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SOME OBSERVATIONS MADE DURING AN EXPERIMENTAL STUDY OF MULTILAYER DEFORMATION AND THEIR SIGNIFICANCE

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Summary

In a series of model experiments designed to simulate certain aspects of the development of large-scale folds in bedded sedimentary rocks, it was observed that in the course of fold development, fold asymmetry may be reversed as a result of fold rotation. It has been inferred that because of the reversal of fold asymmetry this phenomenon is probably not a conclusive criterion for deducing tectonic transport in deformed belts. Conical folds were arranged *en echelon en echelon* and that this enechelon echelon array of conical folds existed side by side with the near cylindrical folds. It is deduced that the association in the field of conical folds, echelon array of conical folds and cylindrical folds can be expected as a consequence of a single deformation. In multilayer rock deformation in which differential vertical uplift is involved, gravity plays an important role. In all cases, according to the experiments, there is a distinct tensional stress phase during the initial stages of deformation in the zone of uplift, after which when rock masses begin to glide down along the flanks of uplifted areas, compressive stress phase is generated. Then, both compressive and tensional stress phases operate simultaneously.

Introduction

No geologist has ever witnessed a natural tectonic deformation in progress. In nature rock deformations have beginnings and must necessarily have an end. Determining the time of duration of the natural tectonic event is difficult because there is no reliable method of making estimates. However, tectonic deformations whose duration are of the order of 300,000 to 500,000 years such as have been estimated for the Eastern Alps, (Hsu, 1969) are quite reasonable. Within such a tectonic time span many events take place; for example, folds and faults initiate and develop, the final product may have passed through several states not recorded in the final stage.

In modern times the field geologist studies folds and faults in orogenic belts. The field geologist sees only the final product of the deformation process. He has the difficult task of reconstructing the sequence of events of past geological deformation by systematic study of the structural geometry of a number of final products. Structural reconstructions of past events are undertaken by making certain assumptions which when critically viewed are probably not justified.

For example, for a field geologist to deduce the precise mechanism of fold formation in folded regions by resorting to systematic analysis of folded strata the assumption is made that gently folded strata observed in one zone of deformation represents "frozen" early stages of the strongly folded strata in an adjacent region. This is not always valid because the gently folded strata may be the end product of an early strata which developed into a complex folded strata in the course of the deformation but later events led to "unfolding" of the strata to give the final gently folded strata. This suggests that one might question the value of all careful analysis of naturally deformed rocks.

Some geologists appear to be sceptical about the value of field studies and have become more and more interested in basing their interpretations of such problems on laboratory studies of rocks. The problem inherent in experimental work relates to the difficulty in experimentation at low strain rates. In the light of this it appears that the problem of structural geology can only be approached by a close integration of experiment with rocks and model analogues, theoretical analysis and field investigations.

The observations made in this experimental investigation help us to reappraise some of the deductions made in field studies. For example, field geologists attempt to differentiate between purely tensional and purely compressional phases of deformation during a tectonic episode. Sometimes several episodes are delineated, each episode described to contain a compressional stress phase and most are terminated by a tensional stress phase. For example, in the Sun River Canyon in northwest Augusta, Montana, five episodes of deformation are recognized, the sequence of events in each episode was (i) folding, (ii) thrust faulting and folding and (iii) longitudinal normal faulting (Mudge, 1970). This sequence implies an early compressive phase and a later tensional phase.

In the Montana deformed belt, post-thrust tensional structures have also been described and believed to be a distinct stage of a later orogenic episode. In the other parts of the American and Canadian Rockies and other deformed belts throughout the world, zones of tensional and compressional phases of deformation within the same orogenic period have been described (Scholten, 1968; Eardley, 1969; Scholten & Rampott, 1969; Temple, 1968; Seager, 1970; Misch, 1966; Sales, 1969). The paper deals with some observations made by the author in the course of large-scale multilayer deformation experiments in the laboratory. The results are seen as a contribution from experimental geology to the understanding of events associated with multilayer deformation.

Experimental models

The models used in the experiments are shown diagrammatically in Fig. 1a, 1b and 1c.

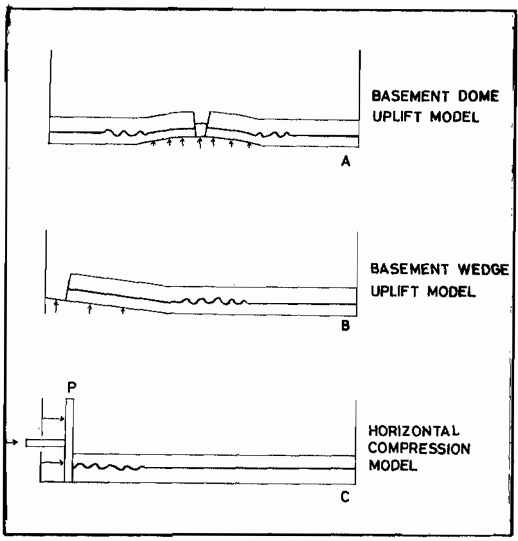

Fig. 1. The experimental models

The model material used is gelatine; the usefulness of gelatine as a rock analogue has been discussed (Woolfe, 1971; Blay, 1974). In Fig. 1a and 1b, a section of the base of the multilayer was slowly raised to simulate a basement dome uplift (A) and a basement wedge type of uplift (B) beneath a simulated sedimentary rock pile. In Fig. 1c, lateral compression produced by gravity sliding is simulated by the movement of the vertical piston (P) which is driven horizontally by a slow moving electric motor. It has been shown that lateral compression of the type shown in Fig. 1c forms part of a general deformation model of gravity tectonics (Blay, 1974; Blay, Cosgrove & Summers, 1977). The above models were not scaled to a specific natural deformed belt and so the results have general application.

Results and discussion

Fold development

Fig. 2a illustrates an initial embryonic fold at a point 'a' in a wedge type uplift. Close examination show that the embrionic fold is slightly asymmetrical away from the zone of uplift. Further examination also shows that the buckling instability at 'a' is only noticeable in the bottom layers. As uplift continues (Fig. 2a, b and c), the buckling instability is progressively propagated upward into the overlying layers until in Fig. 2c and 2 d practically all the layers are folded.

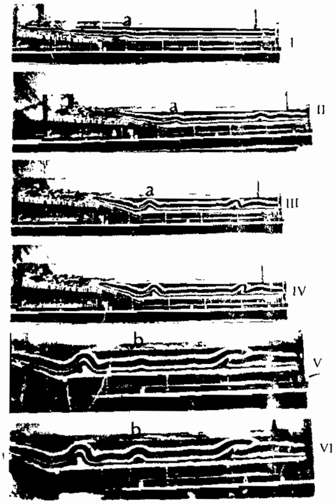

Fig. 2. Fold initiation and development on the "wedge" type uplift model

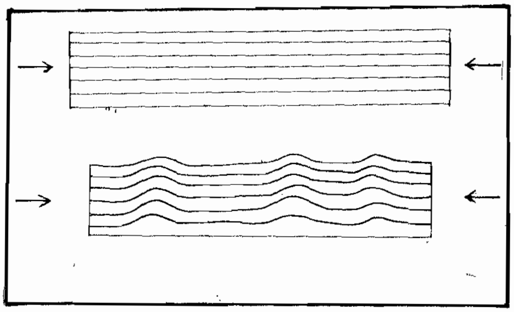

Fig. 3. Simultaneous folding of a multilayer on Ramberg and Biots models

Knowledge of fold initiation is based largely on the theoretical predictions by authors like Biot (1957, 1961, 1965b) and Ramberg (1961b, 1964a). In their models it has been established that on the application of a compressive stress, buckle folds initiate simultaneously in all the layers of the multilayer sequence (Fig. 3). What the experiments attempt to suggest is that fold initiation during deformation involving multilayers of rocks could also have been formed and developed as discussed here and not necessarily on the Biot and Ramberg models.

An important aspect of fold initiation characteristic of the experiments was the serial development of folds. In all cases it was noted that buckle fold developed around an instability and developed to a maximum amplitude through all the three phases as discussed latter, followed by a period of non-folding within the multilayer system during which strain energy is released by the generation of another fold, to be followed by yet a period of fold development, multilayer shortening, build up of strain energy within the multilayer system and again fold initiation. The process is repeated until a fold train (Fig. 4) is

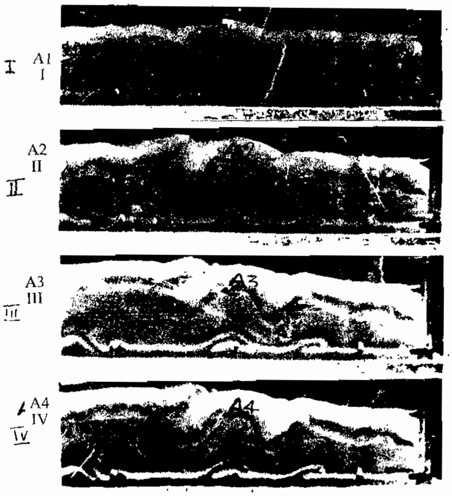

Fig. 4. Serial development of folds

established.

Fold reversal and the concept of fold rotation

Again a close examination of fold 'a' in Fig. 2b reveals some interesting reversals in fold asymmetry in relation to the source of disturbance. At initiation, the embrionic fold exhibits a slight asymmetry in the direction in which the disturbance is moving, that is, from left to right. In Fig. 2b the asymmetry is well defined and it is in the direction in which the disturbance is being propagated. However, from Fig. 2 to Fig. 2d the asymmetry is completely reversed and it is opposed to the direction of movement of the disturbance.

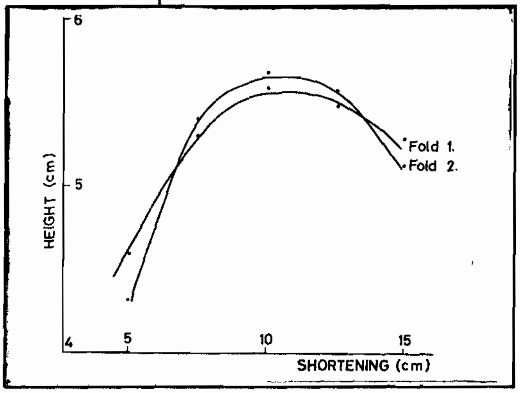

Fig. 5. Locus of a point on fold hinge with progressive layer shortening

A few stages were missed between stages (II) and (III) hence the failure to record the progressive change of asymmetry from the right as in stage (II) to the left as in stages (III) and (IV). However, if the deformation had ceased during stage (II) (Fig. 4), the asymmetry would have suggested a movement picture from right to left. Similarly, the fold asymmetry observed in stages (111) and (1V) in Fig. 4 suggests a movement from left to right.

The two examples illustrated in Fig. 2 and 4 point to a concept of fold rotation during fold development. This concept is further examined in Fig. 5 and 6 by tracing the locus of a point on the fold hinge during layer shortening on the horizontal compression model. The dots show the position of points on two folds which were serially initiated and developed. The maximum points of the curves give an indication of the maximum fold amplitude obtained. The points move in the vertical sense but not in a straight line; the departure from movement in a straight line is due to a rotation effect induced in the fold limbs. Fold asymmetry at the embrionic stage is not always necessarily the same as the final asymmetry.

An important observation made was that a fold may be asymmetric in one direction, but in the course of its development, it may progressively undergo asymmetry reversal through fold rotation. If this had been the natural situation, deducing the tectonic transport across a deformed belt based on the asymmetry of folds as discussed above would probably be misleading. What causes the asymmetry changes and the folds to rotate cannot be dealt with here. However, these changes could be partly due to the resultant effect of the principal compressive stress being transmitted through the multilayered sequence and the local stress around a particular fold. A mathematical treatment of fold rotation is given by Price (1967)

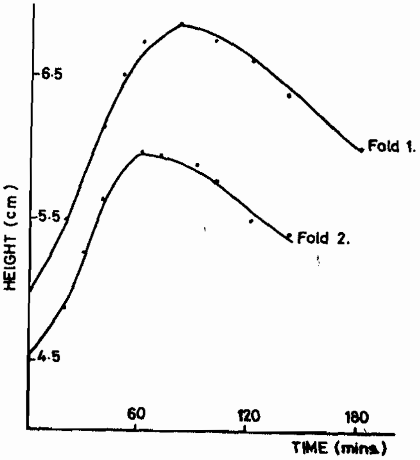

Fig. 6. Locus of a point on fold hinge with time

Phases and rates of fold development

An important observation made during the experiment relates to the rates at which individual folds developed. This observation throws some light into the strain-rates associated with the development of a single fold. The experimental observation suggests that three distinct phases are probably associated with the development of a simple single fold structure (Fig. 7). In the initial phase A, fold amplification was found to be very slow and this represents the initial elastic buckling phase B which is the inelastic buckling phase when the elastic limit of the folding layer is exceeded. During this phase, fold development is very rapid and may be described as the "explosive phase" of fold development. Phase B ceases when maximum fold amplification is attained. In phase C, it was noted that, in general, shortening and thickening in anticlinal hinge zone is the rule.

Another significant observation is that between phases A and C the strain-rates associated with the fold development varied considerably. The onset of phase A usually begins at very slow strain-rates, followed by fast strain-rates during phase B and finally during phase C the strain-rate is practically zero; hence it could be misleading to quote an average strain-rate for the development of all the three phases in the fold history as discussed above.

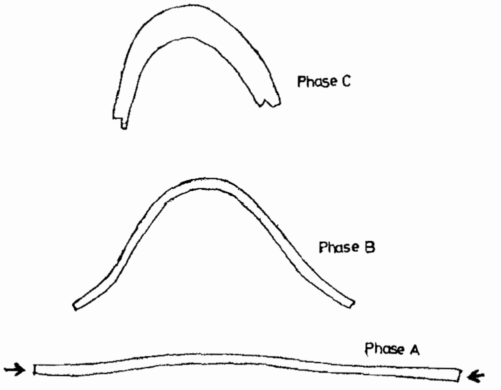

Fig. 7. Phases of fold development of a single fold

Conical and cylindrical fold development

In the geological literature conical or non-cylindrical and cylindrical folds have been described. In orogenic or deformed belts where both occur together the conical and cylindrical structures have been assigned to different phases of folding. It has also been suggested that the conical structure represents a re-modification of preexisting cylindrical structure (Ross & McGlynn, 1963). Evans (1963) strongly argued that the conical structure does not represent a refolding of an earlier cylindrical structure, but initially originated as a conical fold structure.

An echelon array of conical folds experimentally produced is shown (Fig. 8), although the progressive initiation and development of the individual folds is not illustrated here. The experiments were designed to generate, in two dimensions, only cylindrical folds but in practice non-cylindrical or conical folds were initially produced. The conical fold either developed at the side of the compressive box or inside it. The

Fig. 8. En echelon array of conical folds

progressive development of a single fold which formed at the side of the box is illustrated (Fig. 9). A cross-section view illustrating the development of a single conical fold with double plunge is shown (Fig. 10). Fold propagation from one side of the perspex box (Fig. 9) or to the sides of the perspex box from inside (Fig. 10) was observed to be along the fold axis and vertically as the arrows indicate. It was quite common during the experiments for conical folds to initiate and propagate in opposite directions, that is, towards opposite perspex walls. Considering two conical folds propagating in opposite directions, fold development proceeded along one or two trends.

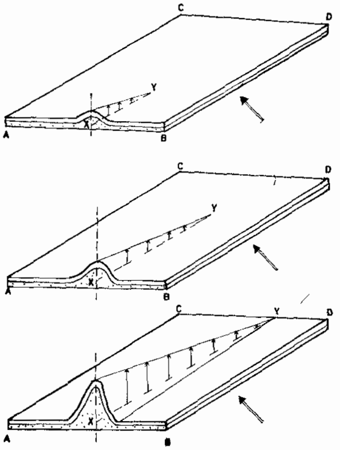

Fig . 9. Progressive development of a conical fold from wall to wall (AB to CD). Vertical arrows represent upward displacement perpendicular to central axis, XY

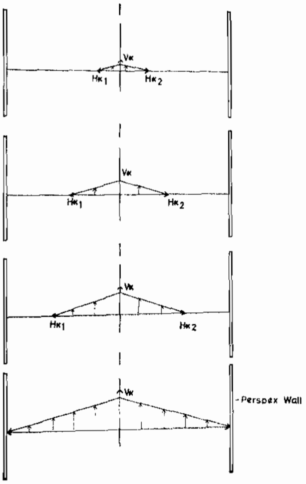

Fig. 10. **Cross sectional view of conical fold with** double plunge showing progressive stress propagational around the three vertices

First, fold hinges shifted laterally and merged, the resulting fold axis being curved (Fig. 11, BB^{I}). As deformation continued the fold axis becomes progressively less curved and the final structure approached a cylindrical geometry. Second, in the course of the development, the conical structure may become "arrested" or "frozen", may and *en echelon* array of folds, result (Fig. 8); or as indicated above, three conical folds may merge into each other at their apical regions resulting in bifurcating fold structure (Fig. 11,DD^{I}).

The question to consider is what determines when two non-cylindrical folds should merge and when they should follow independent development. The problem was experimentally found

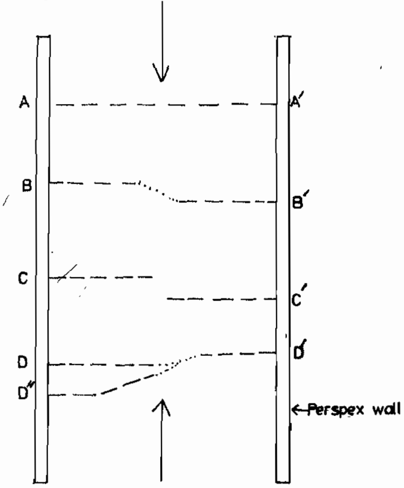

Fig. 11. Behaviour of fold axes during the **experimental** deformation (map view). A A^{I}= single folds axis; BB^{I}=two folds with axes merged; CC^{I}=axes of en echelon folds; DD^{II} D^{I}= bifurcating fold axes·

to be related to the interhinge separation of adjacent folds. Measurements of the interhinge separation (h) from several experiments in terms of the wavelength were made. If the interhinge separation is less than one-quarter of the wavelength, fold axes merged; if 'h' is about half the wavelength an en echelon array of folds developed. On the other hand, if 'h' is greater than half the wavelength, the initial non-cylindrical fold developed independently into a near cylindrical fold.

From the observations made during the experiments it is quite clear that the conical structure is earlier and that the cylindrical structure developed from the conical structure. Again, the experiments attempt to suggest that an association of conical, en echelon and cylindrical folds can be expected as a consequence of a single phase of deformation.

Tensional and compressive phases in tectonic deformation

The sequence of events observed in experimental deformation in which a "basement dome" is "intruded" into a multilayer sequence made up of thin sheets of gelatine is illustrated (Fig. 12). From the onset of uplift the layers above the uplifted zone are under tension, consequently the slow uplift resulted in layer thinning within the zone of uplift. Thinning was first noted in the topmost layer and as the central uplift increased layers lower down the sequence progressively thinned. Layer thinning in the uplifted zone is associated with layer stretching and pulling apart of layers within the zone.

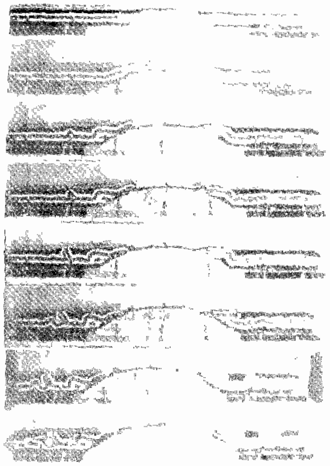

Fig. 12. Fold development on the "dome" type uplift model

After a central uplift of some 2.5 mm, the upper layers developed fractures. The fractures were oriented sub-parallel to the crestline of the rising dome. Fractures developed first in the topmost layer and propagated downwards until the incompetent basal layer was reached. Fractures did not propagate through the soft basal layer, instead the layers overlying the basal layer slid over it as a single moving mass down the flanks of the uplifted zone, producing folds and thrusts (Fig. 12). The layers slid under the influence of their own body forces. The development of folds and thrusts in the flat region was due to the transmission of this body force as a compressive stress through the layered system from the uplifted zone where tensional stress operates.

Within the flat region the development of folds and thrusts does not follow a particular order. Sometimes folds initiated before thrusts and, *vice versa*. In the foreland region a fold may develop to achieve its maximum amplitude, then, it may rotate and undergo asymmetry reversal or fractures develop along the crestline. These fractures are due to stretching and pulling apart action across the crest of the fold, suggesting that in the flat region although deformation is largely due to the compressive stress being propagated through the layered sequence, tensional stresses also occur locally at points where folds are being developed.

To summarise, during differential vertical uplift of the dome type model, the order of deformation events as observed from the experiments is as follows:

(a) In the uplifted zone, rock layers are stretched and pulled apart and as a result fractures are formed. Some of these fractures are definitely normal fault fractures. Layers in the flat region remain stable.

(b) Following the brittle failure in the uplifted zone, the layers slid downslope under the influence of gravity. This action generated a compressive force which acts on the layers in the flat region resulting in the initiation and development of folds and thrusts.

(c) In the flat region tension fractures develop within the domain of fold erests, and this is attributed to the generation of local tensional stress fields around folds developing in this region.

Conclusion

Experimental geology be it in structural geology, petrology or any other discipline related to geology aims at studying the natural phenomena. Some experiments are designed to study structures to give an insight into how these structures have originated. Others like what have been discussed in this paper and by other authors (Willis, 1891; Ramberg, 1963b, 1967) are designed to study large-scale multilayer deformations.

Certain observations in relation to multilayer deformation under the influence of gravity have been discussed. It has been demonstrated that folds may rotate and fold asymmetry may be reversed during fold development. As a result of the asymmetry reversal the point has been made that fold asymmetry is not conclusive criterion for deducing tectonic transport across a deformed belt in the natural situation.

It has been established that in the deformation of a multilayered sequence in which gravity plays a leading role, there is always an initial tensional phase, followed in time by a compressive stress phase, then, both the compressive and tensional stress phases operate simultaneously although towards the final phase the compressive stress regime is more important.

Some non-cylindrical folds have their surfaces arranged so as to form part of a cone in which case these folds may be referred to as conical folds (Dahatrom,1954; Evans, 1963; Staufner, 1964). According to Ramsay (1967) conical folds are very rare in nature. Most of the folds generated in the experiments were conical in geometry. However, with prolonged deformation the initial conical geometry developed into a near cylindrical geometry. This could have a parallel situation in nature, in which case, it could be inferred from the experiments that most conical folds developed into cylindrical folds, thus explaining the rare nature of conical folds in the field.

From observations made in the experiments it was evident that interpretations or deductions made in relation to possible sequence of events in the natural situation may be quite misleading. In the light of what has been described above, this paper must be viewed as a contribution to an understanding, through experimentation, of the end product of the natural deformation phenomena.

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