MOVEMENT PICTURE IN CONFINED INCOMPETENT LAYERS IN FLEXURAL FOLDING

— DEFORMATION OF HETEROGENEOUSLY LAYERED ROCKS IN FLEXURAL FOLDING (I) —

Ikuo HARA*

(Received December 6, 1965)

I. INTRODUCTION

In flexural folding of heterogeneously layered rocks, some layers are competent, whereas others are incompetent. Mechanisms of formation of such heterogeneously layered folds have been discussed by many authors up to now. It has been frequently stated that styles of fold are determined by the most competent layers, that folding mechanism of the competent layers involves buckling, that material of incompetent layer adjusts itself to interspace by passive flow, that shearing stress developed parallel to the layer boundaries during the buckling of the competent layer plays an important part in the deformation of incompetent layer, and that the most important mechanism of folding of the sequence of competent and incompetent layers is flexural slip on layer boundaries. However, structural characteristics of most natural folds of flexural type do not appear to conform strictly with ideal conditions of flexural fold which were assumed by many authors.

On the basis of his investigations of the geometry of natural folds of flexural and similar types, RAMSAY (1962) considered that natural flexural folds may be divided into two types: pure flexure fold, in which thickness of layer as measured at right angles to the layer surface is constant from place to place, and modified flexure fold, in which layers are thickened in the fold hinges and thinned on the limbs and this modification of the constancy of layer-thickness is due to flattening. Further he (1963, p. 147) says, "study of the way that folds deform pre-existing structures (especially folds and linear structures) can lead to the determination of the mechanism of deformation that produced the fold. Detailed investigations of the cross-sectional shapes of the folds themselves can also be used to determine the mechanisms that led to their formation." DONATH et al. 1963, pp. 45 and 53—54) say, "flexural folding represents a true bending of layers and can be produced by slip

between layers, flexural-slip, or by flow within layers, flexural-flow. In flexural-slip folding, flow within layers is negligible, and initially parallel layer boundaries remain essentially parallel after folding...Where flow has occurred within layers, the layer boundaries no longer remain parallel, and the characteristics of the resulting fold are quite different from those of the simple flexural-slip fold....", and further they (p. 51) say, "folding by slip between layers is common in layered sequences of rocks deformed under conditions favouring brittle to moderately brittle behaviour (low mean ductility)... Flexural-flow is important in rocks folded while moderately ductile and is often the predominant mechanism in a layered sequence of rock with moderate to high ductility contrast..." However, the solution of above-described problems, given by RAMSAY and DONATH et al., appears to require first the determination of stress and strain distribution and that of the nature of behaviour of rock material in individual flexural folds.

The author (1963) described a heterogeneously layered fold, where the stress distribution corresponding to the neutral surface folding was developed in a lithic unit comprising several competent layers (quartz-rich layer) and incompetent layers (mica-rich layer), showing a combined action of those layers involved in the unit. And then he (1965, b. in press) analysed the quartz dimensional fabric in a concentric fold of a quartz-rich layer embedded in the mica-rich layers showing shear folding and indicated a strain distribution corresponding to the neutral surface folding in the quartz-rich layer which was combined with the shear folding in the surrounding mica-rich layers. On the basis of data obtained by the author (1963, and 1965b, in press), therefore, it may be clearly concluded that natural flexural folds in the heterogeneously layered rocks are divided into two types: Type I, in which the flexural folding occurs by neutral surface folding having the neutral axis within the individual competent layers respectively, and Type II, in which the flexural folding occurs by neutral surface folding having a neutral axis in a unit comprising several competent layers and incompetent layers, (HARA, 1965b, in press).

* Institute of Geology and Mineralogy, Faculty of Science,
Hiroshima University
JOURNAL OF THE GEOLOGICAL SOCIETY OF JAPAN,
Vol. 72, No. 8, p. 363—369 August 1966.

However, our knowledge on flexural folds, with reference to the strain and movement pictures developed in the individual layers during folding, does not seem to be always adequate for rigorous treatments of their folding mechanisms. In this paper, some small-scale folds found in the Sambagawa crystalline schist (especially in the "black schist") of the Kune district, Shizuoka Pref., Central Japan, will be described and discussed with reference to the strain and movement pictures developed in the individual layers during the folding, and, on the basis of obtained data, will be discussed some problems on the deformation of heterogeneously layered rocks in flexural folding, the relationship between the deformation style of the competent layers and that of the interstratified incompetent layers in the flexural folding of Type I and Type II, the nature of variation in thickness of the competent layer induced during the flexural folding of Type I and Type II, the relationship between the flexural folding and shear folding, and some others.

The "black schist" of the Kune district is a multilayered system consisting of alternating quartz-rich layers and mica-rich layers, showing a distinct foliation (in the sense of HARKER, 1939). In most outcrops the foliation (here termed S_1) is markedly folded in various styles and scales. The folds in the black schist, observed on the scale of outcrop, can be grouped into three types; that is, 1) kink bands, which were previously described by the author (1965a), 2) intrafolial folds (cf., TURNER and WEISS, 1963), which occur as tectonic inclusions in the foliation, (here termed B_1^L -fold), and 3) folds, whose axial surfaces are generally inclined at moderate to high angles to the foliation. The folds of the last type are subdivided as follows: 1) fold having wave-length of several centimeters to some tens centimeters (here termed B_2^L -fold), 2) fold having wave-length of several millimeters to a few centimeters (here termed B_2^M -fold), and fold having wave-length of less than a few millimeters (here termed B_2^S -fold). The B_2^S -fold is found only

in the mica-rich layer. Generally, the B_2^M -fold is referred to the type of parasitic fold in relation to the B_2^L -fold, and the B_2^S -fold is referred to that in relation to the B_2^M -fold, as shown in Fig. 1.

Some macroscopic characteristics of the B_2^M -fold, observed where folds and other deformation structures of different generations do not occur together, are listed as follows: 1) The axial surface of the B_2^M -folds involved in any B_2^L -fold are parallel or subparallel to the axial surface of the B_2^L -fold, and the axial surfaces of the B_2^S -folds involved in any B_2^M -fold are parallel or subparallel to the axial surface of the B_2^M -fold (Fig. 1). 2) The axial surface of the B_2^M -fold is generally planar or gently curved. 3) For many of the B_2^M -folds hinge is rectilinear, but for some of them it is markedly curved. 4) Many of the folds are seen to be essentially plane cylindrical, but some of them plane noncylindrical (cf., TURNER et al., 1963). 5) Profile of the fold is generally bilaterally asymmetric across the axial surface and shows open to acute form. 6) In some places is found a fold system of the same generation having such geometric property that within the fold system the axial surfaces are constant in trend, while hinge lines show markedly various trends. However, other fold systems observed in many outcrops, each of which is of the same fold generation, appear to have generally such a geometric property as constant trend of axial surfaces and hinge lines within the system. 7) In the limbs of many B_2^M -folds is frequently found a cleavage formed by transposition of the quartz-rich layers and mica-rich layers (Fig. 1). The cleavages (here termed S_{2q}) are commonly parallel or subparallel to the axial surface of the B_2^L -fold. The S_{2q} -cleavage corresponds to the axial plane cleavage in relation to the B_2^L -fold. Detailed microscopic observations indicate that deformation structures, macroscopically described in term of B_2^S -fold, are generally identical with a cleavage structure referred to the type of the strain-slip cleavage (in the sense of TURNER et al., 1963). The cleavage structure (corr

Fig. 1 Relationship between the B_2^L -fold, B_2^M -fold and S_{2m} -cleavage (B_2^S -fold).
Q: quartz-rich layer.

esponding to the B_2^S -fold) is newly named S_{2m} . The S_{2m} -cleavage corresponds to the axial plane cleavage in relation to the B_2^M -fold (e. g., Plates 1-A and B, 2-A and B and 3, and Fig. 1), that is developed only in the mica-rich layer.

In order to discuss some problems on the deformation of heterogeneously layered rocks in flexural folding mentioned in the preceding page, will be first described and discussed the S_{2m} -cleavage, and then will be examined the B_2^M -fold and intrafolial fold in some selected specimens, on the basis of the microscopic observations of many thin sections for S_{2m} -cleavage, B_2^M -fold and intrafolial fold. Style of deformation of the mica-rich layer in the deformation related to the formation of the B_2^M -fold and intrafolial fold will be examined with reference to the type of cleavage and attitude of the cleavage in the fold. While style of deformation of the quartz-rich layer in the deformation related to the B_2^M -fold and intrafolial fold will be examined with reference to the quartz dimensional fabric. Then mutual relationships between style of deformation of the quartz-rich layers (competent layer) and that of the mica-rich layers (incompetent layer) in folding will be discussed. S_{2q} -cleavage formed by the transposition of quartz-rich layers and mica-rich layers, which corresponds to the axial plane cleavage in relation to the B_2^L -fold, suggests that the mechanism of formation of most B_2^L -folds involves shear folding on the S_{2q} -cleavage. While, as will be analysed in the next paper, the mechanism of formation of most B_2^M -folds, which correspond to the parasitic fold in relation to the B_2^L -fold, involves neutral surface folding. Therefore, the relationship between the formation of S_{2q} -cleavage (process of shear folding) and that of B_2^M -fold (process of neutral surface folding) in the B_2^L -folding will be also discussed.

In analysing the dimensional fabric of quartz grains in the quartz-rich layers involved in the folds examined, the following points are focused: the direction and the degree of the preferred grain orientation. Measurement of the orientation was made on 50 grains in each of selected positions in the quartz-rich layers in question, by using the petrographic microscope of 280 magnification. Grains were measured without selection; at each position the grains were measured one by one in the field of microscope until the number of measurement attains to 50.

The orientation of each grain is measured as the direction in which the two most closely spaced parallel lines can be drawn tangent to the outline of the grain. As a means of statistical representation of the direction and the degree of preferred orientation of grains, a simple two-dimensional scheme of vector analysis has been adopted, following CURRAY (1956). As the final criterion for the significance of preferred orientation, the RAYLEIGH

test of significance (CURRAY, 1956) has been used. No distribution has been accepted as being significantly different from uniformity, unless the probability is less than 0.05.

ACKNOWLEDGEMENTS

The author is especially indebted to Prof. G. KOJIMA for his critical review of the manuscript. Thanks are due to the staff of the Kune mine, Furukawa Mining Co. Ltd., Messers H. FUKUMOTO, T. AOKI and S. KANDA, for their kind helps in various ways. The field work for this study has been supported in part by the Grant in Aid for Scientific Researches from the Ministry of Education.

II. DEFORMATION STYLE OF THE MICA-RICH LAYERS IN THE B_2^M -FOLDING AND B_1 -FOLDING

A. *Types of Cleavage in the Mica-Rich Layers Involved in the B_2^M -Folds and B_1 -Folds*

Microscopic observations of the cleavage structures S_{2m} in the mica-rich layers involved in the B_2^M -folds indicate that they do not always possess the same structural property, and that, although the author can not perfectly arrange all of the examined cleavage structures into some distinct types, many of them appear to be grouped into following four types. Namely, in the first type the S_{2m} -cleavages occur as discrete surfaces of microfault sharply cutting across the S_1 -surface, unaccompanied with crinkles of the S_1 -surface. Any preferred mineral orientation does not occur along the cleavage surface. In his description of various types of cleavage structure, LEITH (1905, p. 12) says, "fracture cleavage is conditioned by the existence of incipient, cemented or welded fractures and is independent of a parallel arrangement of the mineral constituents." Therefore, the S_{2m} -cleavages of this type are referred to the type of fracture cleavage after LEITH. For convenience' sake, however, the S_{2m} -cleavage of this type is designated Type I.

In the second type the S_{2m} -cleavages are displayed as parallel row of crinkles (corresponding to the B_2^S -fold), unaccompanied with any microfault. The S_{2m} -cleavage of this type is designated Type II. The S_{2m} -cleavage of Type II appears to represent an initial stage in the development of the cleavage structures of two types described in the following paragraphs.

In the third type the S_{2m} -cleavages are displayed as a combination of discrete surfaces of microfault and crinkles of the S_1 -surface (corresponding to the B_2^S -fold). Microfaults are developed on both limbs and hinge of the crinkles. The S_{2m} -cleavage of this

type is weakly or not associated with parallel orientation of mica flakes resulting from the folding of the pre-existing schistosity S_1 . The cleavage of this type is designated Type III. The cleavage of Type III seems to be referred to the slip cleavage in the metamorphosed sediments of East-Central Vermont described by WHITE (1949). The cleavage of Type III is most commonly found in the mica-rich layers of the black schist of the Kune district, and it is commonly together with the cleavage of Type I and/or Type II as the structure of the same generation. Essential character of the S_{2m} -cleavage of Type III is both crinkles of the S_1 -surface and discrete surfaces of microfault parallel to the axial surface of the crinkles. WHITE (1949, pp. 590 and 592) says, "... the crinkles are essential to development of the microfaults, or slip cleavage, and determine the orientation of this cleavage. This is shown by the fact that the axial planes of the crinkles have the same attitude, whether or not their limbs are faulted. The crinkles are the independent part and the slip cleavage the dependent part of the phenomenon. The microfaults, or slip cleavage planes, appear to be an end product of the process, and fundamentally dependent on the crinkling for their genesis, location, and orientation." In the development of the cleavage of Type III, the first stage appears to be marked by crinkles of the S_1 -surface, referred to the cleavage of Type II, like in the case reported by WHITE.

In the fourth type the S_{2m} -cleavages are defined by a combination of crinkles of the S_1 -surface (corresponding to the B_2^S -fold) and narrow bands parallel to the axial surface of the crinkles where individual mica flakes, though parallel to each other, are preferably oriented slightly oblique to the length of the band. The S_{2m} -cleavage of this type seems to be referred to the type of crenulation cleavage after RICKARD (1960). For convenience' sake, however, in this paper the S_{2m} -cleavage in question is named Type IV. Generally, narrow bands parallel to the axial surface of the crinkles are more micaceous than zones of the crinkles are. Especially, this point is clearly recognizable where the former has greater width. In two specimens, zones of the crinkles are not mica-rich, but quartz-rich. Preferred orientation of mica flakes in the quartz-rich zones (corresponding to the zones of the crinkles) indicate a relict of the S_1 -surface, while mica flakes in the mica-rich zones are preferably oriented parallel to the length of the zones. The boundary between the former and the latter zones is displayed as a sharp discontinuous surface. In some other specimens, quartz grains and mica flakes in the quartz-rich zones (corresponding to the zones of the crinkles) show a markedly preferred orientation of their longest

dimension parallel to the length of the zones, indicating a transition of the cleavage of Type IV into a new schistosity-foliation. Analogous transition of a crenulation cleavage into a new schistosity was described by RICKARD (1960). The cleavage of Type IV occurs commonly together with the cleavage of Type II. The first stage in the development of the former is marked by crinkles of the S_1 -surface, referred to the cleavage of Type II, like in the case described by RICKARD (1960). Co-existence of the cleavage of Type IV and that of Type I could not be found in the Kune district.

On the basis of above descriptions, it may be said that the S_{2m} -cleavages of Type I, Type II, Type III and Type IV are collectively referred to the type of strain-slip cleavage in the sense of TURNER et al. (1963). In the deformation related to the formation of the S_{2m} -cleavage in the mica-rich layers involved in the B_2^M -folds, generally, the mechanism of crinkling (B_2^S -folding) of the S_1 -schistosity (constructed by the parallel arrangement of mica flakes) appears to involve flexural slip along the grain boundaries of mica flakes, a process analogous to the bend gliding in deformed crystal.

In the mica-rich layers involved in the B_1 -fold are generally found transversal cleavages of one set parallel to the axial surface. The transversal cleavages are defined by the preferred orientation of mica flakes, indicating that they are referred to the type of flow cleavage after LEITH (1905 and 1923). The cleavage of this type is named S_1' .

B. Attitudes of the Cleavage in the B_2^M -Fold and B_1 -Fold

One of the essential features concerning the strain-slip cleavage and flow cleavage is that they commonly lie parallel to the axial surface of both major and minor folds, as pointed out so far by many authors. Broadly speaking, analogous relationship for the attitude of the cleavage in the fold appears to be equally obvious for between the B_2^M -fold and S_{2m} -cleavage and for between the B -fold and S_1' -cleavage in the Kune district. However, detailed microscopic observations on many B_2^M -folds indicate that attitude of the S_{2m} -cleavages in the mica-rich layers confined between the quartz-rich layers in the B_2^M -fold does not always possess the same pattern, and that, although the author can not perfectly arrange all of the examined patterns of cleavage-orientation in the B_2^M -folds into some distinct types, many of them appear to be related to four types described in the following paragraphs.

Namely, in the first type (Fig. 2-a and Plate 1-A), the S_{2m} -cleavages are uniformly developed through the mica-rich layer from the top to the bottom of the

Fig. 2. Four types of attitude of the cleavage in the mica-rich layer (M) confined between the quartz-rich layers (Q) in fold.

B_2^M -fold, though their development is weaker in the bottom than in the top. The attitude of the S_{2m} -cleavage in the B_2^M -fold is as to form a fan-like arrangement with upward convergence, like in the case described by many authors. This orientation pattern of the S_{2m} -cleavage in the B_2^M -fold is named Type B. The S_{2m} -cleavage showing the orientation pattern of Type B are of Type I, Type II Type III and Type IV.

In the second type (Fig. 2-b and Plate 1-B), the S_{2m} -cleavages do not occur uniformly through the mica-rich layer from the top to the bottom of the B_2^M -fold, but they are found in the part of the B_2^M -fold for the individual mica-rich layers except the bottom. The cleavages tend to converge toward the top of the fold in such an attitude as to form a fan-like arrangement. This orientation pattern is named Type C. The S_{2m} -cleavages showing the orientation pattern of Type C are of Type I, Type II and Type III.

The third type of the orientation pattern of the S_{2m} -cleavage through the mica-rich layer in the B_2^M -

fold is illustrated in Fig. 2-c and Plates 2-B and 3. In the upper half side of the fold, the cleavages tend to converge toward the bottom of the fold. The pattern appears to be referred to the form of sheaf arrangement described by LAUGEL (1855), rather than a fan-like arrangement. In the bottom of the fold, a fan-like arrangement of the cleavage occurs in opposite sense to the case of the upper half side mentioned just above. This orientation pattern of the S_{2m} -cleavage in the B_2^M -fold is named Type D. The S_{2m} -cleavages showing the orientation pattern of Type D are of Type II and Type IV.

The fourth type of cleavage-attitude in the B_2^M -fold is found in the mica-rich layers of the flexural fold of Type II. The cleavage-attitude of this type was previously described by the author (1963). As illustrated in Fig. 3, in this case, the transversal cleavage, which is referred to the S_{2m} -cleavage of Type III, is developed only in the mica-rich layers involved in the inner side of the fold (but not in all of the mica-

Fig. 3 Diagram showing attitude of transversal cleavage (C) in the mica-rich layers on the heterogeneously layered fold (involving quartz-rich layers and mica-rich layers), which was previously described by the author (1963). b, d, f, h, j, l, n, p and r : mica-rich layer. a, c, e, g, i, k, m, o and q : quartz-rich layer. 1 : fold I. 2 : fold II.

rich layers involved in the fold), showing such an attitude as to form a fan-like arrangement (similar to that of Type B). This orientation pattern of the cleavage in the fold is named Type E. The S_{2m} -cleavages showing the orientation pattern of Type E are of Type II, Type III and Type IV.

The attitude of the S_1' -cleavage in the B_1 -fold is generally characterized by that the cleavage is oriented strictly parallel to the axial plane at any position of the fold (Fig. 2-d). This orientation pattern of the cleavage in the fold is named Type A.

There are five types of the attitude of the cleavage in the mica-rich layers confined between the quartz-rich layers in the fold, as described in the preceding paragraphs as Type A, Type B, Type C, Type D and Type E. It seems to be necessary, however, to treat these as end members (principal types) of a series of movement pictures developed in the mica-rich layers (incompetent layer) confined between the quartz-rich layers (competent layer) during folding, as will be mentioned in the next paper.

REFERENCES

- CURRAY, J. R. (1956), The analysis of two-dimensional orientation data. *Jour. Geol.*, vol. 64, p. 117—131.
- DONATH, Fred. A. and PARKER, R. B. (1963), Folds and folding. *Geol. Soc. Am. Bull.*, vol. 74, p. 45—62.
- HARA, I. (1963), Petrofabric analysis of a drag fold. *Geol. Rep. Hiroshima Univ.*, vol. 12, p. 463—492.
- (1965a), Quartz fabrics in a kink band. *Jour. Sci. Hiroshima Univ.*, Series C, vol. 5, p. 1—13.
- (1965b, in press), Dimensional fabric of quartz in a concentric fold. *Jap. Jour. Geol. Geogr.*
- HARKER, A. (1939), *Metamorphism*. Methuen, London.
- LAUGEL, M. Aug. (1855), Du clivage des roches. *Bull. Soc. Geol. France*, vol. 12, p. 363—370.
- LEITH, C. K. (1905), Rock cleavage. *Geol. Soc. Am. Bull.*, 239.
- (1923), *Structural Geology*. Holt, New York.
- RAMSAY, J. G. (1962), The geometry and mechanics of formation of "similar" type folds. *Jour. Geol.*, vol. 70, p. 309—327.
- (1963), Structure and metamorphism of the Monine and Lewisian rocks of the North-West Caledonides. in "The British Caledonides" edited by M. R. W. JOHNSON and F. H. STEWART. *Oliver and Boyd*, Edinburgh.
- RICKARD, M. J. (1960), A note on cleavages in crenulated rocks. *Geol. Mag.*, vol. 97, p. 324—332.
- TURNER, F. J. and WEISS, L. E. (1963), *Structural Analysis of Metamorphic Tectonites*. McGraw-Hill, New York.
- WHITE, W. S. (1949), Cleavage in East-Central Vermont. *Trans. Am. Geophys. Un.*, vol. 30, p. 587—594.

Flexural folding における incompetent layers の変形様式

— Flexural folding における不均質多層岩石系の変形 (I) —

原 郁 夫

(要 旨)

1. Flexural folds は基本的な2つの型 (Type I と Type II) に分類される: Type I = neutral surface folding が個々の competent layer において独立に発達する. したがって, neutral axis は個々の competent layer 内に位置する. Type II = 数層の competent layers と incompetent layers を含む岩層単位 (unit) が一つの neutral surface folding をおこなう (neutral axis はこの岩層単位内に一つだけ発達する).

2. ふたつの型の flexural folding (Type I と Type

II) に特徴的な strain-movement picture が解析される. その結果にもとづき, 一般の flexural folds について, flexural folding の型 (問題とする褶曲が, flexural fold の Type I と Type II のいずれに属するものであるか. neutral axis は褶曲内のどのような位置にあるか—— 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, とくに不均質多層岩石系の flexural fold における incompetent layer について, 上記の問題が解析されている.

地 名

Sanbagawa 三波川

Kune 久根