STRAIN AND MOVEMENT PICTURES IN COMPETENT LAYERS IN FLEXURAL FOLDING

— Deformation of Heterogeneously Layered Rocks in Flexural Folding (II) —

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(Received December 6, 1965)

I. INTRODUCTION

In the previous paper (HARA, 1966 in press) was examined deformation style of confined incompetent layers in flexural folding, in order to discuss some problems on the deformation of heterogeneously layered rocks in flexural folding. In this paper will be first examined deformation style of competent layers in flexural folding. Then mutual relationships between the deformation style of competent layer and that of incompetent layer in flexural folding will be discussed. Finally will be discussed mechanism of flexural folding in the thinly foliated rocks consisting of alternating competent layers and incompetent layers.

II. STRAIN AND MOVEMENT PICTURES DEVELOPED IN THE QUARTZ-RICH LAYERS DURING THE B_2^M -FOLDING AND B_1 -FOLDING

A. Dimensional Fabric of Quartz

In this section will be examined the strain and movement pictures in the deformation related to the formation of the B_2^M -fold and B_1 -fold (HARA, 1966) observed in four selected specimens, with special reference to the dimensional fabric of quartz developed in the quartz-rich layers during the folding.

Specimen I (H64IIX2019): Some macroscopic characteristics of the B_1 -fold observed in the specimen are enumerated as follows. 1) Style of the fold is correlated with that of intrafolial fold (cf. TURNER et al., 1963) which occurs as a tectonic inclusion in the foliation. 2) The fold is referred to the type of cylindrical plane fold with reference to its geometric property. 3) The form is asymmetric bilaterally across the axial surface. The fold has a monoclinic symmetry, (Fig. 1).

Microscopic observations of the quartz-rich layers and mica-rich layers involved in the fold in question indicate that mica flakes and quartz grains in both layers are markedly preferably oriented with their longest

dimension parallel to the axial surface but not to the layer boundaries, showing a distinct axial plane schistosity S_1' (flow cleavage after LERTH, 1905 and 1923). Strictly speaking, the direction of preferred dimensional orientation of quartz grains and mica flakes in the quartz-rich layers is parallel to that in the mica-rich layers, and that is constantly parallel to the axial surface, regardless of position on the fold. The attitude of the schistosity in the fold is not as to form fan-like arrangement. The cleavage-attitude in the mica-rich layers can be referred to the Type A. It is clear that, in the formation of the fold in question, the layer boundaries did not exercise any active control on the deformation, but that the principal mechanism of folding was heterogeneous passive flow parallel to the axial plane of the fold, and so that there was no available difference in

Fig. 1 Schematic sketch of a B_1 -fold observed in the specimen I. Q: quartz-rich layer. M: mica-rich layer

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JOURNAL OF THE GEOLOGICAL SOCIETY OF JAPAN,
Vol. 72, No. 9, p. 413-425 August 1966.

Fig. 2 Data for a mica-rich layer and a quartz-rich layer involved in a B_2^M -fold observed in the specimen II

- Diagram showing 32 positions for measurement of the direction of quartz grain orientation in the quartz-rich layer
- Attitude of the S_{2m} -cleavage in the mica-rich layer (M), and directions of quartz grain orientation at 32 positions (shown in Fig. 2-a) in the quartz-rich layer (Q). Dotted lines: directions of quartz grain orientation which is not statistically significant.
- Thickness of the quartz-rich layer (shown in Fig. 2-b) measured in a direction parallel to

the axial plane

- Thickness of the quartz-rich layer (shown in Fig. 2-b) measured normal to the bedding plane

the ductility between the quartz-rich layer and mica-rich layer during the stage of B_1 -folding. Therefore, the fold in question is referred to the type of flow fold (WEISS, 1959; WYNNE-EDWARDS, 1963) or passive flow fold (DONATH et al., 1963).

Specimen II (H62VI0215): Some macroscopic characteristics of the B_2^M -fold observed on the specimen are enumerated as follows. 1) The fold is referred to the type of cylindrical plane fold with reference to its geometric property. 2) The angle between the limbs is about 90° . 3) The form is nearly symmetric bilaterally across the axial surface. The fold has a near orthorhombic symmetry. 4) In the quartz-rich layers is not found any macroscopic structural surface cutting across the S_1 -surface except the S_{2q} -cleavage on the limb

In the interstratified mica-rich layers is found the S_{2m} -cleavage in one set, which is referred to the Type II, Type III and Type IV. Attitude of the S_{2m} -cleavage in the B_2^M -fold is of Type B, as shown in Fig. 2-b.

Dimensional fabric of quartz in a quartz-rich layer involved in the B_2^M -fold in question was analysed, with regard to the strain and movement pictures in the deformation related to the B_2^M -fold. The grain orientation on the plane normal to the fold axis (the plane of the ac-section) has been examined at 32 positions, as shown in Fig. 2-a. The result is illustrated in Fig. 2-b and Table I. The field on the thin section necessary for the measurement of 50 grains did not exceed 0.35 mm^2 at any position. The author (1965, in press) discussed a method for the kinematic interpretation of the dimensional fabric of quartz grains in a metamorphic tectonite, with regard to the data and ideas given by FAIRBAIRN (1950), FLINN (1956), BRACE (1955 and 1961) and TURNER et al. (1963). The quartz dimensional fabric for the present specimen and others examined in this paper will be interpreted according to the author's method.

As mentioned in the preceding page, the fold in question is of the type of cylindrical plane fold. On the assumption that the symmetry of the deformation is reflected in the symmetry of resultant structure (SANDER, 1948; PATERSON and WEISS, 1961), therefore, it may be inferred that at any position on the fold the principal strain axis Y is parallel to the fold axis. And, on the assumptions analogous to those for the kinematic interpretation of the quartz dimensional fabric in a concentric fold analysed previously by the author (1965, in press), the directions of vector mean, so far as they are statis-

Fig. 3 Diagram showing the trajectories of the principal strain axis Z through the mica-rich layer and quartz-rich layer in the B_2^M -fold drawn with reference to Fig. 2-b
Crosses : neutral axis.

tically significant, and their normals at any position on the ac-section are regarded as representing the directions of the principal strain axes X and Z respectively. Fig. 3 shows the trajectories of the principal strain axis Z through the fold, drawn on the basis of Fig. 2-b. It can be pointed out that the vector magnitude in the axial zones (positions 7 to 12 and positions 25 to 30) tends to decrease from the inner side to the outer side of the fold knee, and that the grain orientation at the outer side of the fold knee is not statistically significant. At the outermost side of the fold knee (positions 12 and 25) the direction of vector mean, though it is not statistically significant, is parallel to the foliation surface, unlike the case at the remaining positions in the axial zones that the directions of vector mean are commonly approximately parallel to the axial surface. Analogous pattern of the grain orientation is equally obvious for that in the surrounding quartz-rich layers.

On the basis of above descriptions and considerations, it can be said that the mechanism of formation of the B_2^M -fold in question (for the quartz-rich layer) is not passive flow parallel to the axial surface, but that the mechanism of B_2^M -folding involves neutral surface folding (ICKES, 1923; HILLS, 1963; HARA, 1965, in press), and that the neutral axis is developed at the outer side of the fold knee (in the vicinity of positions 11 and 12, and that of positions 25 and 26).

Specimen III (H65I2003): Some macroscopic characteristics of the B_2^M -fold observed within the specimen are listed as follows. 1) The fold is referred to the type of cylindrical plane fold with reference to its geometric property. 2) The form is asymmetric bilaterally across the axial surface. The fold has a monoclinic symmetry. 3) In the quartz-rich layer is not found any macroscopic structural surface cutting across the S_1 -surface.

Fig. 4 Data for a mica-rich layer and a quartz-rich layer involved in a B_2^M -fold observed in the specimen III

- Diagram showing 34 positions for measurement of the direction of quartz grain orientation in the quartz-rich layer
- Attitude of the S_{2m} -cleavage in the mica-rich layer (M), and directions of quartz grain orientation at 34 positions (shown in Fig. 4-a) in the quartz-rich layer (Q). Dotted lines : directions of quartz grain orientation which is not statistically significant.
- Thickness of the quartz-rich layer (shown in Fig. 4-b) measured in a direction parallel to the axial plane
- Thickness of the quartz-rich layer (shown in Fig. 4-b) measured normal to the bedding plane

Fig. 5 Diagram showing the trajectories of the principal strain axis Z through the mica-rich layer and quartz-rich layer in the B_2^M -fold drawn with reference to Fig. 4-b. Crosses : neutral axis

In the interlayered mica-rich layers is found the S_{2m} -cleavage in one set, which is referred to the Type II and Type III. Attitude of the S_{2m} -cleavage in the fold is of Type C, as shown in Fig. 4-b.

The quartz grain orientation in a quartz-rich layer involved in the B_2^M -fold in question has been analysed at 34 positions on the ac-section, as shown in Fig. 4-a. The results are shown in Fig. 4-b and Table 2. The field on the thin section necessary for the measurement of 50 grains did not exceed 0.35 mm^2 at any position. On the assumptions analogous to those for the kinematic interpretation of the quartz grain orientation in the previous specimens, the quartz grain orientation in question will be interpreted as follows. At any position on the fold the principal strain axis Y is parallel to the fold axis, and the directions of vector mean, so far as it is statistically significant, and their normals at individual positions are regarded as representing the directions of the principal strain axes X and Z respectively. The trajectories of the principal strain axis Z through the fold are drawn as shown in Fig. 5, on the basis of Fig. 4-b. In the points of inflection on the limbs (in the vicinities of the positions 13, 14, 16, 29, 30 and 31), the grain orientation is not statistically significant. At the positions 2 and 24, it is also not statistically significant. Analogous pattern of the grain orientation is equally obvious for that in the neighbouring quartz-rich layers.

From the nature of the quartz grain orientation mentioned above, it can be pointed out that the mechanism of formation of the B_2^M -fold in question (for the quartz-rich layers) involves neutral surface folding, and that the positions of the neutral axis do not seem to coincide strictly with the mid-point of the axial zones but they seem to be placed at the inner side of the fold knee (in the vicinities of the positions 2 and 24), showing prevalence of the tension side.

Specimen IV(H65I1707); Within the specimen are found two folded quartz-rich layers embedded in the mica-rich layers, that is, B_2^M -fold I and B_2^M -fold II in Fig. 6; see also Plates 2-B and 3 of the previous paper (HARA, 1966). At the fold knee, the thickness of the quartz-rich layer and that of the mica-rich layer involved in the B_{2m} -fold I are about 7 mm and 3 cm, respectively, and the former and the latter in the B_2^M -fold II are about 6 mm and 3 cm, respectively.

In the mica-rich layers is found the S_{2m} -cleavage in one set, which is referred to the Type II and Type IV. Attitude of the S_{2m} -cleavage in the B_2^M -fold I and that in the B_2^M -fold II are commonly of Type D, as shown in Fig. 6; see also Plates 3 and 2-B of the previous paper. The sheaf-arrangement of the S_{2m} -cleavage is markedly more clearly developed in the latter than in the former.

The fold I and fold II share the same fold axis and the same axial surface in common, showing nearly similar form. Both folds are commonly referred to the type of cylindrical plane fold with reference to its geometric property, and they have a monoclinic symmetry.

As shown in Fig. 6, a part of the right limb of the fold I and fold II is transposed along a S_{2q} -cleavage. As measured within the specimen, the angle between the limbs for the fold I is about 70° and the angle for the fold II is about 65° .

Distances between the axial surface and the S_{2q} -cleavage cutting across the right limb of the fold I and fold II were measured in two methods. Distances measured across the right limb in a direction normal

Fig. 6 Schematic sketch of a B_2^M -fold observed in the specimen IV, showing attitude of the S_{2m} -cleavage (dotted lines) in the fold Q: quartz-rich layer. M: mica-rich layer. ap: axial surface. 1: B_2^M -fold I. 2: B_2^M -fold II

Fig. 7 Directions of quartz grain orientation at 20 positions in the quartz-rich layer involved in the B_2^M -fold I observed in the specimen IV (see Fig. 6)

Dotted lines : directions of quartz grain orientation which is not statistically significant

Fig. 8 Directions of quartz grain orientation at 15 positions in the quartz-rich layer involved in the B_2^M -fold II observed in the specimen IV (see Fig. 2-6). Dotted lines : directions of quartz grain orientation which is not statistically significant

to that of the axial surface are not constant from the outer side of the fold I to the inner side of the fold II. There is a distinct decrease in distance toward the inner side of the fold II— T_1 (for the quartz-rich layer involved in the fold I) = 1.2 cm— T_2 (for that involved in the fold II) = 0.8 cm. As measured across the right limb along the layer surface, t_1 (for the quartz-rich layer involved in the fold I) = 1.6 cm— t_2 (for that involved in the fold II) = 1.0 cm.

Quartz grain orientation in the quartz-rich layers involved in the fold I and fold II has been examined at 35 positions on the ac-section, as shown in Figs. 7 and 8. The results are shown in Figs. 7 and 8 and Tables 3 and 4. On the assumptions analogous to those for the kinematic interpretation of the quartz grain orientation in the previous specimens, the quartz orientation data in question will be roughly interpreted as follows. The trajectories of the principal strain axis Z through the fold I and fold II for the quartz-rich layers are drawn as shown in Fig. 9, on the basis of Figs. 7 and 8.

Fig. 9 Diagram showing the trajectories of the principal strain axis Z through the mica-rich layers and quartz-rich layers in the B_2^M -fold drawn with reference to Fig. 6, 7 and 8. N : neutral surface. Cross : neutral axis. Q : quartz-rich layer. M : mica-rich layer. 1 : B_2^M -fold I. 2 : B_2^M -fold II

For the fold I of the quartz-rich layers, vector magnitude is higher in the inner side of the fold knee than in the outer side, and in the middle part the grain orientation is not statistically significant. While in the limbs the grain orientation shows generally low vector magnitude, and at 11 positions of 14 positions it is not statistically significant.

From the nature of the quartz grain orientation mentioned above, it may be pointed out that the mechanism of formation of the B_2^M -fold I (for the quartz-rich layer) involves neutral surface folding, and that the neutral surface is developed along the upper middle horizon of the quartz-rich layer.

For the fold II of the quartz-rich layer, in the limbs and the middle to inner part of the fold knee the grain orientation is statistically significant, but in the outer side of the fold knee it is not statistically significant. Generally, the directions of vector mean, which is statistically significant, are radially arranged on the form surface. From the nature of the quartz grain orientation described above, it may be pointed out that the mechanism of formation of the B_2^M -fold II for the quartz-rich layer involves neutral surface folding, and that the neutral axis is developed in the outermost side of the fold knee.

On the basis of above descriptions and considerations, it may be pointed out that the strain and movement

pictures in the deformation related to the B_2^M -fold I are not strictly identical with those for the B_2^M -fold II, that the discrepancy between the former and the latter reflects difference in intensity of the lateral compressive force acting on the layers concerned during the B_2^M -folding, that is, the lateral compressive force was considerably greater for the B_2^M -fold II than for the B_2^M -fold I, and so that the variations in distances T and t mentioned above reflect the variation in amount of flattening normal to the axial surface which is dependent upon the variation in intensity of the lateral compressive force.

B. Variation in thickness of the quartz-rich layers involved in the B_2^M -folds

In this section will be examined the variation in thickness of the quartz-rich layers involved in the B_2^M -folds, and then mutual relationship between the nature of variation in thickness and the pattern of strain and movement pictures assumed from the quartz dimensional fabric for those quartz-rich layers.

"DE SITTER (1958) has calculated that crustal shortening by the method of flexure folding alone can never exceed 36 per cent of the original length of the beds, and he had suggested that one method by which crustal shortening can be further developed is by flattening the previously formed flexure fold——" (from RAMSAY, 1962). While, RAMSAY (1962) indicated some examples in which modification of the constancy of thickness of the layer is induced before the folded layers have reached a condition of maximum shortening by flexure alone, and he concluded, "many natural flexural folds appear to have been modified by flattening."

Fig. 2-d shows the variation in thickness of a quartz-rich layer involved in the B_2^M -fold in the specimen II, in which quartz dimensional fabric was examined in the preceding section, as measured at right angles to the S_1 -surface through the fold. The thickness of the layer is not constant from the fold knee to the limbs. Fig. 2-c shows the variation in thickness of the same layer as measured in the direction parallel to the axial surface. Here is a distinct variation with minimum values at the fold knees. Those figures of the variation in the layer-thickness, shown in Figs. 2-d and c, conform strictly neither to the ideal figure for the similar fold nor that for the concentric fold.

With reference to the pattern of quartz dimensional fabric, it was clarified that the mechanism of B_2^M -folding of the quartz-rich layer in question involves neutral surface folding, and that the neutral axis was developed at the outer side of the fold knee (Fig. 3). The nature of variation in the layer-thickness, shown in

Figs. 2-c and d, appears to correspond closely to the strain picture of Fig. 3.

Fig. 4-d shows the variation in thickness of a quartz-rich layer involved in the B_2^M -fold in the specimen III, in which quartz dimensional fabric was examined in the preceding section, as measured at right angles to the S_1 -surface through the fold, giving a rough impression that the layer is of constant thickness. Broadly speaking, therefore, the geometry of the fold appears to conform with the theoretical condition of the concentric fold. However, detailed observation of the layer indicates that there is a slight increase in thickness toward the limbs. Measurements of thickness of the same layer have been made in the direction parallel to the axial surface, as shown in Fig. 4-c. Here is a great variation with minimum values at the fold knee.

With reference to the pattern of quartz dimensional fabric, it was clarified that the mechanism of B_2^M -folding of the quartz-rich layer in question involves neutral surface folding, and that the neutral axis was developed at the inner side of the fold knee (Fig. 5). The nature of variation in the layer-thickness, shown in Figs. 4-c and d, appears to correspond closely to the strain picture of Fig. 5.

Fig. 10 shows the variation in thickness of the layers (i, g, and d-e-f) involved in the flexural fold of Type II shown in Fig. 3 of the previous paper (HARA, 1966), which was previously described by the author (1963), as measured at right angles to the layer surface. The layer d-e-f and layer g are involved in the com-

Fig. 10 The variation in thickness of the layers involved in the flexural fold of Type II shown in Fig. 3 of the previous paper (HARA, 1966), as measured at right angles to the layer surface. a) Diagram for the layer i. b) Diagram for the layer g. c) Diagram for the layers d, e and f. H: position of hinge

pression side of the fold in question, while the layer *i* is involved in the tension side. Fig. 10-c and b for the former two show great variation in thickness with maximum values at the fold knee, though increasing in thickness toward the fold knee is greater for the layer e-d-f than for the layer g. While, Fig. 10-a shows approximately constant thickness for the layer *i*. Therefore, it can be pointed out that the nature of variation in the layer-thickness, shown in Fig. 10, appears to correspond closely to the stress and strain picture which was previously analysed by the author (1963, plate 54-4). On the basis of above descriptions and considerations, it may be concluded that detailed investigations of the cross-sectional shapes of the flexural folds can also be used to determine the type of flexural folding (Type I or Type II) and the position of neutral axis in the folded layer (Table 6).

III. RELATIONSHIPS BETWEEN DEFORMATION STYLE OF THE QUARTZ-RICH LAYERS AND THAT OF THE MICA-RICH LAYERS IN THE FOLDING

Deformation style of the mica-rich layers in the B_2^M -folding or B_1 -folding is indicated by types of cleavage and orientation patterns of the cleavage of particular type in any B_2^M -fold or B_1 -fold. It has been stated by many authors (LEITH, 1923; WILSON, 1946; NEVIN, 1949; and others) that strain-slip (including fracture) cleavage in the incompetent layers, which occurs as the axial plane cleavage in a fold, is due to the shearing stress developed parallel to the layer boundaries during the buckling of surrounding competent layers, applying the strain ellipsoid theory of BECKER. While, DE SITTER (1956) says, "...the cleavage is not restricted to the flanks. It is equally well developed on the hinges, even when they are broad crestral zones where the dragging effect of the competent beds is surely absent." And he (1956) regards much of the axial plane cleavage, which is developed in the folded incompetent layers, to be slip-planes in the direction of dilatation, which occurs in a direction parallel to the axial surface in the folding. On his modeled investigation of movement picture developed in the incompetent layer confined between competent layers during folding, WILLIAMS (1961) concluded, "...the effect of bedding drag is negligible, and the structures described as slaty cleavage, fracture cleavage, and drag folds can be explained by the laminar flow of the incompetent whilst accomodating itself to the interspaces determined by the more competent layers." Another interpretation on the axial plane cleavage

developed in the rocks during passive folding was represented by DONATH et al. (1963): "Macroscopic slip surfaces may develop attendant to passive flow in which case they possibly represent velocity discontinuities in flow...."

Movement picture developed in the mica-rich layers during the B_2^M -folding seems to be represented by four types of S_{2m} -cleavage, Type I, Type II, Type III and Type IV, and four types of orientation pattern of the S_{2m} -cleavage of particular types in the B_2^M -fold, Type B, Type C, Type D and Type E. Therefore, if the S_{2m} -cleavages of four types possess the same kinematic significance that they are commonly parallel to the direction of mass elongation in the system concerned, as suggested by SORBY (1853), DE SITTER (1956), WILLIAMS (1961) and others, at this time the B_2^M -fold for the mica-rich layer is generally referred to the type of passive fold. On the basis of above assumption, will be examined the strain picture corresponding to four types of orientation pattern of the S_{2m} -cleavage in the B_2^M -fold. The specimens for the orientation patterns of Type B, Type C and Type D correspond respectively to the specimens II, III, and IV, where deformation styles of the quartz-rich layers in the B_2^M -folding were examined with reference to the quartz grain orientation in the preceding pages. However, for the examination of the orientation pattern of Type E will be used the specimen examined previously by the author (1963).

Even for the cylindrical passive fold, the fold axis is not necessarily normal to the direction of flow (WEISS, 1955, and TURNER et al., 1963). For the B_2^M -folds of the mica-rich layer in question, which are commonly referred to the type of cylindrical plane fold, however, it is assumed that the fold axis is generally normal to the direction of flow, and further that the principal strain axis *Y* coincides with the fold axis at any position of the fold. The principal strain axes *Z* and *X* correspond respectively to the directions normal and parallel to the S_{2m} -cleavage surface on the ac-section. Figs. 3, 5 and 9 show the trajectories of the principal strain axis *Z* through the mica-rich layer involved in the B_2^M -folds in question, which were drawn with reference to the orientation patterns of the S_{2m} -cleavage, Type B, Type C and Type D for the specimens II, III and IV, respectively.

WILLIAMS (1961) says, "... the directions of flow planes can vary according to the degree of incompetence of the material, and the character and degree of flexuring of the confining competent beds." In Figs. 3, 5 and 9 can be examined mutual relationships between the trajectories of the principal strain axis *Z* through the quartz-rich layer and those through the mica-rich layer, that is, mutual relationships between the

strain picture in the quartz-rich layer and that in the mica-rich layer during the B_2^M -folding. In those three cases, the former is consistently related to the latter, indicating that during the B_2^M -folding deformation style of the quartz-rich layer exercises generally an active control on that of the adjacent mica-rich layer. The Type B, Type C and Type D of orientation pattern of the S_{2m} -cleavage in the B_2^M -fold are commonly associated with the neutral surface folding in each of the quartz-rich layers during the whole stage of B_2^M -folding. For the Type B of orientation pattern of the S_{2m} -cleavage in the mica-rich layer, the neutral axis for the B_2^M -folding in the surrounding quartz-rich layer is developed in the outer side of fold knee, showing prevalence of the compression side, (Fig. 3). The presence of the neutral axis in the outer side of fold knee, that indicates high intensity of the lateral compressive force acting on the system concerned, appears to be favourable to cause the development of the S_{2m} -cleavage at the bottom as well as at the top of knee of the fold for the surrounding mica-rich layers. For the Type C of the S_{2m} -cleavage-orientation, the neutral axis for the B_2^M -folding in the surrounding quartz-rich layer is developed in the inner side of fold knee, showing prevalence of the tension side. The prevalence of tension side in the B_2^M -fold for the quartz-rich layer appears to be responsible for the development of the tension side in the mica-rich layer at the bottom of fold knee (Fig. 5). For the Type D of the S_{2m} -cleavage-orientation, the directions of the principal strain axis X in the inner side of knee (compression side) of the B_2^M -fold for the quartz-rich layer are radial. The knees for the B_2^M -folds I and II are markedly broad crestral zones, unlike the cases (Specimens II and III) mentioned above. In the B_2^M -fold for the quartz-rich layer of Fig. 3, the neutral axis is commonly developed in the outer side of fold knee. Therefore, it may be said that the radial arrangement of the principal strain axis X in the broad knee of the quartz-rich layer is responsible for the sheaf arrangement of the S_{2m} -cleavage in the surrounding mica-rich layer. Discrepancy between two types of the orientation pattern of the principal strain axes Z and X in the compression side of the quartz-rich layer, shown in Figs. 2-b and 4-b and Figs. 7 and 8 respectively, comes into question in the dynamic and rheologic sense.

In three examples discussed above, the neutral axis is commonly developed within individual quartz-rich layers. While the Type E of the cleavage-orientation in the fold appears to be developed in the flexural fold of Type II, where the strain picture corresponding to the neutral surface folding is developed in a unit comprising several quartz-rich layers and mica-

rich layers, showing a combined action of those layers involved in the unit (HARA, 1963). For the flexural fold of this type, that in the mica-rich layers involved in the outer side of fold knee (layers j, l, n and p in Fig. 3 of the previous paper; HARA, 1966) was not developed any transversal cleavage reflects passive flow of incompetent micaceous material parallel to the layer surfaces occurring in the tension side of the neutral surface folding, and that in the mica-rich layers involved in the inner side of fold knee (layers d, f and h in Fig. 3) was developed transversal cleavage parallel or subparallel to the axial surface reflects passive flow of incompetent micaceous material traversing the layer surfaces occurring in the compression side of the neutral surface folding. It is clear that the cleavage-attitude of Type E corresponds to the presence of the neutral axis at the middle to inner part of knee of the folded unit in question. Therefore, it can be assumed that, if the neutral axis is developed at the outermost side of knee of the folded unit, the transversal cleavage is induced into all of the mica-rich layers involved in the fold knee, showing a fan-like arrangement with upward convergence.

The cleavage-attitude of Type A, in which the axial plane cleavage in the mica-rich layers is oriented parallel to the axial plane at any position of fold, was found in the B_1 -fold, which is referred to the type of flow fold.

Therefore, it may be said that the deformation style of the quartz-rich layer in the folding can be indirectly inferred from that of the adjacent mica-rich layer, that is, the orientation pattern of the axial plane cleavage in the mica-rich layer in any fold (Table 6), if the fold form is not markedly acute. However, this method must be carefully used on individual layers because the lateral compressive force acting on the individual layers during the folding appears to show variable intensity, like in the case of the specimen IV described in the preceding pages (cf. CLOOS, 1947; RAMSAY, 1962). In the B_2^M -fold, generally, the layer boundaries do not appear to occur as discrete displacement discontinuity, separating the buckled quartz-rich layer from the mica-rich layer deformed by passive flow (cf. TURNER et al., 1963). Flexural slip on the layer boundaries, which is generally believed to be the most important process in the flexural folding of the heterogeneously layered rocks (KNOPF and INGERSON, 1938; NEVIN, 1949; FAIRBAIRN, 1949; BILLINGS, 1952; DE SITTER, 1956; BELOUSSOV, 1962; and others), is considered to play no or little part in the deformation related to the formation of the B_2^M -folds.

IV. MECHANISM OF FLEXURAL FOLDING IN THE THINLY FOLIATED ROCKS CONSISTING OF ALTERNATING COM-

PETENT LAYERS AND INCOMPETENT LAYERS

In the limbs of many B_2^M -folds is frequently found the S_{2q} -cleavage formed by transposition of the quartz-rich layers and mica-rich layers (Fig. 1 of HARA, 1966). The S_{2q} -cleavage in the mica-rich layers coincides with the S_{2m} -cleavage. The S_{2q} -cleavage corresponds to the axial plane cleavage in relation to the B_2^L -fold.

Two types of transposition of the quartz-rich layer along the S_{2q} -cleavage were found. In the first type, the S_{2q} -cleavage is displayed as "discrete discontinuity such as separated cards in a deformed deck" (TURNER et al., 1963, p. 367), as shown in Fig. 11-a. The S_{2q} -cleavage of this type is named S_{2q}^F . In the second type, the S_{2q} -cleavage is displayed as displacement discontinuity such as "a very narrow domain of intense deformation" (TURNER et al., 1963, pp. 367—368, Fig. 10-1c), as shown in Fig. 11-b. The S_{2q} -cleavage of this type is named S_{2q}^S . The S_{2q} -cleavages of those two types, S_{2q}^F and S_{2q}^S , occur commonly as the structure of the same generation (Fig. 12-a).

Quartz dimensional fabric in a quartz-rich layer showing the S_{2q} -cleavage (Specimen V H62VI0118—Fig. 12-a) has been analysed on the ac-section, giving the result of Fig. 12-b and Table 5. In the narrow zone of intense deformation corresponding to the S_{2q}^S -cleavage, the direction of grain orientation is generally parallel to the length of the zone (see Plate 1-C of the previous paper (HARA, 1966)), showing high degrees of grain orientation. Within the displaced domain on either side, the pattern of grain orientation is not homo-

geneous, as shown in Fig. 2-12-b and Plate 1-C of the previous paper. Broadly speaking, the pattern is essentially the same as that commonly developed in the neutral surface fold (e. g., that for the B_2^M -folds examined in the preceding pages, and that for recrystallized bent steel bar experimentally given by SEIDL, 1934). For the present specimen, it is clear that the formation of S_{2q}^S -cleavage and the neutral surface folding in the quartz-rich layer are ascribed to the same generation. In this specimen are also found the S_{2q}^S -cleavage and S_{2q}^F -cleavage as the structure of the same generation. It may be therefore said that there is no evidence suggesting that the S_{2q}^S -cleavage, S_{2q}^F -cleavage and neutral surface fold (most B_2^M -folds) represent three different sets of physical conditions on the basis of above-described data and considerations.

Quartz dimensional fabric in a thicker quartz-rich layer (thickness at the fold hinge=2.5 cm) showing a B_2^L -fold has been previously examined by the author (1965, in press). The mechanism of the B_2^L -folding, which was inferred from the quartz dimensional fabric in question, involves neutral surface folding. The S_{2q}^S -cleavage, whose quartz grain orientation was examined in the preceding paragraph, is for a thinner quartz-rich layer embedded in the mica-rich layer within the specimen for the B_2^L -fold in question. The quartz-rich layer showing the B_2^L -fold is not cut across by the S_{2q} -cleavage. Attitude of the S_{2q} -cleavage in the B_2^L -fold observed within the specimen in question is as to form weakly fan-like arrangement, which is similar to the Type B of the orientation pattern of the S_{2m} -cleavage in the B_2^V -fold.

On the basis of above descriptions and considerations,

Fig. 11 Two types of transposition of the quartz-rich layer along the S_{2q} -cleavage

Fig. 12-b Directions of quartz grain orientation at 13 positions in the quartz-rich layer displaced along the S_{2q} -cleavage in Fig. 12-a. Dotted lines: directions of quartz grain orientation which is not statistically significant

it may be pointed out that, in most cases, the mechanism of B_2^L -folding involves the processes of shear folding (corresponding to the formation of the S_{2q} -cleavage and S_{2m} -cleavage) and neutral surface folding (corresponding to the formation of the B_2^L -fold in the thick quartz-rich layer and B_2^M -fold in the thin quartz-rich layer according to the competence law for flexural fold). Generally, geometric and genetic relationships between the B_2^L -fold and the S_{2q} -cleavage and B_2^M -fold appear to be essentially the same as those between the B_2^M -fold and the S_{2m} -cleavage and B_2^S -fold. In the deformation related to the formation of the S_{2m} -cleavage in the mica-rich layers, generally, the mechanism of crinkling (B_2^S -folding) of the S_1 -schistosity

Fig. 12a Sketch of coexisting two types of S_{2q} -cleavage (S_{2q})
Q: quartz-rich layer. B_2^m : B_2^M -fold

Fig. 13 B_2 -fold displayed as the enveloping surface for the B_2^L -folds
ap: axial surface of B_2^L -fold

(constructed by parallel arrangement of mica flakes) appears to involve flexural slip, a process analogous to the bend gliding in deformed crystal. DONATH et al. (1963) say, "—Most 'slip' or 'shear' folds are probably passive flow folds in which differential displacement on secondary foliation is incidental to rather than essential to the folding process." For the present author, however, most shear folds in the heterogeneously layered rocks, which have macroscopic slip surfaces, do not seem to be passive flow fold, but they seem to be formed by combined action of the processes of shear folding and neutral surface folding in such a fashion as is the case of the formation of the B_2^L -fold.

Within outcrops, generally, the axial surfaces of the B_2^L -folds, which are ascribed to the same generation, have a constant trend, and the enveloping surface (cf. TURNER et al., 1963) for those B_2^L -folds shows a fold form, whose wave-length is several meters or more (Fig. 13). The fold displayed by the enveloping surface is named B_2 -fold. The axial surface of the B_2 -fold is generally parallel to that of the B_2^L -fold. Geometric and genetic relationships between the B_2 -fold and B_2^L -fold appear to be essentially the same as those between the

B_2^L -fold and B_2^M -fold and those between the B_2^M -fold and B_2^S -fold. It is probable that the B_2^L -folding was responsible for the development of the B_2 -fold, that is, the formation of the B_2 -fold was due to a combination of the B_2^S -folding (including formation of the S_{2m} -cleavage—in the mica-rich layer), B_2^M -folding (including formation of the S_{2q} -cleavage—in the thin quartz-rich layer) and B_2^L -folding (in the thick quartz-rich layer). On his investigation of oolite deformation in the South Mountain Fold, Maryland, CLOOS (1947, pp. 877–878) observed, “a deformation of 10 per cent can already be recognized easily in an alignment of the longest axes of ooids, but matrix and mud pellets remain unaffected. Twenty per cent deformation is very obvious—If a bedding plane has been included in the thin section it is mildly undulating—”, and at a “thirty per cent deformation—cleavage begins to appear.... Bedding planes may suffer considerable crenulation—” The development of the crenulation and cleavage is in the direction of the maximum extension in the system concerned, which is assumed from the shapes of deformed ooids. The genetic relationship between the

development of bedding plane crenulation and transversal cleavage demonstrated by CLOOS, with regard to the mean pure strain in the system concerned, may be correlated with that between the B_2^S -fold and S_{2m} -cleavage and that between the B_2^M -fold and S_{2q} -cleavage. RAMSAY (1962) says, “the most important process that leads to their development (most natural folds of similar type) is that of flattening and, in particular, that of differential flattening in an ac-section. This variable flattening leads to differential shear and the production of folds.” The process that led to the development of the B_2 -folds appear to be essentially the same as that for the development of the fold of similar type assumed by RAMSAY (cited above), although the mechanism of flattening of the thinly foliated rocks consisting of alternating quartz-rich layers and mica-rich layers was due to flexural folding in various wavelengths (corresponding to the formation of B_2^S -fold, B_2^M -fold and B_2^L -fold) according to the competence law. The S_{2m} -cleavage and S_{2q} -cleavage (corresponding to the type of strain-slip cleavage) were produced

Table 1 Summary of grain-orientation data for Specimen II

Position No.	Vector Magnitude (%)	Probability	Significant
1	44.5	$<10^{-4}$	Yes
2	52.4	$<10^{-5}$	Yes
3	43.0	$<10^{-4}$	Yes
4	31.3	<0.01	Yes
5	13.2	>0.40	No
6	40.3	$<10^{-3}$	Yes
7	72.3	$<10^{-10}$	Yes
8	65.4	$<10^{-5}$	Yes
9	44.9	$<10^{-4}$	Yes
10	32.4	<0.01	Yes
11	20.4	>0.10	No
12	5.9	>0.80	No
13	51.6	$<10^{-5}$	Yes
14	66.2	$<10^{-5}$	Yes
15	33.9	<0.01	Yes
16	26.8	<0.03	Yes
17	24.5	<0.05	Yes
18	42.5	$<10^{-3}$	Yes
19	21.5	>0.10	No
20	18.3	>0.10	No
21	35.4	<0.01	Yes
22	41.7	$<10^{-3}$	Yes
23	54.8	$<10^{-5}$	Yes
24	29.3	<0.02	Yes
25	11.9	>0.40	No
26	10.8	>0.50	No
27	35.4	<0.01	Yes
28	50.2	$<10^{-5}$	Yes
29	65.9	$<10^{-5}$	Yes
30	73.9	$<10^{-10}$	Yes
31	63.5	$<10^{-5}$	Yes
32	61.7	$<10^{-5}$	Yes

Table 2 Summary of grain-orientation data for Specimen III

Position No.	Vector Magnitude (%)	Probability	Significant
1	54.2	$<10^{-5}$	Yes
2	7.6	>0.70	No
3	70.2	$<10^{-10}$	Yes
4	76.0	$<10^{-10}$	Yes
5	86.6	$<10^{-15}$	Yes
6	30.8	<0.01	Yes
7	36.6	<0.01	Yes
8	39.8	$<10^{-3}$	Yes
9	59.2	$<10^{-5}$	Yes
10	75.2	$<10^{-10}$	Yes
11	37.0	$<10^{-3}$	Yes
12	35.2	<0.01	Yes
13	19.8	>0.10	No
14	21.2	>0.10	No
15	33.6	<0.01	Yes
16	22.3	>0.05	No
17	82.0	$<10^{-10}$	Yes
18	77.2	$<10^{-10}$	Yes
19	48.0	$<10^{-5}$	Yes
20	38.8	$<10^{-3}$	Yes
21	22.0	>0.05	No
22	92.2	$<10^{-15}$	Yes
23	82.0	$<10^{-10}$	Yes
24	59.8	$<10^{-5}$	Yes
25	9.2	>0.60	No
26	41.2	$<10^{-3}$	Yes
27	68.6	$<10^{-10}$	Yes
28	51.6	$<10^{-5}$	Yes
29	21.8	>0.05	No
30	21.4	>0.05	No
31	10.2	>0.50	No
32	5.8	>0.80	No
33	28.4	<0.02	Yes
34	25.6	<0.04	Yes

Table 3 Summary of grain-orientation data for Specimen IV (fold I)

Position No.	Vector Magnitude (%)	Probability	Significant
1	21.2	>0.10	No
2	17.2	>0.20	No
3	48.2	<10 ⁻⁵	Yes
4	22.3	>0.05	No
5	19.9	>0.10	No
6	68.2	<10 ⁻¹⁰	Yes
7	24.6	<0.05 ⁻⁴	Yes
8	14.2	>0.30	No
9	73.3	<10 ⁻¹⁰	Yes
10	45.3	<10 ⁻⁴	Yes
11	6.4	>0.80	No
12	78.2	<10 ⁻¹⁰	Yes
13	18.7	>0.10	No
14	21.2	>0.10	No
15	51.3	<10 ⁻⁵	Yes
16	15.0	>0.30	No
17	18.5	>0.10	No
18	8.6	>0.60	No
19	12.2	>0.40	No
20	10.8	>0.50	No

Table 4 Summary of grain-orientation data for Specimen IV (fold II)

Position No.	Vector Magnitude (%)	Probability	Significant
1	11.4	>0.50	No
2	36.0	<0.01	Yes
3	66.9	<10 ⁻⁵	Yes
4	1.0	<0.99	No
5	36.7	<0.01	Yes
6	68.8	<10 ⁻¹⁰	Yes
7	7.9	>0.70	No
8	35.8	<0.01	Yes
9	84.3	<10 ⁻¹⁵	Yes
10	16.2	>0.20	No
11	44.2	<10 ⁻⁴	Yes
12	60.3	<10 ⁻⁵	Yes
13	23.9	>0.05	No
14	24.5	<0.05	Yes
15	42.3	<10 ⁻³	Yes

Table 5 Summary of grain-orientation data for Specimen V

Position No.	Vector Magnitude (%)	Probability	Significant
1	25.2	<0.05	Yes
2	31.3	<0.01	Yes
3	12.2	>0.40	No
4	45.0	<10 ⁻⁴	Yes
5	48.1	<10 ⁻⁵	Yes
6	61.1	<10 ⁻⁵	Yes
7	97.9	<10 ⁻²⁰	Yes
8	96.0	<10 ⁻²⁰	Yes
9	53.5	<10 ⁻⁵	Yes
10	25.0	<0.05	Yes
11	14.4	>0.30	No
12	9.7	>0.60	No
13	4.9	>0.80	No

by differential shear which was led by differential flattening. B_2^M -folds referred to the noncylindrical plane fold were produced in response to variation in the amount of flattening in the axial plane (cf. RAMSAY, 1962). Generally, folding mechanism analogous to that for the B_2 -fold, which was described and discussed up to now, appears to play an important part in the processes of folding in the thinly foliated rocks consisting of alternating competent layers and incompetent layers.

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Table 6 Summary of data

Type of folding in the multilayered system consisting of alternating quartz-rich layers and mica-rich layers	Flow folding (B_1 -folding)	Flexural folding (B_2 -folding)	(Type II)
Predominant mechanism of folding			
in the quartz-rich layer	heterogeneous laminar flow across layer boundaries, having constant flow direction parallel to the axial plane	(active) neutral surface folding having the neutral axis within the individual quartz-rich layers, accompanied with shear folding (formation of the S_{B_2} -cleavage)	neutral surface folding in a unit comprising several quartz-rich layers and mica-rich layers, showing a combined action of those layers in the unit, accompanied with shear folding (formation of the S_{B_2} -cleavage and S_{B_1} -cleavage)
in the mica-rich layer		(passive) a combination of shear folding (formation of the S_{B_2} -cleavage) and flexural slip folding on the pre-existing schistosity (formation of crinkles..... B_2 -fold)	
Distribution and orientation pattern of the cleavage in the mica-rich layers confined between the quartz-rich layers in the fold	The cleavage is developed in all of the mica-rich layers involved in the fold and at any position of the fold. strictly parallel to the axial plane at any position of the fold.	The cleavage is developed in all of the mica-rich layers involved in the fold. (cleavage-attitude in the upper half side of fold knee for the individual mica-rich layers) fan-like arrangement with upward convergence—corresponding to the radial arrangement of the principal strain axis X_1 in narrow zone of compression side of the quartz-rich layer (only in the vicinity of hinge) (cleavage-attitude in the lower half side of fold knee for the individual mica-rich layers) absent or weak, showing a pronounced fan-like arrangement with upward convergence—corresponding to the presence of the neutral axis in the inner side of fold knee for the individual quartz-rich layers	The cleavage is developed only in the mica-rich layers involved in the compression side of the fold, corresponding to the presence of the neutral axis in the middle to inner part of the fold knee for the unit. fan-like arrangement with upward convergence
Nature of variation in thickness of the quartz-rich layers		variation in thickness with minimum values in the fold knee—corresponding to the presence of the neutral axis in the inner side of fold knee for the individual quartz-rich layers	When traversed from the outer side to the inner side of the fold, the layers involved in the fold indicate the corresponding variation in thickness with minimum values to maximum values in the fold knee, and the neutral axis is placed at the transitional point of the nature of variation in thickness.

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Flexural Folding における Competent Layers の変形様式

—— Flexral Folding における不均質多層岩石系の変形(Ⅱ) ——

原 郁 夫

(要 旨)

1. 不均質多層岩石系における flexural folding の型 (neutral surface folding が個々の competent layer において独立に発達する=Type I と, 数層の competent layers と incompetent layers を含む岩石单元が一つの neutral surface folding をおこなう=Type II のいずれに属するか. Neutral axis の位置—outer knee に位置するか, inner knee に位置するか) を決定する方法を考察する. この論文では, とくに competent layer について, 上記の問題が解析されている.

2. 不均質多層岩石系の flexural folding における, competent layer の変形様式と incompetent layer の変

形様式との相互関係が解析されている.

3. 不均質多層岩石系の flexural folding は, 必然的に shear folding によつてともなわれること, および, flexural folding において, 最も基本的な機構とされている layer boundary にそう flexural slip は "flexural fold" の形成において重要な意味をもたないこと, layer boundary はむしろ単なる strain discontinuity の面であるにすぎない場合が多いことが指摘されている.

4. 問題の考察のための基礎資料としては, 三波川・三郡変成岩中のいくつかの小褶曲構造の解析結果がもちいられている.