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Variation of interlayer slip in space and time during flexural folding

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Abstract—This paper describes the results of an experiment which was performed with a Plasticine model to investigate the progressive evolution of flexural-slip folds. The model analyses the relationship between bulk shortening and the amount of flexural slip on fold limbs and in hinge zones. In the light of the experimental results, the theoretical relationship between limb dip and angular shear strain proposed by Ramsay (1967, p. 393) needs modifying to take into account the effect of hinge dilation and limb thinning at large deformations.

INTRODUCTION

THE INITIATION and development of chevron folds has been studied using field techniques, numerical methods and physical modelling under controlled laboratory conditions. Some important contributions in this field have been made by de Sitter (1956, 1958), Paterson & Weiss (1966), Ramsay (1967, 1974), Weiss (1968), Ghosh (1968), Cobbold *et al.* (1971), Cobbold (1976), Chapple (1968, 1969), Dieterich (1969, 1970), Dieterich & Carter (1969), Johnson & Ellen (1974), Johnson & Honea (1975a, 1975b), Johnson & Page (1976) and Dubey (1977, 1980). However, most of these models do not analyse the relationship between shortening and amount of flexural slip on fold limbs and in hinge zones. Ramsey (1967, pp. 392–393) has established a relationship between limb dip and angular shear strain for flexural slip folds but his theoretical model does not incorporate the commonly observed geological fact that chevron folds with large limb dips do not maintain a constant orthogonal thickness around the fold profiles, and that folds are usually characterised by limb thinning and hinge thickening. A series of experiments have therefore been carried out with Plasticine models to investigate this phenomenon. One of these experiments is described here.

THE EXPERIMENT

Plasticine was chosen to construct an analogue model because its rheological properties are similar to those of rock when considered at the scale of the model (McClay 1973, 1976). The experimental data on fold shapes can therefore be related to those seen in naturally folded rocks (Hubbert 1937).

The method of construction of multilayer models, the lubricants and the equipment used were the same as those described in an earlier publication (Dubey & Cobbold 1977). Individual layers were produced by rolling Plasticine between two plates of the required uniform thickness (0.15 cm). Interlayer boundaries were smeared with talcum powder to reduce interlayer friction and to encourage flexural slip during deformation. The model consisted of thirty layers of Standard Plasticine of alternating white and yellow colour. This multilayer was sandwiched between two slabs of violet Standard Plasticine. The external dimensions of the model were 9.5 × 6.5 × 5.0 cm. The layering was vertical in the press and the model was shortened along the layering. The resulting expansion took place in a direction normal to the layering, or to the enveloping surface of the folds. A transparent (perspex) plate constrained the model from the front—at right angles to the layering and so imposed bulk plane strain. Photographs were taken of the fold profiles through the perspex plate, without separating the model from the press.

In order to study the strain patterns around fold profiles and to measure the amount of displacement on fold limbs and hinge zones during development of folds, an orthogonal grid was embossed on the cross-sectional multilayer profile by using a serrated roller. Every fifth grid line, perpendicular to the length of the layering, was marked by a coloured felt pen. This helped in determining displacement of grid lines around the fold profiles.

Successive stages in the deformation of the model are shown in Fig. 1(a–d).

The following features were observed in the experiment.

1. The total amount of slip, S, between adjacent layers on fold limbs (Fig. 2a) progressively increased with total model shortening $(1 + e)$ until $(1 + e) > 35–45\%$. The amount of slip at the hinge zone (Fig. 2b) increased progressively with increasing model shortening, but the rate of slip was rather less than that seen on the limbs, especially during the initial stages of fold development, $(1 + e) < 20\%$.

2. When the model shortening exceeded 45% slip increments ceased, indicating a locking of the fold structure (de Sitter 1958, Cobbold 1977). Unfortunately,

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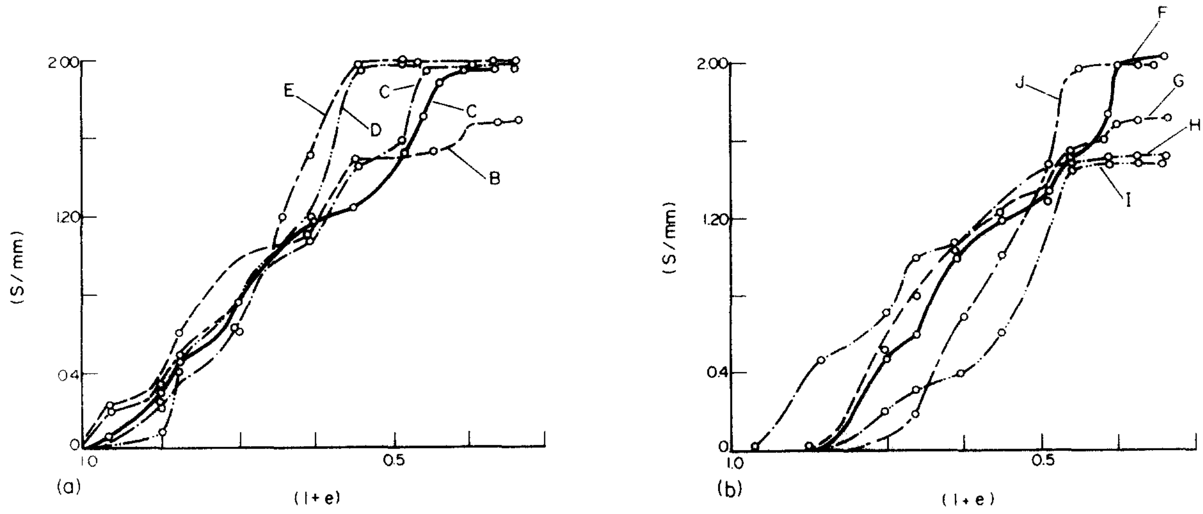

Fig. 2. (a) Total slip (S) at points A, B, C, D, E (Fig. 1c), on fold limbs vs total model strain (1 + e) = final length/original length. Likely error ranges 0.1 mm and $(1+e) \simeq 0.1$. (b) Total slip (S) at points F,G,H,I,J (Fig. 1c) in the fold hinge zone vs total model strain (1 + e).

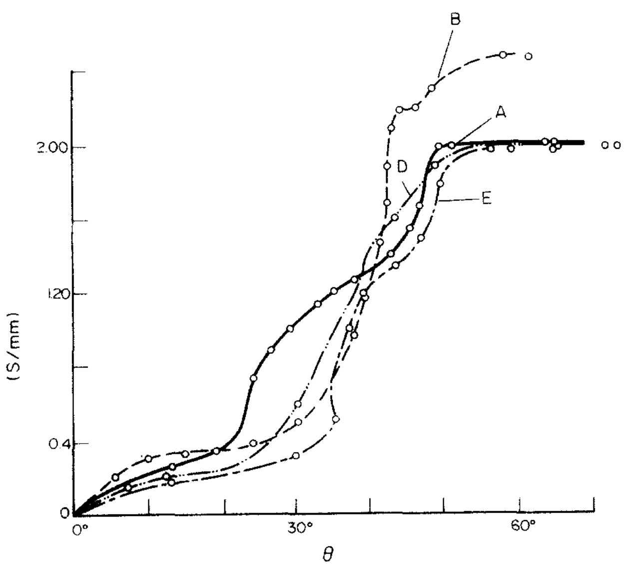

Fig. 3. Total slip (S) at points A, B, D, E (Fig. 1c) on fold limbs vs limb dip (θ). (Likely error ranges 0.1 mm and 0.5°.)

during later stages of deformation, the grid lines and the coloured markers became indistinct and it was not possible to determine any later displacement near the hinge zones.

It is interesting to plot the total slip, S, as a function of limb dip, θ, of the fold limbs (Fig. 3). During the initial development of folding ($1+e<10\%$) limb dip increased rapidly up to a value of about 30°. At an intermediate stage, the limb dip increased more slowly, whereas the slip increased rapidly. With further deformation of the model, the limb dip continued to increase but little or no interlayer slip took place.

Changes of interlimb angle, α, with shortening are shown in Fig. 4. Initial changes of interlimb angle per unit shortening were high compared with changes that took place during late stages of folding. For $\alpha > 80°$, changes in

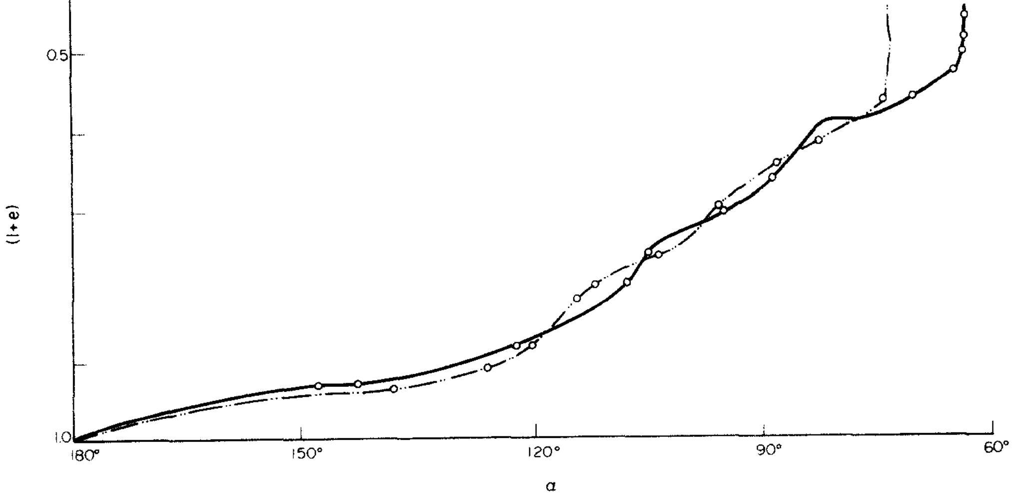

Fig. 4. Total model strain (1 + e) vs interlimb angle (α) of folds. (Likely error ranges 0.1 mm and 0.5°.)

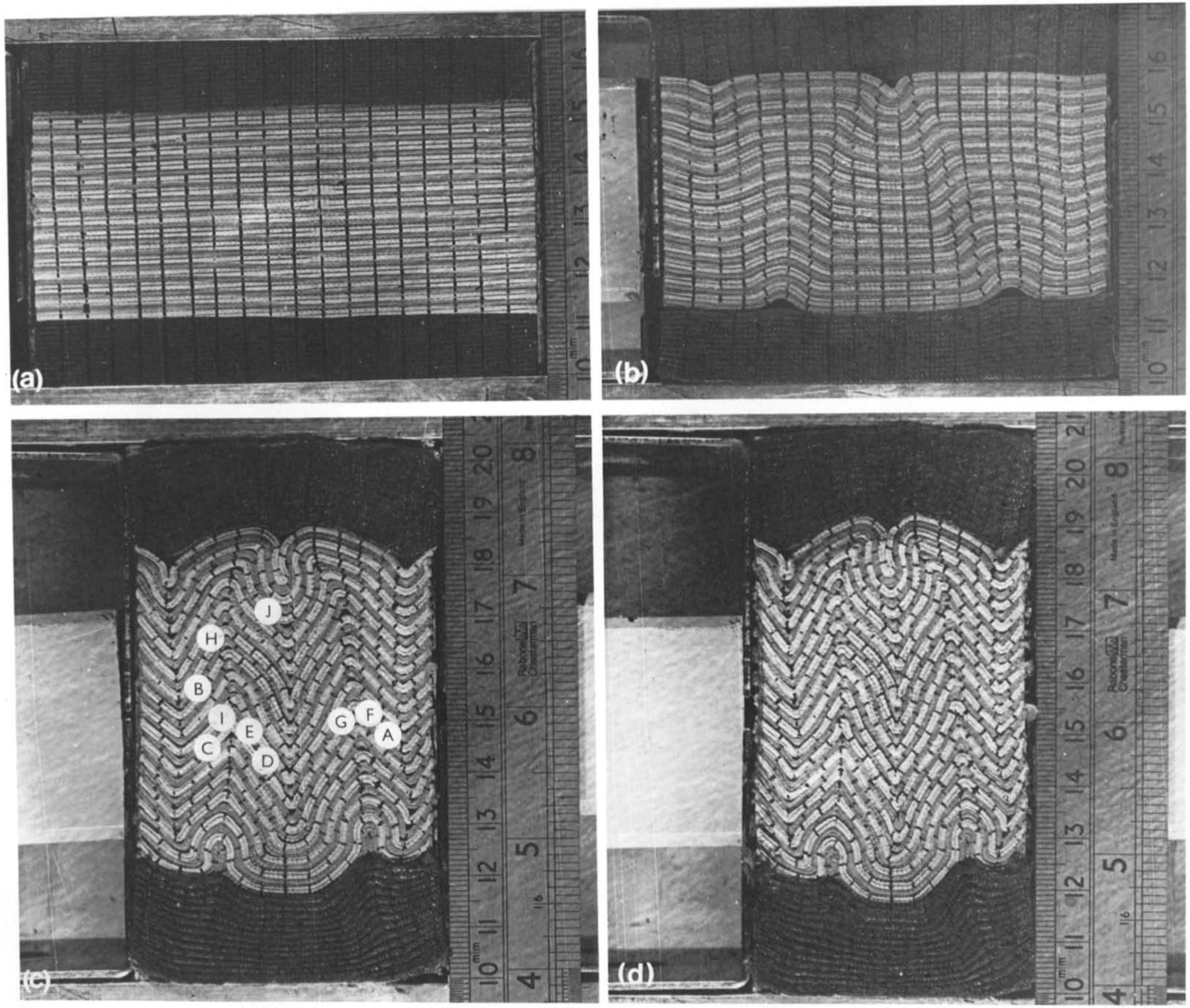

Fig. 1. Four stages in the deformation of the multilayer model. The total model shortening is 0 % (a), 12 % (b), 44 % (c) and 49 % (d).

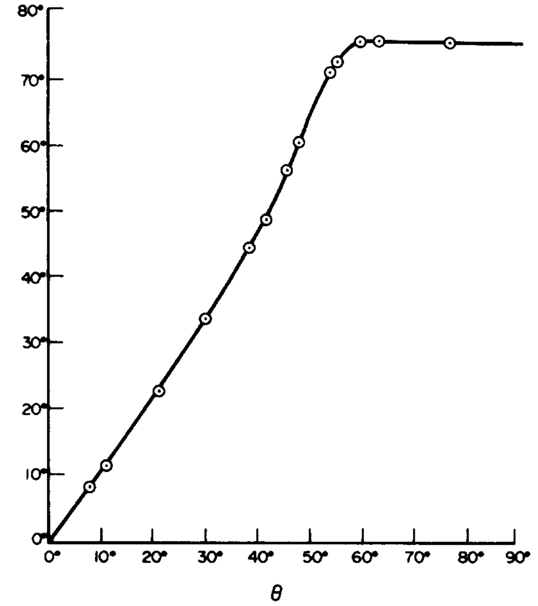

Fig. 5. Angular shear strain (ψ) vs limb dip (θ). The diagram is produced from measurements at point D (Fig. 1c). (Likely error ranges 0.5° and 0.5°.)

fold shapes were few and eventually the folds locked up at about 45% of total model shortening.

The angular shear strain (ψ) within the layer at point D (Fig. 1c) was measured directly using enlarged projections of the negatives on a fixed screen: it is the angle between the slip and the normal to the layering (Ramsay 1967, fig. 7–56). The relationship between limb dip, θ, and angular shear strain, ψ, is shown in Fig. 5. At low limb dips, the resulting curve fits the theoretical model of Ramsay (1967, p. 393) very well. However, at higher limb dips the present graph shows higher values of ψ. This discrepancy is attributed to the development of dilation in the fold hinge zone and limb thinning at high limb dips.

SUMMARY AND CONCLUSIONS

The experimental results show that during progressive development of flexural-slip folding the nature and amount of relative slip between adjacent layers varies on fold limbs and in hinge zones. At the onset of deformation, folding may develop by a true flexural slip mechanism but during late stages of folding, after folds lock up, the geometrical modifications of folds may be accompanied by only small amounts of slip. A relationship may be established between limb dip and angular shear strain. At large deformations the folded layers may not maintain a constant orthogonal thickness around fold profiles.

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