Journal of Structural Geology, Vol. 5, No. 3/4, pp. 465 to 470, 1983
Printed in Great Britain

0191–8141/83 $3.00 + 0.00

Strain fields in and around boudins in a clay experiment

NURIT HILDEBRAND-MITTLEFEHLDT*

The Institute for Petroleum Research and Geophysics,
P.O. Box 1717, Holon 58117, Israel

(*Received* 28 *June* 1982; *accepted in revised form* 23 *December* 1982)

Abstract—Boudins were deformed by stretching of a three-layer wet clay cake on a deformation table. The middle layer was more competent than the others. One edge of the boudin was sampled for strain measurements and a total of twenty three sample points were studied. The preferred orientation of the basal plane of kaolinite crystals was measured for each sample point with an X-ray goniometer. From these preferred orientations, strain was determined according to the theory of March. Strain due to the compaction of the clay under its own weight was removed from the total strain observed in order to isolate the strain due to boudinage.

Local changes in volume, related to water migration within the clay cake, took place during deformation. Appropriate corrections were made in the procedure of strain removal.

The strain field due to boudinage was compared with previous results of stress obtained in theoretical and experimental studies, and found to be in general agreement.

INTRODUCTION

THE TERM 'boudinage' encompasses a large variety of phenomena which are the result of different materials and conditions. It is possible that a strain field which is related to one kind of boudinage is considerably different from that which is related to another kind. However, it is believed that the basic features of strain fields which are related to most types of boudinage should be similar to each other, or at least fall into a few distinctive groups. A strain field related to boudinage has been studied and is presented with the hope that it will be applicable to some, if not most, of the natural phenomena.

THE CLAY EXPERIMENT

Three layers of wet clay paste were deformed by stretching them on Oertel's (1965) deformation table in order to simulate boudinage. The clay in this experiment was a commercial clay mixture, mostly kaolinitic, called 'C&C' (½ Champion–½ Challenger) and provided by H. C. Spinks Clay Company, Paris, Tennessee.

* Present address: PAMA (Energy Resources Development) Ltd., Mishor Rotem, D.N. Arava 86800, Israel.

The lower and upper layers were made of very soft clay with the consistency of butter, whereas the middle layer was of a stiffer consistency (the same clay with less water content). Details of the cake-building procedure can be found in Oertel (1965). The stiff layer was cut and put on a softer layer and then covered by another softer layer. The dimensions of the sample cake were approximately 20 × 10 × 5 cm.

In the first few runs, the middle layer was made to be continuous, but many faults were formed in the cake before rupturing of the stiffer layer into boudins. In order to study the strain attributable only due to boudinage, without the interference of strain due to other structures such as faults, the stiffer layer was pre-cut and the resulting pieces pre-separated so that the middle layer consisted of alternating soft and stiff clay paste. It is believed that the strain pattern should not be significantly affected by this procedure, as discussed below.

Right-handed coordinates were used, where x_1 was parallel to the long dimension of the cake, x_2 parallel to its width and x_3 parallel to its thickness (Fig. 1).

The experiment was concluded within 18 min and the overall lengthening of the cake in the x_1 direction was about 25%. Neither lengthening in the x_1 direction nor shortening in the x_3 direction were uniform throughout the cake: where the stiff layer was present, shortening of about 10% took place, whereas in between the boudins

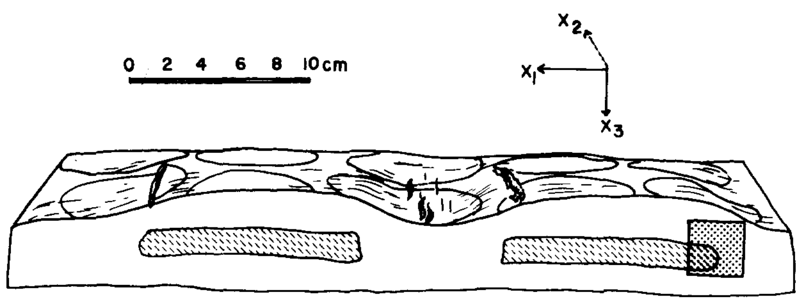

Fig. 1. Setup of the clay cake in the deformed state (cut open; drawn from a photograph). Dashed zones: boudins. Dotted zone: sampling area.

shortening was up to 30%. This resulted in topography of 'hills' above the boudins and 'valleys' in between them (Fig. 1). Most of the significant shortening and lengthening took place along the x_1 and x_3 axes and hence the study is restricted to plane strain.

Technique of strain measurement

The right end of the right boudin was sampled. This choice was made mainly to avoid interference of strain due to faulting. Samples were taken by pressing a wire through the soft clay, while pouring water into the cut slot to prevent the two sides of the cut sticking together. The samples were then hardened with the aid of 'Carbowax 6000', a low temperature (60–65°C) melting plastic fully miscible with water, which replaces water in the clay. The replacement is achieved without any change in the inner fabric of the clay as demonstrated in petrographic (Mitchell 1956, p. 696, Martin 1966, p. 274) and in experimental (Hildebrand-Mittlefehldt 1979, pp. 133–135) studies.

Six parallel, partly overlapping 2 mm slabs were cut in the x_1–x_3 plane. Twenty-three sample points were measured in these, 12 outside the boudin and 11 inside. A 100 μm thick section was made of each slab for scanning on an X-ray goniometer in the transmission mode, in order to determine the statistical distribution of the clay grain orientations (Baker *et al.* 1969, Oertel 1970). An X-ray apparatus which was modified by Oertel and described by Lipshie *et al.* (1976, pp. 92–93) was used.

Strains were determined from these preferred orientations according to March's (1932) geometrical method. This method gives the relations between the principal normalized distributions of poles to the platy minerals, ρ_i, and the principal finite strains, ϵ_i, as $\epsilon_i = \rho_i^{-1/3} - 1$. The procedure of applying the method to geological needs was described in detail by Oertel (1970, pp. 1176–1178), Oertel & Curtis (1972, p. 2599) and Wood *et al.* (1976, pp. 30–32).

The application of March's method to calculate strain in rocks was discussed in detail by Owens (1973), Lipshie *et al.* (1976), Siddans (1977, 1978), Oertel (1978), Etheridge & Oertel (1979) and many others. A discussion particularly relevant to strain measurements in material under conditions similar to those described in the present study is given by Hildebrand-Mittlefehldt (1979, p. 134).

Owing to the small size of the area studied, measurements could be made in only one section for each point, rather than from 2 or 3 sections as recommended by Oertel (1970, p. 1176). However, the maxima of the preferred orientations were well concentrated within each of those single measurements and the only result of taking measurements in one section for each point was a slight distortion in the overall strain field. Since the qualitative nature of the strain field (i.e. strains relative to each other) was of more interest than an absolute strain measurement at each point, this distortion was not considered to be of great importance (see also Hildebrand-Mittlefehldt 1979, p. 134).

The clay cake was strained while being built, as a result of compaction of the clay under its own weight. These strains, which became part of the total strains measured, were removed with the aid of a mathematical procedure introduced by Oertel (1970, pp. 1181–1182) and further developed by Hildebrand-Mittlefehldt (1979, pp. 135–137). The strains due to compaction were measured in a separate cake, prepared simultaneously with, and under the same conditions as, the deformed clay cake. Strains were measured separately for a stiffer bed, similar to the boudinaged layer in the deformed cake, and a softer one similar to the upper layer in the deformed cake. Because of technical difficulties, attention was focused on the deformation of the upper and middle layers of the clay cake only. The strain in the undeformed cake was assumed to be homogeneous for each layer but was nonetheless measured at three points in each layer and averaged. These strains (change in length over original length) were found to be $\epsilon_i = 0.21$, 0.21 and -0.34 in the stiffer layer and $\epsilon_i = 0.39$, 0.39 and -0.48 in the softer one, and were removed from the total strains measured in the deformed cake. In this way, strains due to 'tectonic' effects alone were obtained.

RESULTS

The distribution of extensional and compressional components of the strain are presented in Fig. 2. Examining them together with the distribution of the mean strain $1/3(\epsilon_1 + \epsilon_2 + \epsilon_3)$ (Fig. 3), a picture of high and low strain zones is revealed: zones of high strain magnitude exist diagonally outside the boudin at '2 o'clock' with respect to the upper corner of the boudin and inside it near its upper and lower borders. Accordingly, zones of low strain magnitudes exist between boudins, above the boudin and just inside its vertical border.

The second invariant of the strain tensor, $I_2 = \epsilon_1\epsilon_2 + \epsilon_2\epsilon_3 + \epsilon_3\epsilon_1$, was used as a measure for the octahedral shear strain (Freudental & Geiringer 1958, p. 240). Zones of low shear strain exist diagonally at 45° to the upper corner of the boudin, in the matrix and within the boudin near the upper and lower borders (Fig. 4). Relatively high shear strain occurred between the boudins and above the boudins in the matrix and just inside of the vertical border of the boudin.

The displacement field was reconstructed by 'unstraining' the studied area, i.e. looking at it in Lagrangean coordinates and superposing the resultant configuration on the strained, Eulerian one (Fig. 5). Unstraining of the studied area was carried out by piecemeal fitting of unstrained subdomains using Oertel's method (Oertel & Ernst, 1978) which is based on equations of Ramsay (1967, pp. 124–126, 129–130).

The three-dimensional subdomains were arbitrarily chosen in the Eularian coordinates, such that all their boundaries were either parallel or perpendicular to the x_1–x_3 plane (Fig. 5a).

Fitting the unstrained domains was carried out by translation and rigid body rotation of the elements. All

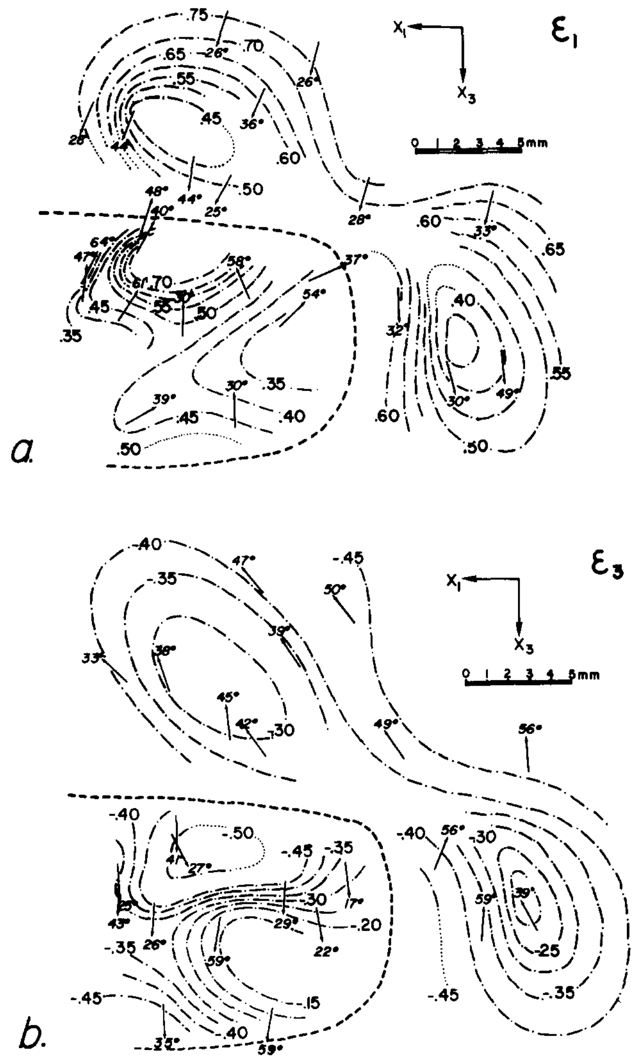

Fig. 2. Patterns of the principal strains in the boudin sample area (Fig. 1). (a) Tensional strain, ϵ_1; (b) compressional strain, ϵ_3. Arrows and smaller numbers: directions and plunges of strain components into the plane of the paper. Contour interval 0.05. Sample point at the base of each arrow.

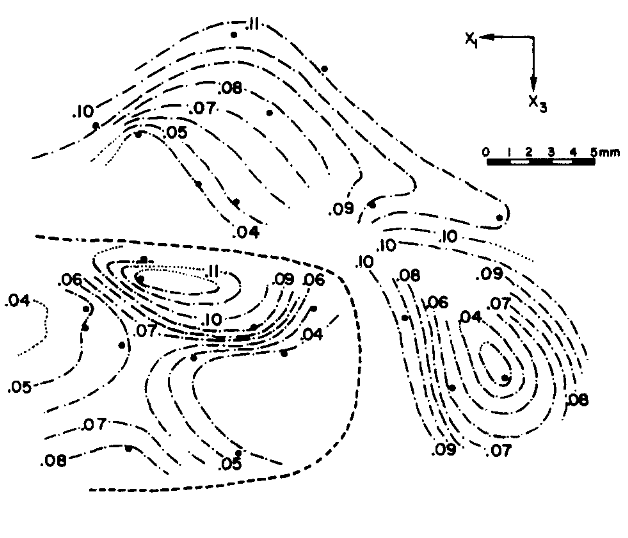

Fig. 3. Pattern of the mean strain, $1/3(\epsilon_1 + \epsilon_2 + \epsilon_3)$ in the sample area (Fig. 1). Dots: sampling points. Contour interval 0.01.

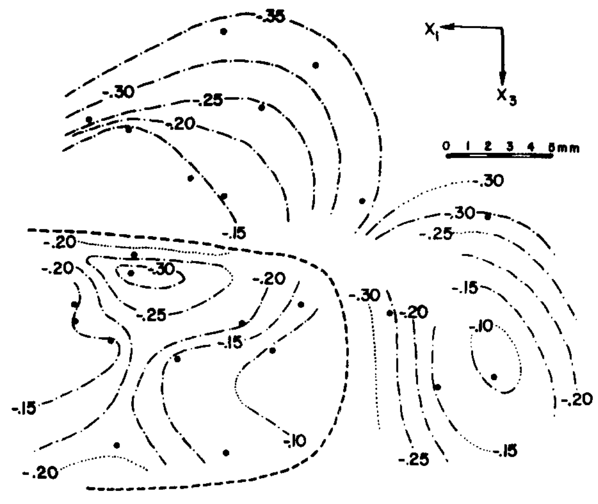

Fig. 4. Pattern of the second invariant, $I_2 = \epsilon_1\epsilon_2 + \epsilon_2\epsilon_3 + \epsilon_3\epsilon_1$, representing the shear strain (see text). Dots: sampling points. Contour interval 0.05.

necessary rotations were counter-clockwise (Fig. 5b). This is consistent with Schwerdtner's observation (1970) of clockwise tectonic rotation of material near the edge of natural boudins (for a boudin in an orientation similar to the one described in the present study). As soon as the unstrained subdomains were fitted together, it became clear that some local volume changes in the matrix took place during the experiment, as measurements of the clay cake before and after the experiment were available. These changes were in the form of volume reduction along the x_3 axis above the boudin and addition of material along the x_1 axis in between boudins. These volume changes may be explained by the movement of water in the cake during deformation. Corrections for volume changes were made to fit the measurements. Domains F_2, E_2, F_1, C_4, E_1 and B_1 were given a 'linear dilatation' (Oertel & Ernst 1978, p. 88) which compensated for 30% volume loss along the x_3 axis; domains D_2, D_3 and D_4 were given such a linear dilatation as to compensate for 10% gain of volume along the x_1 axis; domain C_1 was similarly compensated for 45% volume loss along the x_3 axis, C_2 for 40% volume loss along x_3 and 10% gain of volume along x_1 and domain D_1 for 25% volume loss along x_3 and 10% gain of volume along x_1. Within the sampled area there is no complete volume compensation (i.e. increase for decrease) because this small area is part of the larger system.

One of the assumptions for the unstraining procedure was that strain was homogeneous throughout a single domain. Though essential for the procedure adopted, this assumption is not accurate and results in incompatibilities between unstrained subdomains which are expressed as gaps and overlaps in their borders. Cobbold (1979) and Cobbold & Percevault (this issue) proposed a least-squares method for removing these incompatibilities by imposing translations and rigid body rotations. In the present case, however, minimizing the incompatibilities by visual inspection rather than by going through the suggested rigorous procedure was judged to be sufficient.

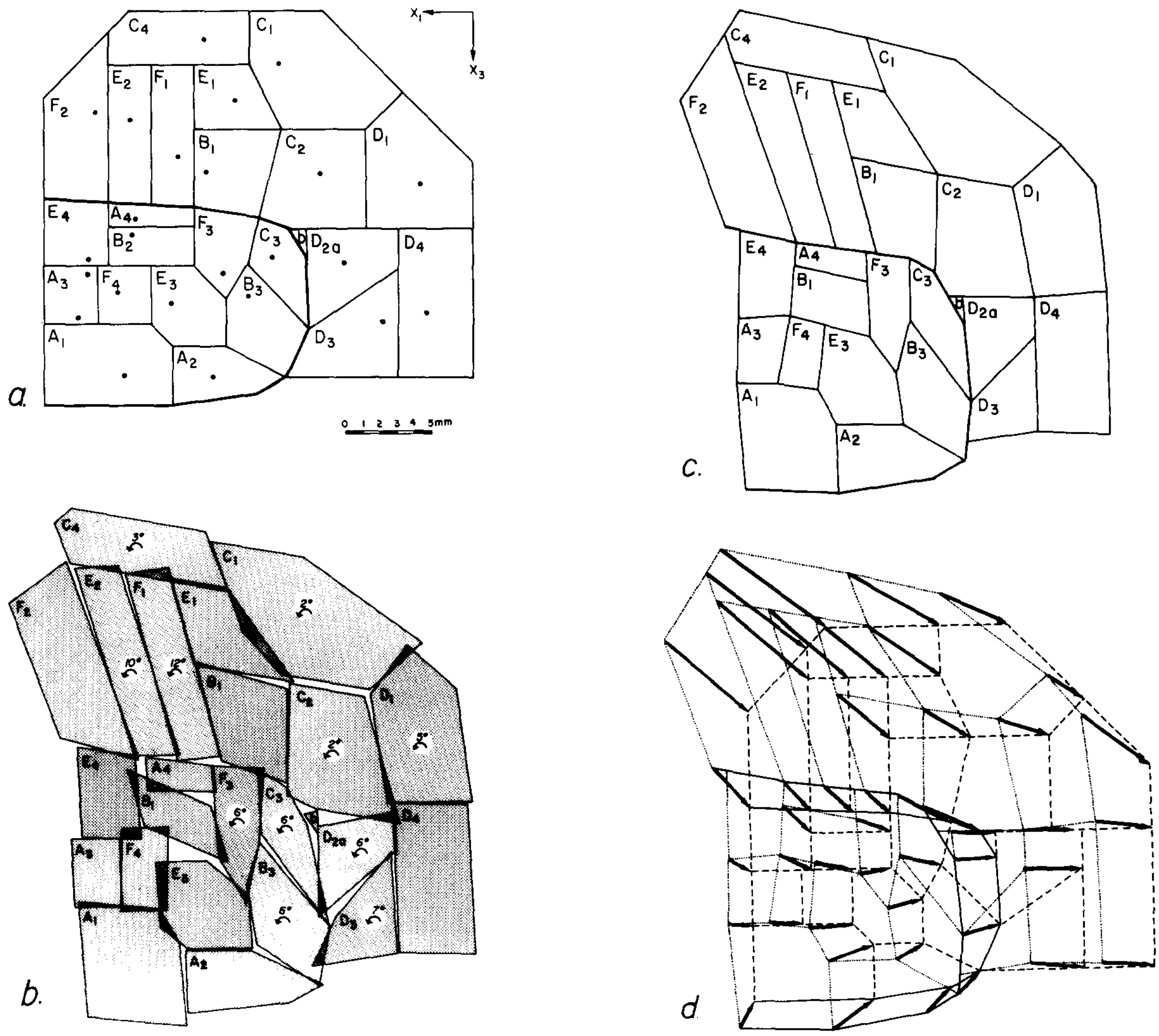

Fig. 5. (a) Projections of strained, arbitrarily-chosen subdomains onto the x_1–x_3 plane (Eulerian coordinates). Dots: sampling points. (b) Projections of the unstrained subdomains (Lagrangean coordinates) onto the x_1–x_3 plane. Arrows and numbers above them indicate sense and amount of rotations. (c) Projections of the unstrained domains, incompatibilities removed. (d) Displacement field; arrows from unstrained configuration (dotted lines) to strained one (dashed lines).

The incompatibilities were removed by drawing gap/overlap bisecting borders between the subdomains (Fig. 5c). Common points for superposing the two configurations were established as follows: it was assumed that the boudin's vertical mid-line (parallel to the x_3 axis) remained stationary and that lengthening proceeded equally in both directions along the x_1 axis. Hence, each end-point was displaced by half of the total lengthening, which was measured. Similarly, it was assumed that the boudin's horizontal mid-line (parallel to x_1) remained stationary and shortening towards it along the x_3 axis proceeded equally from the bottom and top of the boudin. The superposition of the strained configuration (Eulerian coordinates, Fig. 5a) on the unstrained one (Lagrangean coordinates, Fig. 5c) yielded the differential displacement field (Fig. 5d).

DISCUSSION

Hardening the samples involves migration of water and liquid 'Carbowax 6000' in the sample. Nevertheless, it was shown that the movement of liquids hardly, if at all, affects the preferred orientation of the clay platelets (Mitchell 1956, Martin 1966, Hildebrand-Mittlefehldt 1979). Similarly, water migration during the experiment is apt to contribute little, if at all, to the present deformation. As Oertel & Curtis (1972, p. 2603) stated, the greater concentration of diffractions from particles in the compressed clay does not affect the results because of the normalization procedure. The same should be true for lesser concentration in diffractions in the clay.

Orientations of the strain components, shown in Fig. 2, suggest a distinct asymmetry in the strain pattern. Such an asymmetry could be due to edge and base effects, or due to the resultant topography of the upper surface of the model (which is in the order of the average thickness of the top layer), or both.

Only a few numerical studies have been carried out on the stress distribution within and around boudins (e.g. Stephansson & Berner 1971, Strömgård 1973, Selkman 1978). Some of these are based on physical experiments (e.g. Ramberg 1955). Even fewer studies deal with strain distribution and those that do, deal mainly with theoretical aspects (e.g. Schwerdtner 1970), in some cases based on experimental study (e.g. Tan 1974).

Despite the relatively complex relationship between stress history and finite strain, and notwithstanding the different materials involved in the various studies (which are, in turn, different from those in nature), it is of interest to compare the strain field measured in the present study with the theoretical stress fields described in the literature. Considering fields of stress and strain analogous components will be compared; that is, the shear stress component with that of shear strain, the compressional stress component with that of compressional strain, etc.

Selkman (1978) studied the distribution of stress and displacement in boudinage structures by means of the finite-element method. One of his four models is analogous to that of the present study. In it he considered a quarter of an incipient boudin, the centre of the boudin being at rest and displacements taking place towards the free short edge. In this model, he found that "large compressive stresses are concentrated . . . in the matrix, close to the boundary above the corners of the boudin"; an observation which is consistent with the situation in the present study (Fig. 2a). The compressive-stress distribution within the boudin studied by Selkman, however, does not agree with the strain distribution found in the present study: in contrast to the clay cake, his model has the form of a barrel, implying the existence of compressive stresses along the vertical border just inside the boudin. Selkman found low values of compressive stress in the gap between the boudins, a fact which is again in agreement with the present strain pattern. Selkman found the highest tensile stresses in the 'boundary between the gap and the matrix', in agreement with the present strain measurements, assuming this boundary area means the area just above the zone between boudins.

Strömgård, in constructing and analyzing photo-elastic models, showed that the lowest tensile stresses in the matrix occur above the boudin (Strömgård 1973, fig. 17, left-handed part). Somewhat higher values exist between boudins, whereas the highest values are found within the boudin near its upper boundary. A similar picture is presented here for the tensile finite strain component in the clay experiment study (Fig. 2a).

The mean strain distribution (Fig. 3) may be compared with the available patterns of theoretical mean stress: Stephansson & Berner (1971, fig. 6), Strömgård (1973, right-hand fig. 17) and Selkman (1978, fig. 10). All three have similar patterns of high and low values to the mean strain obtained in the present study. The pattern of the second strain invariant, as a measure of the shear strain (Fig. 4), can be compared with Strömgård's photoelastic results (1973, fig. 13A). Zones of high and low values observed in the two studies have similar distributions.

CONCLUSIONS

The strain field determined in the present study proved to be in general agreement with stress fields obtained in numerical studies and observed in physical experiments. Such agreement indicates that (a) pre-cutting and pre-separating the boudins did not affect the general pattern, and (b) that water migration during deformation could not have significantly affected the preferred orientation of the clay platelets and, hence, the strain pattern.

Some of the strain components observed here are hardly surprising and were both predicted in the theoretical studies and observed in nature. However, the patterns of strain trajectories were neither predicted nor observed previously. These patterns (Fig. 2) suggest some asymmetry of the strain field. It might be beneficial to test whether this aspect of the strain field exists also in nature and is not merely a result of the experimental conditions.

In a previous strain-field study, which was performed with a similar kind of experimental procedure and material, the analytical results agree with those obtained from natural phenomena in faults (Hildebrand-Mittlefehldt 1979, 1980). It may thus be expected that, in spite of the many dissimilarities between the experimental material and conditions and the natural ones, natural structures will display similar strain patterns.

Acknowledgements—Gerhard Oertel kindly allowed the use of his deformation table and X-ray pole-goniometer. George H. Davis interested me in this project and followed the experimental work throughout with advice and help. Steven Lipshie assisted in the experimental procedure. Ram Alkaly prepared the special sections for the X-ray work. Reginald Shagam, John Morgan and C. K. Mawer reviewed and greatly improved the manuscript. Gerhard Oertel and Reginald Shagam are thanked for many helpful discussions. This research was supported by the Earth Sciences Section, National Science Foundation of the U.S.A., Grant EAR 78-23404. All these contributions are gratefully acknowledged.

REFERENCES

Baker, D. W., Wenk, H. R. & Christie, J. M. 1969. X-ray analysis of preferred orientation in fine-grained quartz aggregates. *J. Geol.* **77**, 144–172.

Cobbold, P. R. 1979. Removal of finite deformation using strain trajectories. *J. Struct. Geol.* **1**, 67–72.

Cobbold, P. R. & Percevault, M. N. 1983. Spatial integration of strain using finite elements. *J. Struct. Geol.* **5**, 299–305.

Etheridge, M. A. & Oertel, G. 1979. Strain measurements from phyllosilicates preferred orientation—a cautionary note. *Tectonophysics* **60**, 107–120.

Freudenthal, A. M. & Geiringer, H. 1958. The mathematical theories of the inelastic continuum. In: *Encyclopedia of Physics* (edited by S. Flügge). Springer, Berlin, Vol. 6, 229–433.

Hildebrand-Mittlefehldt, N. 1979. Deformation near a fault termination, Part I: A fault in a clay experiment. *Tectonophysics* **57**, 131–150.

Hildebrand-Mittlefehldt, N. 1980. Deformation near a fault termination, Part II: A normal fault in shales. *Tectonophysics* **64**, 211–234.

Lipshie, S. R., Oertel, G. & Christie, J. M. 1976. Measurement of preferred orientation in phyllosilicates in schists. *Tectonophysics* **34**, 91–99.

March, A. 1932. Mathematische Theorie der Regelung nach der Korngestalt bei affiner Deformation. *Z. Kristallogr.* **81**, 285–297.

Martin, R. T. 1966. Quantitative fabric of wet kaolinite. *Proc. 14th Nat. Conf. on Clays Clay Miner.*, pp. 271–288.

Mitchell, J. K. 1956. The fabric of natural clays and its relation to engineering properties. *Proc. High Res. Bd.* **35**, 693–713.

Oertel, G. 1965. The mechanism of faulting in clay experiments. *Tectonophysics* **2**, 343–393.

Oertel, G. 1970. Deformation of a slaty, lapillar tuff in Lake District, England. *Bull. geol. Soc. Am.* **81**, 1173–1188.
Oertel, G. 1978. The development of slaty cleavage in part of the French Alps—Discussion. *Tectonophysics* **47**, 185–187.
Oertel, G. & Curtis, C. D. 1972. Clay-ironstone concretion preserving fabrics due to progressive compaction. *Bull. geol. Soc. Am.* **83**, 2597–2606.
Oertel, G. & Ernst, W. G. 1978. Strain and rotation in a multilayered fold. *Tectonophysics* **48**, 77–106.
Owens, W. H. 1973. Strain modification of angular density distribution. *Tectonophysics* **16**, 249–261.
Ramberg, H. 1955. Natural and experimental boudinage and pinch-and-swell structures. *J. Geol.* **63**, 512–526.
Ramsay, J. G. 1967. *Folding and Fracturing of Rocks*. McGraw-Hill, New York.
Schwerdtner, W. M. 1970. Distribution of longitudinal finite strain in lenticular boudins and bending folds. *Tectonophysics* **9**, 537–545.
Selkman, S. 1978. Stress and displacement analysis of boudinages by the finite-element method. *Tectonophysics* **44**, 115–139.
Siddans, A. W. B. 1977. The development of slaty cleavage in part of the French Alps. *Tectonophysics* **39**, 533–557.
Siddans, A. W. B. 1978. The development of slaty cleavage in part of the French Alps—Reply. *Tectonophysics* **47**, 187–191.
Stephansson, O. & Berner, H. 1971. The finite element method in tectonic processes. *Phys. Earth Planet. Interiors* **4**, 301–321.
Strömgård, K. E. 1973. Stress distribution during formation of boudinage and pressure shadows. *Tectonophysics* **16**, 215–248.
Tan, B. K. 1970. Deformation of particles developed around rigid and deformable nuclei. *Tectonophysics* **24**, 243–257.
Wood, D. S., Oertel, G., Singh, J. & Bennet, H. F. 1976. Strain and anisotropy in rocks. *Phil. Trans. R. Soc.* **A283**, 27–42.