be sub-parallel to the maximum-shortening direction of the superimposed deformation, i.e. it can be oblique to the direction of maximum total shortening.

Schistosity in deformed anhydrite appears to have the same kinematic significance as mineral foliation in mica schists, hornblende gneisses and other metamorphic tectonites. It develops perpendicular to the minor axis of the local strain ellipsoid, and becomes conspicuous after compressive strains of 20–30 per cent.

ACKNOWLEDGEMENTS

Grants in aid of research from the National Research Council of Canada are gratefully acknowledged. Thanks are due to Mr. F. Jurgeneit for making the drawings.

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