Journal of Structural Geology, Vol. 5, No. 2, pp. 197 to 210, 1983
Printed in Great Britain

0191–8141/83 $3.00+0.00

Folding of boudinaged layers

SUDIPTA SENGUPTA

Institute of Geology, Uppsala University, Uppsala, Sweden*

Abstract—The boudinage structure in the Väddö area in Sweden developed during an early isoclinal folding. During a second deformation which deformed the axial surfaces and the limbs of the isoclinal folds, the shapes of boudins were variously modified. The resulting structures include folding of the individual boudins into half-waves, a tile-like piling up of straight or gently folded boudins and arrangement of straight boudins in a herring-bone pattern. Similar structures have been produced experimentally in soft models containing 'boudins' of different competencies. The relative importance of the different physical parameters which contribute towards the development of the various structures is examined. In particular, the experiments showed that when the competence contrast between the boudin and the host material was rather small, the shape of the boudins was modified by a second deformation into trapezoidal forms often with flame-shaped projections at the edges. From an analysis of the experimental and natural structures, a set of criteria has been formulated which can be used to identify structures formed by superposed deformations and to give an approximate idea of the competence contrast between the boudin and the host rock during the second deformation.

INTRODUCTION

FOLDS produced by compression of a continuous layer or multilayer are often used by structural geologists to determine the geometry of the bulk strain and the history of deformation of the rocks. If a competent unit of the rock is discontinuous, the morphology of the compressional structures is in general somewhat different from that of a folded continuous unit. The purpose of the present investigation is to determine how the displacements resulting from a layer-parallel bulk compression are modified by the presence of the discontinuous structures of a boudinaged layer.

Unlike folding, boudinage is not recoverable. Even if a compensating amount of shortening were applied to a boudinaged layer, it would not go back to its original shape or continuity; the pattern of displacements would be modified by the discontinuities of the layer. This can be clearly seen in many areas of superposed deformation where the boudinaged units of an earlier deformation have, in a subsequent period, undergone a layer-parallel bulk shortening.

A variety of such structures are exposed in the Precambrian rocks of the coastal region of Sweden near Väddö, about 100 km north of Stockholm. The present study describes (1) the characteristic morphology of the deformed boudins and the boudinaged layers in Väddö and (2) certain experiments with test-models in which different morphological types of structures are produced by shortening of a row of discontinuous rigid (or competent) units embedded in a softer matrix. In the last section of the paper, an attempt has been made to identify the physical factors which favour the development of specific morphological types of such structures.

* Present address: Department of Geological Sciences, Jadavpur University, Calcutta 700 032, India.

DEFORMATION OF BOUDINAGED LAYERS IN THE VÄDDÖ AREA, SWEDEN

In the coastal region of Väddö, Sweden (Fig. 1), a variety of boudinage structures and superposed folds can be seen in the thin siliceous layers interbanded with impure carbonates. The competent siliceous layers show a series of tight and isoclinal folds with development of boudinage along the limbs of the folds. In a later deformation the axial surfaces of the isoclinal folds and the

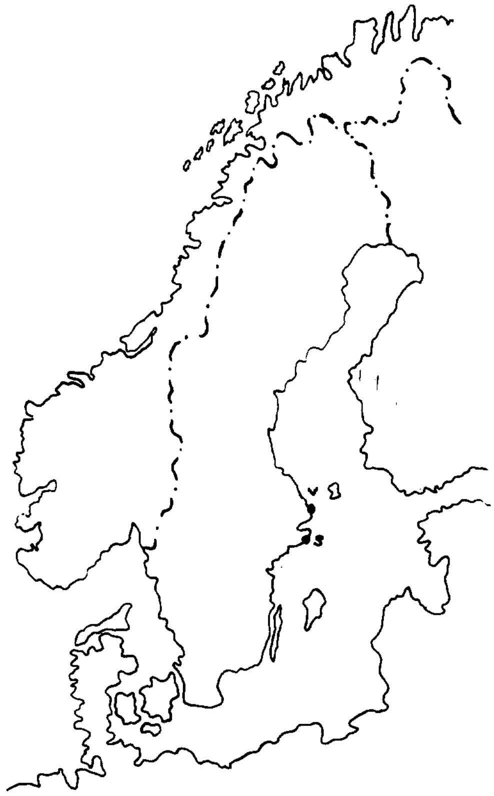


Fig. 1. Location of Väddö in Uppland, Sweden. V = Väddö; S = Stockholm.

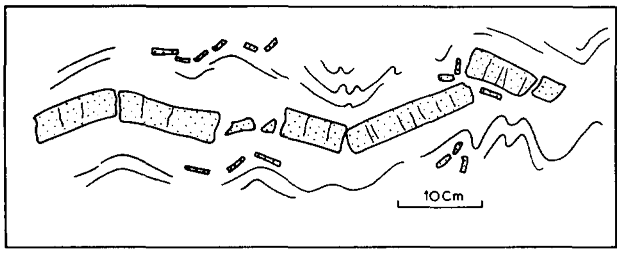


Fig. 2. Zigzag arrangement of competent boudins of siliceous layers in a carbonate rock in Väddö, Sweden.

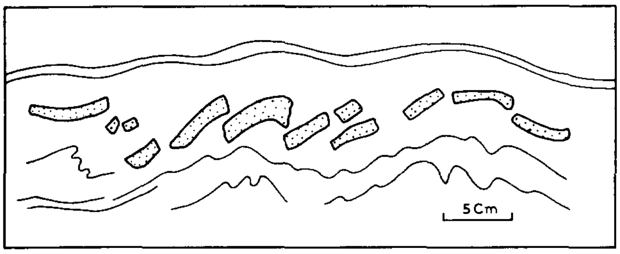


Fig. 3. Imbrication of short boudins in en échelon fashion in Väddö, Sweden.

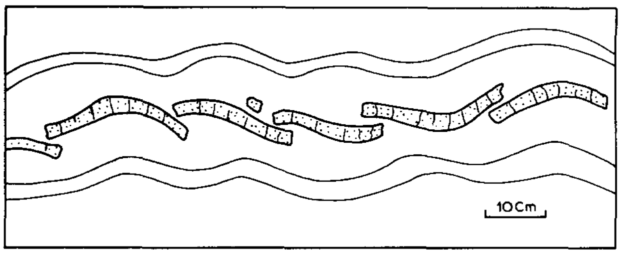


Fig. 4. En échelon arrangement of relatively long boudins with gentle folding of individual boudins. The boudins are of siliceous bands within a carbonate host rock.

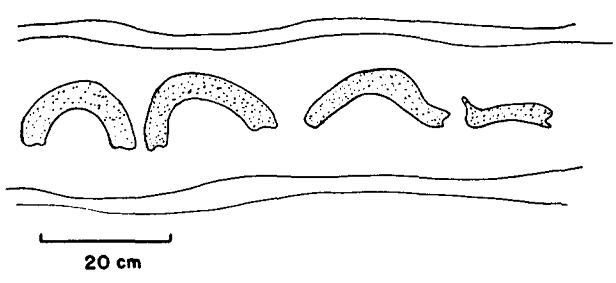


Fig. 5. Individual boudins folded in half waves, with each fold having the same sense of closure.

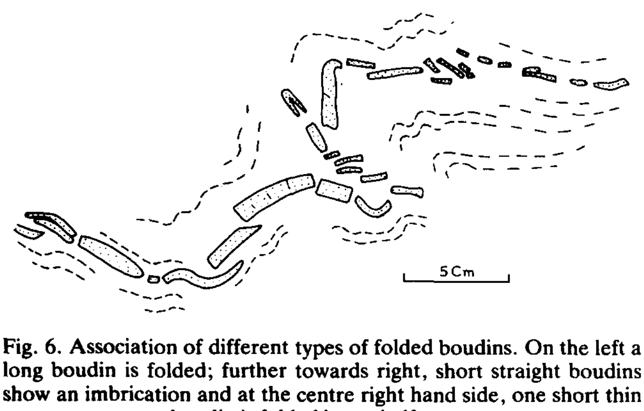


Fig. 6. Association of different types of folded boudins. On the left a long boudin is folded; further towards right, short straight boudins show an imbrication and at the centre right hand side, one short thin boudin is folded into a half wave.

boudinaged limbs were folded by a shortening of much lower intensity. The folds of the second generation are more-or-less upright and are gentle or open. The openness of the second generation folds confirms the conclusion that the boudinage is earlier than these folds.

Several morphological types of deformed boudinage can be identified in the area. In certain cases, the discontinuous competent units show a folded pattern with a herring-bone like arrangements of the individual boudins (Fig. 2). The boudins in cross-section are either rectangular or a rough parallelogram. A fairly common structure in the Väddö area is a tile-like piling up of short, straight boudins in en échelon fashion, with the longer direction of the cross-sections making a moderately high angle with the general orientation of layering (Fig. 3). When the individual boudins are fairly long (with respect to thickness), the imbrication is accompanied by gentle folding of each boudin (Fig. 4). In one type of structure, the individual boudins are separately folded into half-waves; a peculiar feature is that the folds of the neighbouring boudins often have the same sense of closure (Fig. 5). Some of these different morphological types are found together in a single exposure, either in different layers or in different parts of the same layer. In the latter case, the layers show strong strike-wise variation of layer thickness and length of boudins. Thus, on the left side of the Fig. 6, there is a long boudin folded into more than one wave while further towards right, short, straight boudins show an imbrication, and in the centre a short thin boudin is folded into a half wave. In another case (Fig. 7) layers of relatively small boudins are folded in close association with layers of larger boudins. In places the folding of the small boudins is influenced by the folding of the larger ones but in some places no such relationship is apparent, particularly if the smaller boudins are far removed from the large ones (Fig. 7).

EXPERIMENTAL METHOD

Rigid boudins were simulated by using blocks of Perspex or other rigid material. Modelling clay was used to represent flexible but competent boudins. A mixture of modelling clay and painter's putty in equal proportions was used to represent softer or less competent boudins. In the following description these blocks will be referred to as boudins or boudin-blocks. Silicone putty or painter's putty was used as the matrix.

To represent a boudinaged layer, the boudin-blocks were embedded in a row on a thick slab of painter's putty or silicone putty. The model was then deformed by uniaxial compression or simple shear. In the case of uniaxial compression the model was deformed by two rigid plates moving towards each other with the help of a motor-driven rotary drive. The boudinaged layer was either vertical or was inclined to the upper surface of the slab. After deformation, a stretched piano wire was used to cut off a thin slice of the upper surface of the model to have a clear picture of the structure. In the case

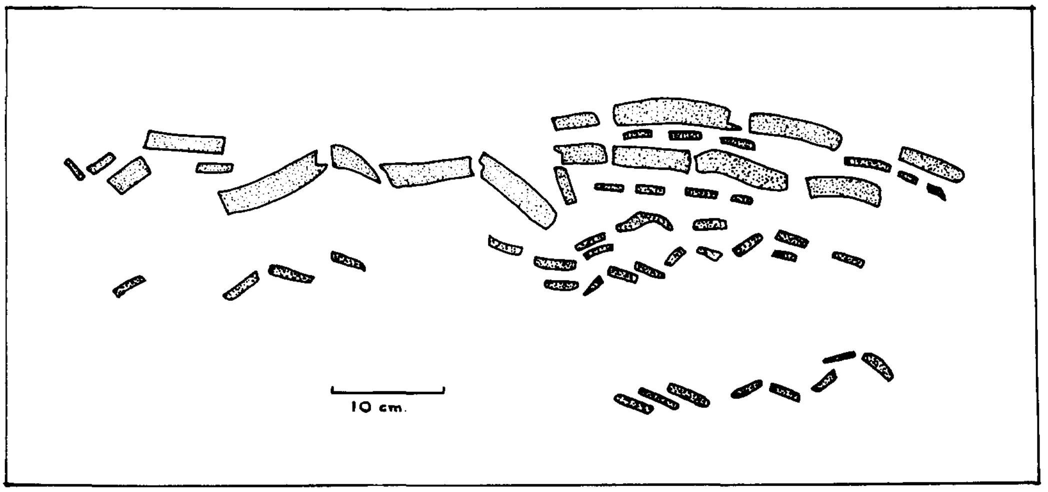


Fig. 7. Deformation of boudinaged layers with different thickness. Where the two layers are closely spaced, the rotation of the smaller and thinner boudins in one layer is influenced by the rotation of the larger boudins in the other layer.

of simple-shear, the models were deformed in a shear-box where one side of the box moved while the opposite side remained stationary. In this case the boudins were initially arranged in a straight row making an angle of 135 or 150 degrees to the shear direction, so that the row of boudins could be shortened to a great extent. Here the two axes of the boudin-blocks remained on the horizontal surface of the model and the third dimension was parallel to the axis of simple shear.

The experimental models were of three types: (a) where the boudins were rigid, (b) where they were flexible but competent and (c) where they were soft but slightly more competent than the matrix.

EXPERIMENTAL RESULTS

Deformation by uniaxial compression with row of boudins parallel to compression direction

Rigid boudins. Rigid blocks with 10 mm × 3 mm cross-section ($R = 3.3$, where R is the ratio of the longest axis, a, and the shortest axis, c, of individual boudins) were embedded in a row in silicone putty with 3-mm gaps between neighbouring boudins and with the a-axes parallel to the compression direction. The third dimension of the boudin blocks (b-axis) remained inside the putty and only the top surface remained flush with the upper surface of the slab of putty. The model was subjected to a compression parallel to the row of boudin-blocks. In the initial stage of deformation the line of boudins was first shortened, thereby closing the gap between individual boudin-blocks. The row of boudins then became folded in a zigzag fashion. The folding was achieved by rigid rotation of the blocks. In general, two types of folds developed, zigzag and conjugate. Where the alternate boudin-blocks showed opposite senses of rigid rotation, the fold pattern was zigzag (Fig. 8); where one of the blocks remained more or less parallel to the original direction of compression, a conjugate fold pattern developed. Generally the rectangular blocks met end to end even after a moderately large amount of deformation. In certain cases small off-sets were noticed.

A few experiments were made with large axial ratios ($R = 10$) of the rigid boudin-blocks. The results were essentially the same as in the experiments with shorter blocks. However, for the longer blocks, there was a tendency for the neighbouring blocks to slide over each other after a moderate amount of bulk deformation.

Moderate viscosity ratio between boudins and embedding medium. In another series of experiments the boudins were made of rectangular blocks of modelling clay and were embedded in silicone putty. The row of boudins was parallel to the direction of compression.

In the experiments with boudin-blocks with $R = 3.3$, the individual blocks were not folded. The folding of the entire *row* of blocks took place by external rotation of alternate blocks in opposite senses (Fig. 9). However, the folding was accompanied by some deformation of the individual boudin-blocks. In the initial stage, before the start of folding, each of the blocks were shortened by more-or-less homogeneous strain. When folding began, the blocks continued to remain end to end but their rectangular shapes were changed; the edges of the blocks were no longer perpendicular to the layering (Fig. 9). Some of the folds were box shaped after a moderate amount of deformation. Again, some of the blocks showed a tendency to slide over their neighbouring blocks.

When fairly long ($R > 5$) boudin-blocks of modelling clay were embedded in painter's putty and were deformed with compression parallel to the layering, the individual boudins buckled into one or more half waves. There was also a tendency for tile-like overlapping of the folded boudins (Fig. 10). Competence contrast remaining the same, the individual boudins show a greater tendency to fold when R is large; when R is small there is a greater tendency for wholesale rotation.

Low competence contrast between boudins and embedding medium. In this series of tests, the ratio of competence between the boudin-blocks and the matrix was kept rather low, so that the folding of the row of boudins could be associated with a large amount of layer-parallel compressional strain. The blocks with $R = 2.8$ were placed at 3-mm intervals (Fig. 11a). A compression was applied parallel to the row of boudin-blocks. The change in shape of the boudins was quite different from the previous experiments. The geometry of the boudins depended on the stage of evolution of the folds in the row as a whole. Three distinct stages could be identified (Fig. 11).

(1) In the initial stage each boudin had undergone a large amount of layer-parallel shortening without any folding. This process was accompanied by a gradual closing of the gaps between boudins. When the boudins came fairly close to each other, the edges of each boudin were dragged in the direction of extension so that the thickening of the edges of each boudin was somewhat greater than the middle part (Figs. 11b and 12b). This process is similar to that of the development of 'fish head' boudins or boudins with concave sides (Ghosh & Ramberg 1976, pp. 67–69, fig. 54). However, in the typical 'fish head' boudins, the concavity appears at the sides along which the boudins initially split and the extension is parallel to the layering. In the present case the concavity appears along the sides parallel to the original layering of the bed and the extension is perpendicular to the layering.

Since the boudin-blocks were more competent than the embedding medium the layer-parallel compression within the boudin-blocks was in general smaller than in the embedding medium. However, the net bulk shortening along the direction of layering was equal in the embedding medium and along the boudinaged layer. Thus, there must have been a concentration of strain in the gaps between the boudins. Compared to the central part of each boudin the instantaneous rate of extension perpendicular to the layering was larger in the edges than in the central part. Moreover, compared to the central part of the boudin, the rate of extension of the incompetent material in the gap increased as the boudins came close together. This caused a greater extension of the boudin-blocks along their edges in the direction perpendicular to the layering and also a greater shear strain along the edges. This is the reason for the development of flame-shaped projections and the concave shapes of the sides parallel to the layering when the boudin-blocks came close together.

(2) Folding of the row of boudins became perceptible only when the gaps between the boudins were considerably reduced. In the early stage of folding, when the amplitude remained small, three processes operated simultaneously: (i) decrease of length of the boudins on the fold profile and hence a reduction in the value of R; (ii) drag along the edges to produce flame-shaped projections and (iii), change in boudin profile at the hinge zones to roughly trapezoidal (Figs. 11c and 12c) due to dissimilar concentric longitudinal strains at the extrados (fold outer arc) and the intrados (fold inner arc).

(3) Thickening of the boudins continued together with a slow increase in the amplitude of the folds. In the experiments, the average value of R of the boudins often became less than unity at the close of deformation. The combined effect of an increase in the curvature and an increase in the thickness led to an increase in the absolute values of the concentric longitudinal strains. Hence, the trapezoidal shape of the boudin profiles at the hinge zone gradually became more pronounced. However, because of a layer-parallel extension along the extrados at the hinge zone, the concavity or the flame-shaped projection at the extrados was gradually flattened out. The flame-structures at the intrados, on the other hand, became more accentuated than in the previous stage (Figs. 11d and 12d).

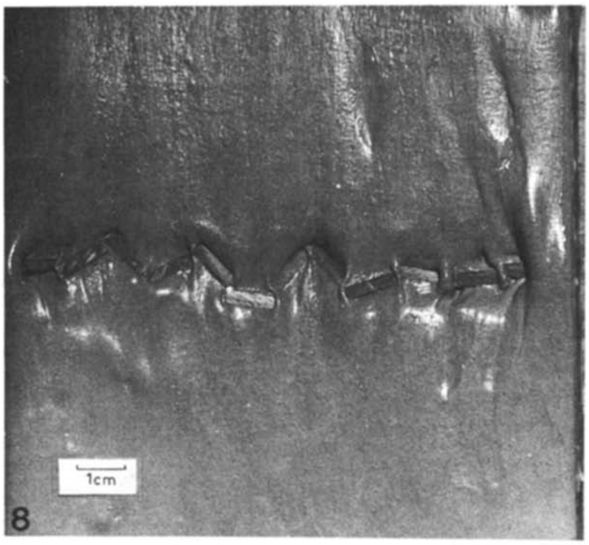
The overall profile of a boudin was roughly trapezoidal where it occurred symmetrically with respect to a hinge of the fold. Because of layer-parallel shear strain along the limbs, the shapes become more and more asymmetrical away from the hinge zone; however, since the side of a boudin-block at the extrados still remains somewhat longer than at the intrados, the term trapezoidal is retained even for these asymmetrical boudins.

In general, the ratio of the length-of-arc to the average thickness of the fold waves in the boudinaged layer was rather low. In the mature stage of folding this ratio was sometimes as low as 4. No doubt, such a low ratio of length-of-arc to thickness resulted from a low contrast in competence between the boudins and the host material. Buckle folding at such a low competence contrast could not be produced experimentally in initially straight continuous layers. It is suggested that folding of the boudin-row at such low competence contrasts was facilitated by the presence of the discontinuities, that is by the presence of the boudinage structure itself.

It should be noted that when the competence contrast between the boudins and the host material was low, a shortening of the boudin row was not accompanied by any tile-like piling up of individual boudins. This contrast in behaviour is strikingly shown in Fig. 13 where the model shows a shortening along two boudinaged layers of dissimilar mechanical properties.

Row of boudins at angles to the compression direction

The instability, leading to zigzag folding of a boudin-row could develop only when the boudins were aligned end to end. When the boudin-row was oblique to the principal axes of strain, the individual boudins and the row as a whole rotated at unequal rates (Ghosh & Ramberg 1976) and hence, the boudins showed an en échelon arrangement (Fig. 14); since they no longer met end to end, folding of the boudin-row was inhibited. The en échelon arrangement or imbrication was particularly prominent when the boudin-axes were oblique to all the principal axes of strain. Even when the b-axis of the boudins coincided with the intermediate strain axis, folding was mostly replaced by imbrication provided the boudin row was initially at a moderately large angle (more than 7° in the experiments) to the compression direction.



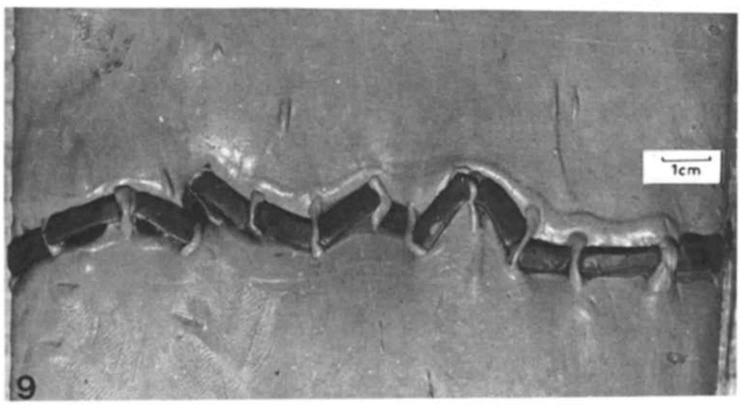


Fig. 8. Zigzag pattern produced by layer-parallel compression of a row of rigid 'boudins' ($R = 3$). Note the association of patterns similar to conjugate and chevron folds.

Fig. 9. Deformation of a row of modelling clay boudins embedded in silicone putty. Model after 32% bulk-shortening. Note that the deformed boudins are no longer rectangular.

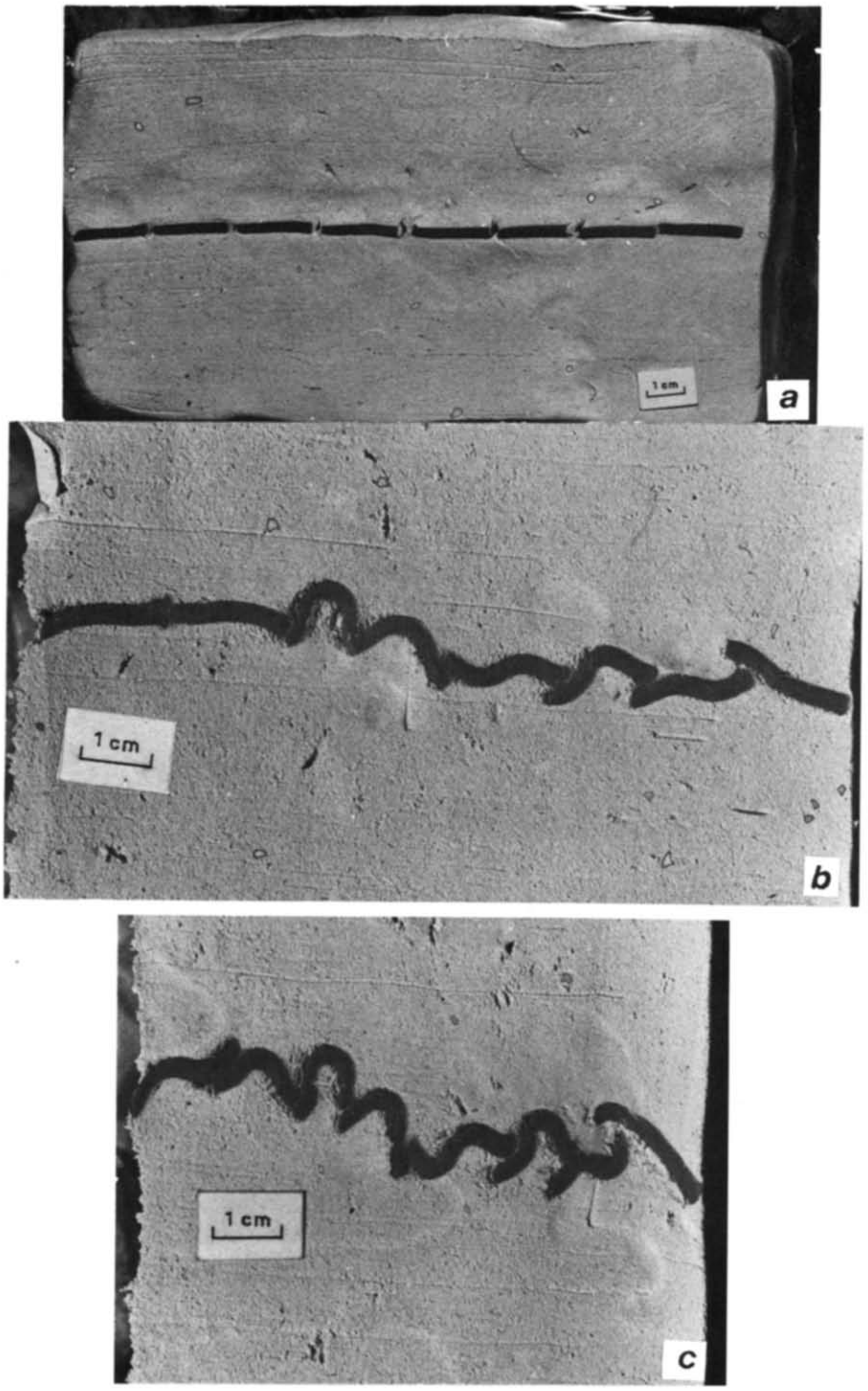


Fig. 10. Uniaxial compression of a row of long thin modelling clay boudin-blocks embedded in painter's putty. The difference from the model shown in Fig. 9 is mainly because of the difference in axial ratios of the boudins in the two models. (a) Undeformed model, (b) model after 37% bulk shortening, (c) model after 56% bulk shortening.

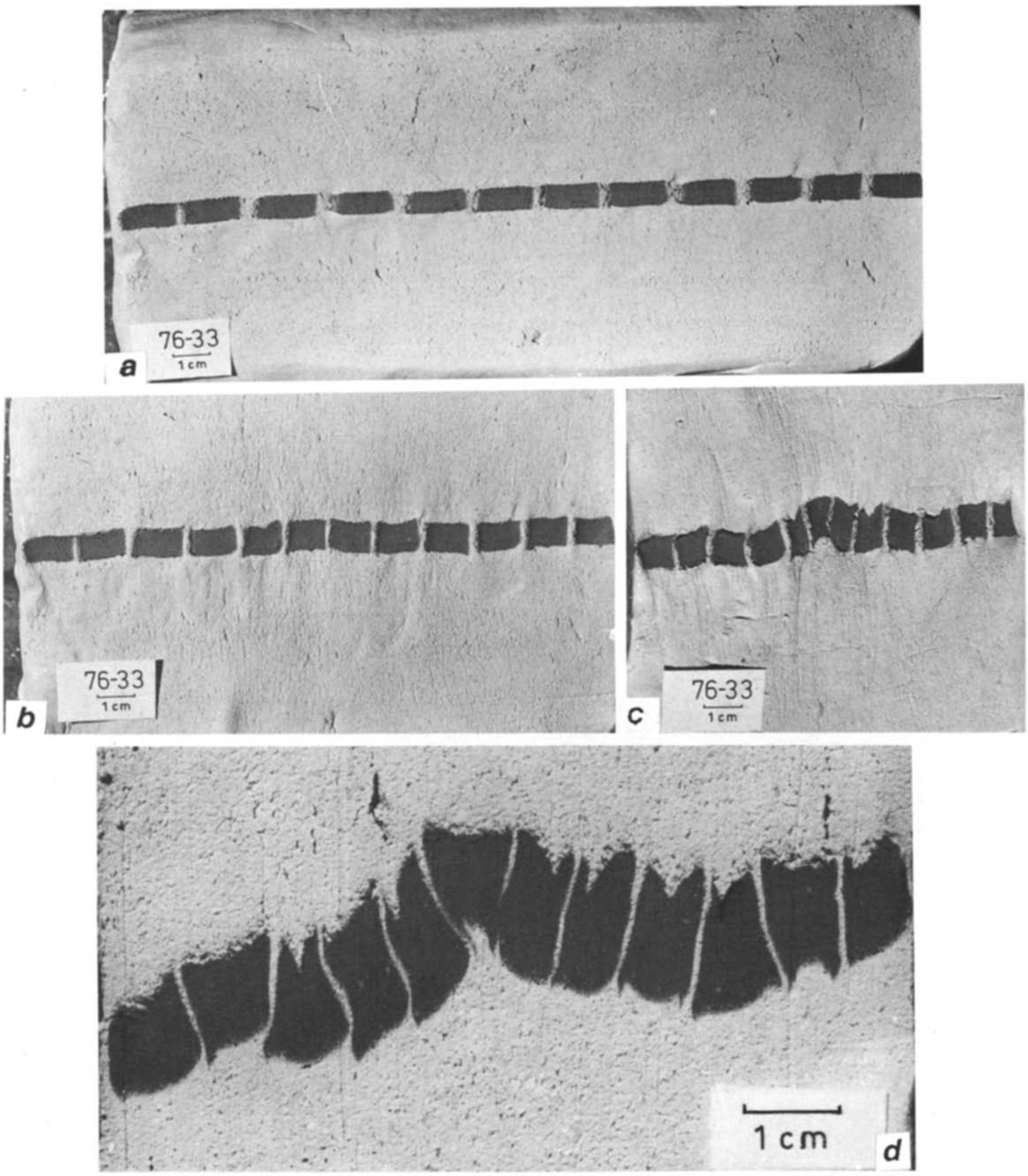
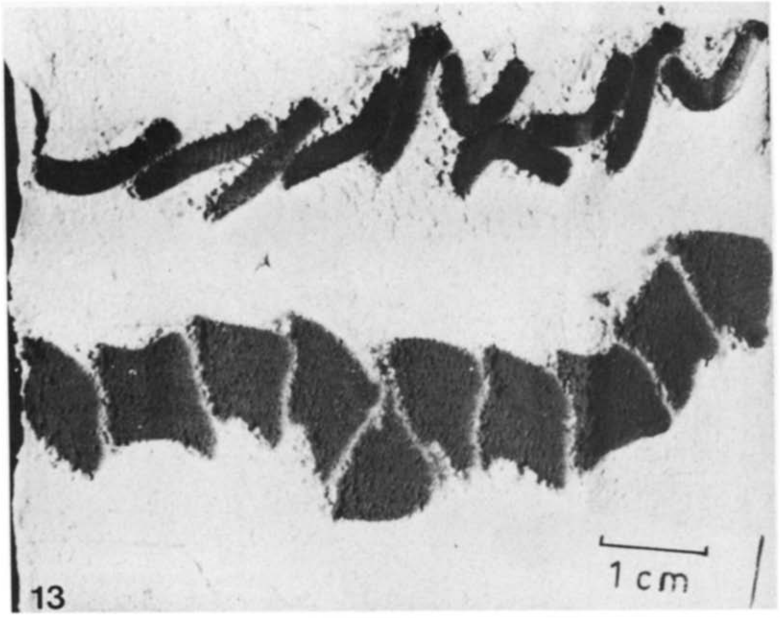


Fig. 11. Experimental deformation of a row of boudin-blocks with low competence contrast with the host material. (a) Undeformed model with $R = 2.8$; (b), (c) and (d) show successive stages of compression. Note the flame-shaped projections at the edges and also note that in the final stage the values of R have become less than 1.



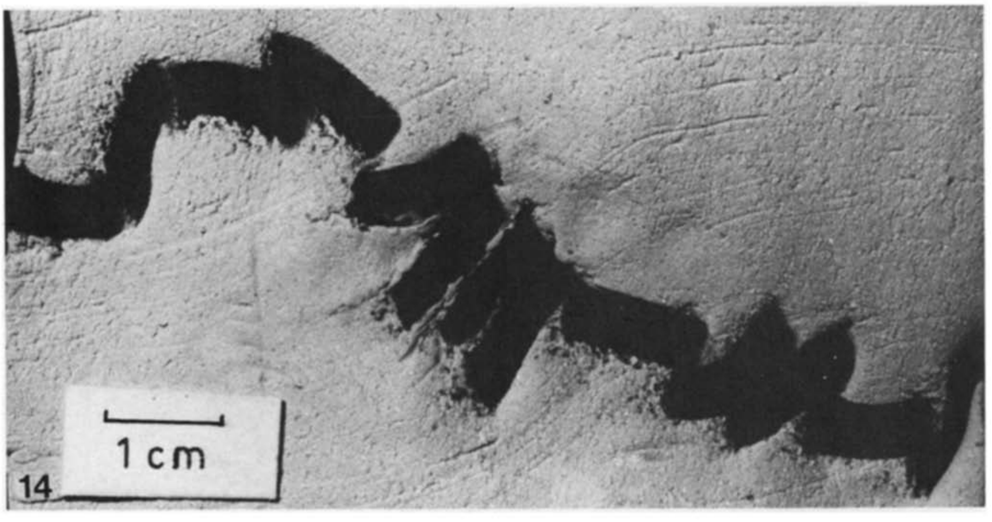
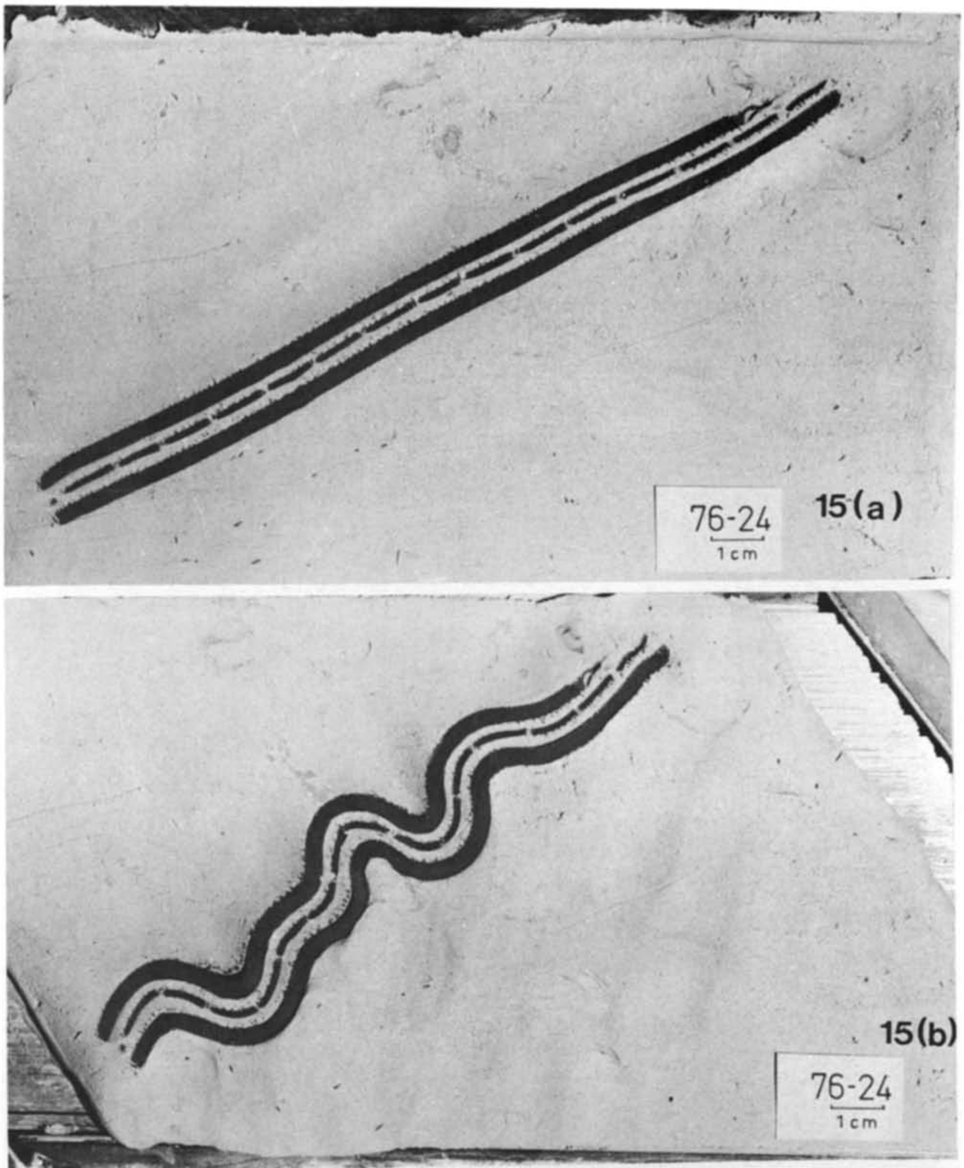


Fig. 13. Two rows of boudins compressed parallel to their layering. The upper row contains blocks of modelling clay (R = 5) and the lower one contains blocks (R = 3) of a softer material (mixture of modelling clay and painter's putty in equal proportions). The matrix is of painter's putty. The model has undergone a bulk-shortening of 48%. Note the contrast in behaviour of the boudin-blocks in the two layers.

Fig. 14. En échelon arrangement of modelling clay boudins after deformation. Initially, the trend of the boudinaged layer on the upper surface of the model made an angle of 7° with the compression direction; the 'layer' was dipping 70° towards the bottom side of the photograph. The pitch of the boudin-lines was 30° towards right.



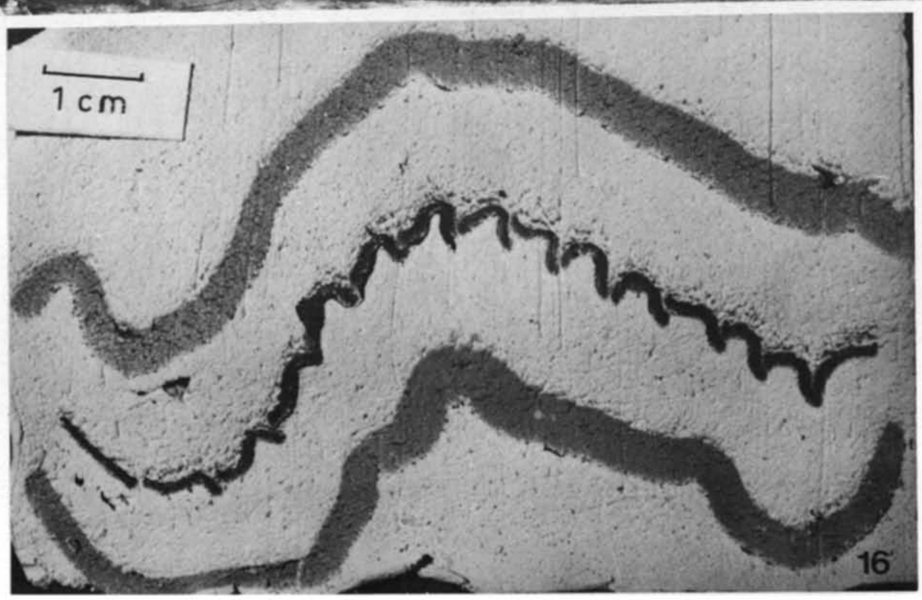


Fig. 15. Boudin-row of modelling clay enclosed between two weaker continuous layers. (a) Undeformed model. (b) Same model after deformation by simple shear. The whole unit was folded as a single close-spaced multilayer.

Fig. 16. Final stage of deformation of a multilayered model where the boudinaged layer and the enclosing continuous layers were widely spaced. In the initial stage of deformation only the boudin-blocks formed a series of separate half-waves while the continuous layers remained straight. At a later stage, the multilayer as a whole was folded into a large wave; the boudinaged layer with its internal half-wave pattern was folded concordantly with the larger wave of the multilayer.

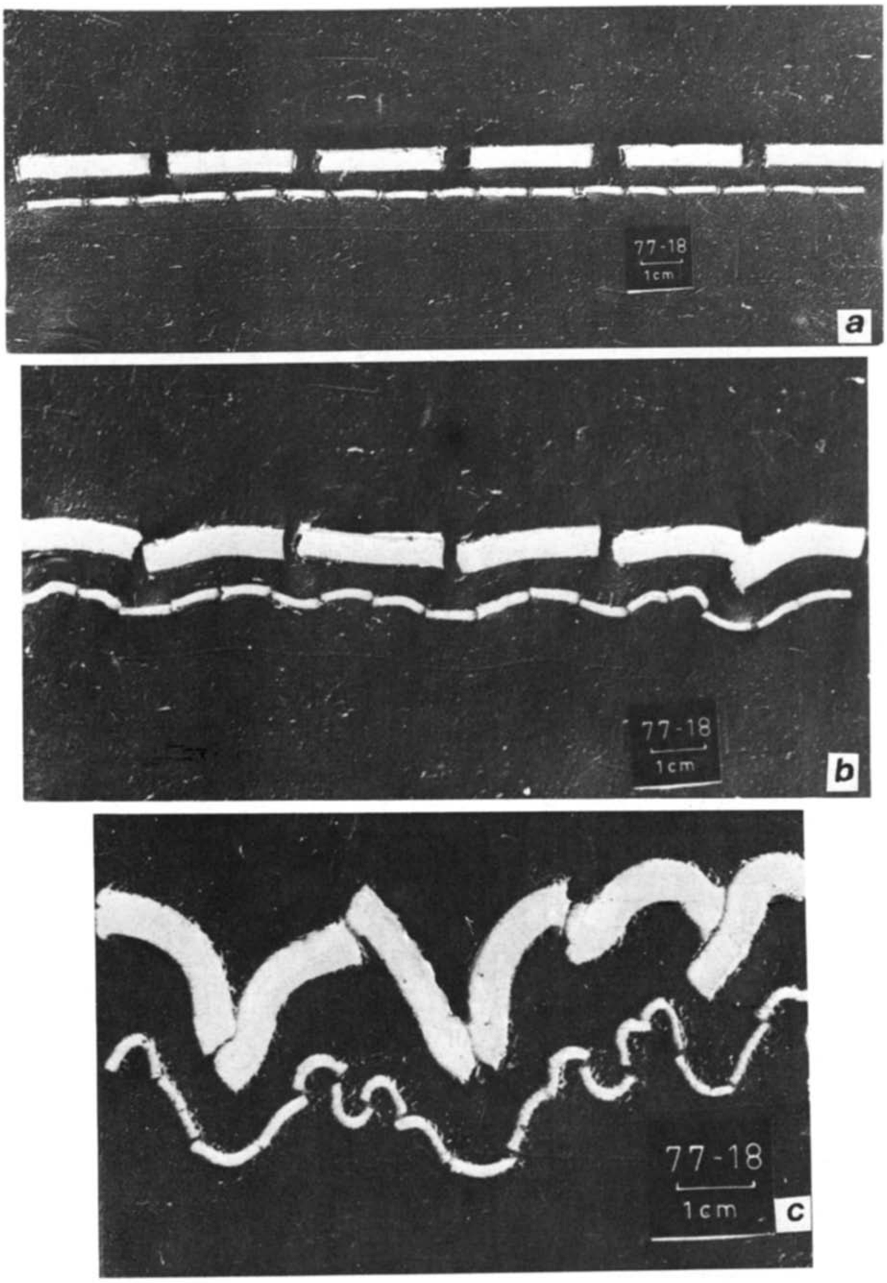


Fig. 17. Deformation of a test model in which two layers of boudin-blocks of dissimilar dimensions are closely spaced. (a) Undeformed model. (b) First stage of deformation where the layer with larger boudins remains more or less straight while the layer with smaller boudins is thrown into a folded pattern. (c) Final stage of deformation in which the row of larger boudins is folded to larger waves, thereby affecting the folds in the row of smaller boudins.

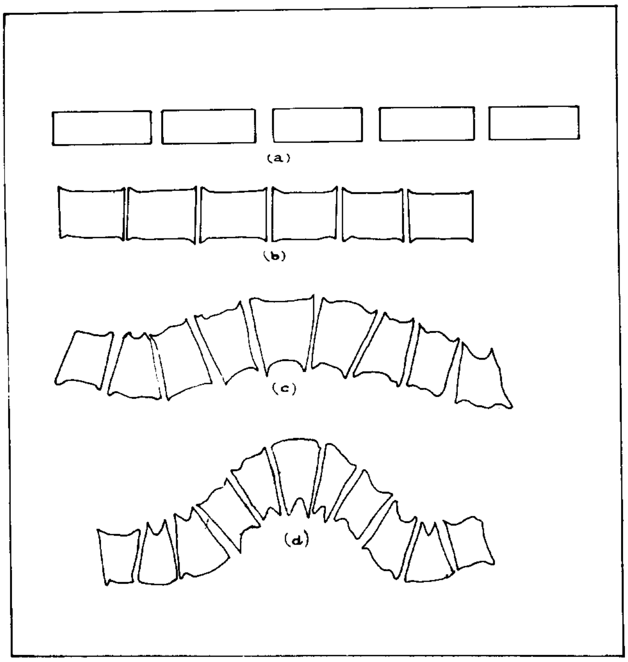


Fig. 12. Diagrammatic representation of deformation of boudins with a low competence contrast with the host rock. (a) Undeformed boudins. (b) Thickening of the boudins after a small amount of layer-parallel compression. Note the more or less symmetrical flame-shaped projections at the edges. (c) Initiation of fold-pattern in the boudinaged layer, with trapezoidal shapes of the boudins and flame-shaped projections at the edges. (d) Final stage of deformation with an accentuation of the trapezoidal form. Note that the 'flames' at the extrados are somewhat smoothened out.

Experiments with multilayers

Interference between boudin-row and continuous competent layers. When the boudin-row and the continuous layers were closely spaced, folding was essentially controlled by the continuous units and the row of boudins was folded harmoniously with the continuous layers (Fig. 15). When the boudin-row and the continuous, competent layers were widely spaced, the row of stiff boudins developed zigzag folds or folds with half-waves, while the thicker and less stiff continuous units were still undergoing layer-parallel homogeneous strain. At a later stage, when the continuous layers started to buckle into larger folds, the row of boudins with the internal folds was thrown into larger folds by contact strain (Fig. 16). If the boudins were fairly stiff in comparison with the matrix, sliding of the boudins over one another was fairly common.

Interference between two rows of boudins. In another series of experiments the models contained two parallel, closely spaced rows of boudins; the boudin-blocks in one of the rows were considerably larger than in the other. In the initial stage of deformation the row of smaller boudins was thrown into a series of folds while the row of larger boudins was not significantly folded (Fig. 17). The incompetent material between the larger boudins was squeezed out in the direction of extension and this caused an outward bending (say in the form of a synform in Fig. 18b) of the row of smaller boudins across the successive gaps between the larger boudins. With continued deformation, the row of larger boudins was itself thrown into zigzag folds.

Where a synform of the larger boudins coincided with a synform of the smaller boudins (Fig. 18c), the two folds remained more or less harmonious. However, where an antiform of larger boudins developed by the side of a synform of the smaller boudins, disharmonic folds developed by contact strain in the row of smaller boudins. When the initial spacing among boudins in a row was fairly large, the disharmony of the smaller boudins was very much accentuated and the orientation of the smaller boudins often became so irregular that no fold pattern could be distinguished in the row as a whole.

DISCUSSION

A layer undergoing buckle folding may develop boudinage on the limbs at a comparatively late stage of folding when the limbs of the fold have rotated into the extension quadrant of strain; these are the boudinaged folds. Again, for those cases of progressive homogeneous deformation where the nature of infinitesimal deformation remains invariant with time, a line once extended will in most cases never enter into a field of contraction. Although folded boudins can develop in the case of the pulsating strain ellipsoids of Ramberg (1975), such deformations are unusual and are unlikely to develop in real geologic situations. Although more general types of progressive non-coaxial deformation may involve later shortening of a stretched element, no instance of folded boudins has as yet been reported for a single period of deformation. While commenting on Talbot's (1970) findings regarding the determination of the orientation and shape of finite strain ellipsoids from folded or boudinaged veins, Elliott (1972) came to the conclusion that the deformation path for the development of folded boudins is a non-coaxial path of a very special type. From the absence of folded boudins in his area he concluded that such a special type of non-coaxial path is uncommon during one period of deformation: "during two periods of deformation the two finite strain ellipsoids are frequently at a large angle, and the combined path may approach the one required" (Elliott 1972, p. 263). Hence, folding of a boudinaged layer should commonly involve superposition of separate deformations, with a prolonged period of layer-parallel extension followed by a period of layer-parallel shortening.

Although the two cases (i.e. boudinaged folds and folded boudins) are easy to distinguish on theoretical grounds, in practice it has often been difficult to decide whether spatially associated boudins and folds developed in a single continuous deformation or by superposed deformations. No doubt, when a row of boudins in cross-section occurs over gentle fold-waves, the boudins can be interpreted as having formed earlier than the gentle folds. Again, we can arrive at the same conclusion when a number of short boudins occurs over the comparatively broad hinge-zone at the core of a fold irrespective of its tightness, since the hinge zone at the

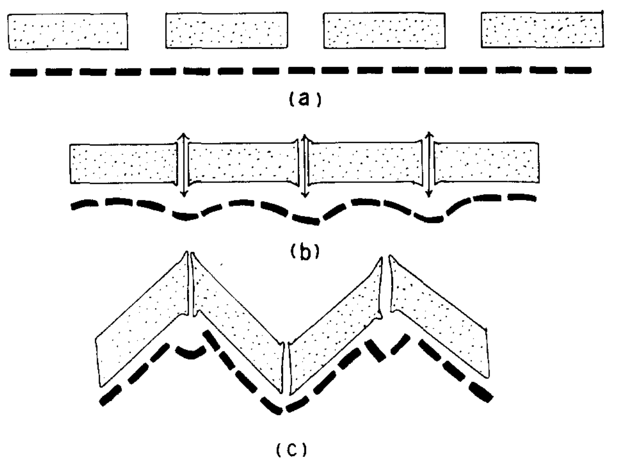


Fig. 18. Diagrammatic sketch showing interference pattern of two rows with boudins of different dimensions. (a) Undeformed model. (b) Folding of the row of smaller boudins; the folding is initiated by squeezing out of the incompetent material from the gaps between the larger boudins. (c) Row of larger boudins thrown into zigzag folds. At the centre where the synforms of both layers coincide, the folding of the two layers is harmonious; but in the adjacent antiforms the folding of the two rows is disharmonic.

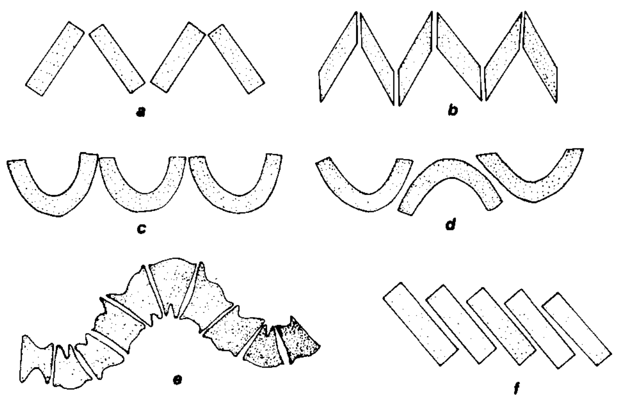


Fig. 19. Different styles of contortion and rotation of boudinaged layers.

core cannot undergo an extension across the axial surface. The present study shows that there are also other types of structures (e.g. herring-bone boudin patterns, folding of individual boudins into half-waves, imbrication of boudins, and trapezoidal boudins and their flame-like edges) which enable us to distinguish structures produced by superposed deformations from those formed in a single deformation. Such structures might also enable us to identify an uncommon type of progressive non-coaxial deformation where a layer first stretched and later entered the field of shortening.

The following conclusions may be drawn from the experimental results:

(1) If boudins with rectangular cross-sections are not individually folded but show a folded pattern by their systematic zigzag arrangements (Figs. 2, 8 and 19a), then we can conclude that during the second deformation the competence contrast between the boudins and the host rock was very large, so that only rigid rotations of the boudins were possible.

(2) If the folded pattern in cross-section shows a similar herring-bone arrangement of the boudins, but the boudins themselves are in the shapes of parallelograms as shown in Figs. 9 and 19b, then we can conclude that during the second (i.e. post-boudinage) deformation, the contrast in competence between the boudinaged layer and its host rock was moderately high.

(3) Moderately large competence contrasts are also indicated by folded boudins with shapes similar to those shown in Figs. 4, 10 and 19(c) & (d). The difference in the patterns is controlled by the difference in R values of the boudins as well as by the spacing between the boudins.

(4) Occurrence of trapezoidal boudins around folds and the development of flame-shaped structures at the boudin-edges indicate that during the second deformation the competence contrast between the boudinaged layer and the host rock was rather low (Figs. 11, 19e, 21 and 22). It is also noted that for the flame-shaped boudins the final ratios of arc-length to layer-thickness of the experimental folds were very low (even as low as 4.5). It is suggested that folding at such low competence contrasts resulted from mechanical instability induced by the discontinuous nature of the layer; that is by the very presence of boudinage structure.

(5) Lastly, the experiments indicate that a conspicuous imbrication of straight or weakly folded boudins (Figs. 3, 14 and 19f) is favoured when the principal axes of compression in the second deformation are distinctly oblique to the layering.

It is encouraging to find that each of these experimental types occurs in nature. While many of these experimental structures are similar to those found in the deformed boudinaged layers of the Väddö area in Sweden (Figs. 2–7), some of them are unrepresented. The absence of trapezoidal boudins and of flame-shaped projections at the boudin-edges indicates that, during the second deformation in the Väddö area, the competence contrast between the boudins and the host rock was fairly high.

Trapezoidal boudins with flame-shaped edges have, however, been found in the Precambrian Chhotanagpur gneiss in Bihar, Eastern India. The rock here is a banded gneiss showing a complex history of superposed deformation and migmatisation. Development of boudinage and pinch-and-swell structures in thin bands of amphibolite took place mainly during an early isoclinal folding; the boudinaged layers were subsequently refolded (Fig. 20). Depending on the mechanical property of the rocks during the later deformation, the boudins were deformed into a variety of shapes including rotated boudins, folded boudins, boudins with half-waves and boudins with trapezoidal cross-sections with flame-shaped edges (Figs. 21 and 22a). During the second phase of folding, the amphibolite bands, because of syn-migmatitic biotitization, appear to have reduced their competence contrast with the host gneisses.

Trapezoidal boudins have also been reported by Gindy (1952, fig. 5), Ramberg (1952, fig. 127) and

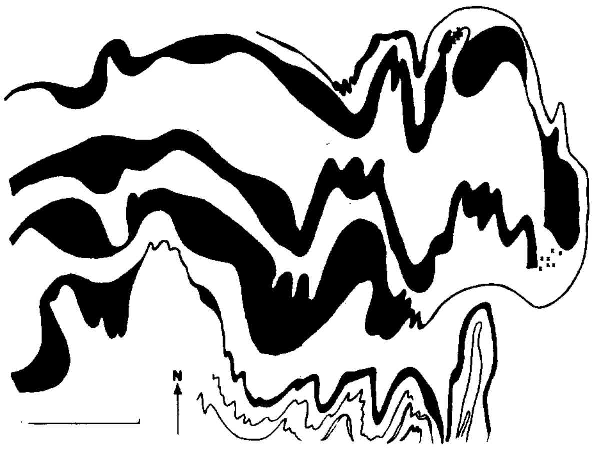


Fig. 20. Amphibolite (black) occurring in granite gneiss, Jashidih, Bihar. The boudinage and pinch-and-swell structures in the amphibolite formed during an early isoclinal folding. The structures were later deformed by upright folding. Scale bar represents 1 m.

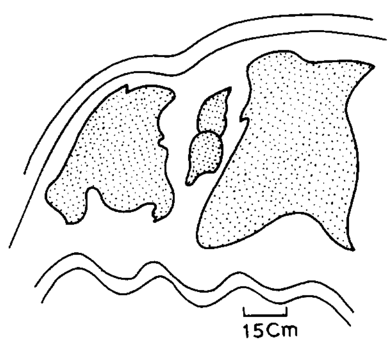
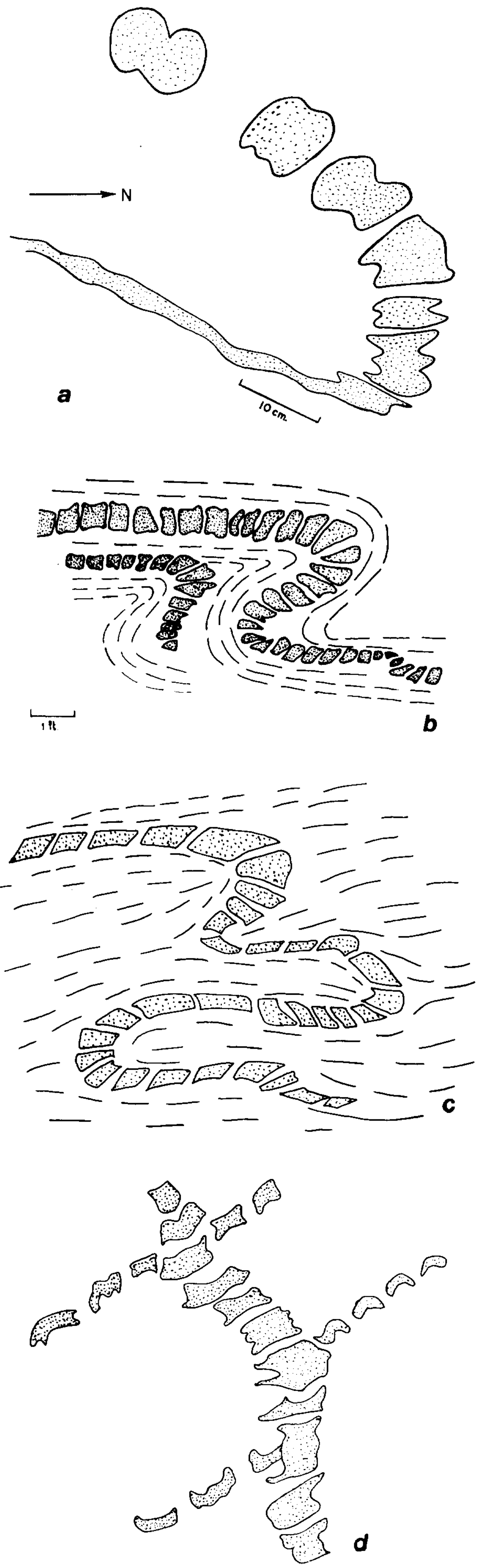


Fig. 21. Amphibolite boudins with trapezoidal and flame-shaped projections. Vertical railway cutting south of Jashidih Railway Station.



Wegmann (1965, fig. 14). The structural significance of such a morphology of the boudins was not discussed by these authors. Although Gindy (1952, fig. 5) did not discuss the time of development of boudinage with reference to the fold, Rast (1956) in discussing the same structure (Fig. 22b), assumed that the boudinage and the fold had developed together. This led him to cite this particular case as evidence of extension along the hinge zone of the fold. This, according to him, is clear evidence for uniform extension of competent layers of limbs and closure alike. Both Gindy's and Ramberg's examples (Figs. 22b & c), however, clearly show trapezium-like sections of the boudins at the fold closures. Thus, the boudinaged layer was extended along the extrados and was shortened along the intrados. This, as the experiments show, is expected if a boudinaged layer as a whole is subsequently shortened by folding and if the competence-contrast between the boudins and the host rock is rather small.

Fig. 22. Natural examples of trapezoidal boudins. (a) Trapezoidal boudins from the hinge zone of a late fold in the Precambrian rocks of Jashidih, Eastern India. The boudinaged layer is an amphibolite occurring within granite-gneiss. (b) Folded and boudinaged quartzite bands in semi-pelite (after Gindy 1952). (c) Folded amphibolite bands in quartzo-feldspathic gneiss (after Ramberg 1952). (d) Diagrammatic representation of deformed boudins (after Wegmann 1965, fig. 14).

Some of the features shown in Wegmann (1965, fig. 14), reproduced in Fig. 22(d), are also very similar to the experimental structures of folded boudinage: the trapezoidal shapes of some of the boudins, the flame-like projections at the boudin-edges and the half-wave fold-forms of some of the individual boudins. Although Wegmann's figure is a *diagrammatic* representation of the different stages of the structural evolution of dykes within a migmatitic complex, from their striking similarity with the experimental structures produced here, it would seem that Wegmann's representation of these different stages was based on accurate observation of *actual* field occurrences.

In the light of the experiments it may be suggested that in each of these cases (i.e. Gindy 1952, fig. 5, Ramberg 1952, fig. 127 and Wegmann 1965, fig. 14), it is likely that (i) the structures had formed by superposed deformations and (ii) in the interval between the periods of the first and the second deformations, there was a considerable reduction in the competence-contrast between the boudinaged layer and its host. It is significant that the structures shown in both Ramberg's and Wegmann's figures are all in metamorphosed basic rocks occurring within a migmatitic milieu where such reduction in competence-contrast is most likely to develop by granitization of the basic rocks.

Acknowledgements—The author is indebted to Prof. H. Ramberg for laboratory facilities and for many helpful suggestions at different stages of the work. The manuscript has been significantly improved by the comments and constructive criticism of Prof. S. K. Ghosh. Financial assistance from the Swedish Institute is gratefully acknowledged.

REFERENCES

Elliott, D. 1972. Deformation paths in structural geology. *Bull. geol. Soc. Am.* **83**, 2621–2638.

Gindy, A. R. 1952. The plutonic history of the district around Trawenagh Bay, Co. Donegal. *Q. Jl geol. Soc. Lond.* **108**, 377–411.

Ghosh, S. K. & Ramberg, H. 1976. Reorientation of inclusions by combination of pure shear and simple shear. *Tectonophysics* **34**, 1–70.

Ramberg, H. 1952. *The Origin of Metamorphic and Metasomatic Rocks*. University of Chicago Press, Chicago.

Ramberg, H. 1975. Particle paths, displacement and progressive strain applicable to rocks. *Tectonophysics* **28**, 1–37.

Rast, N. 1956. The origin and significance of boudinage. *Geol. Mag.* **93**, 401–408.

Talbot, C. J. 1970. The minimum strain ellipsoid using deformed quartz veins. *Tectonophysics* **9**, 47–76.

Wegmann, C. E. 1965. Tectonic patterns at different levels. *Geol. Soc. South Africa* **66** (1963) Annex (A. L. du Toit Mem. Lect. No. 8).