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A Note on "Concentric" Folding of Multilayered Rocks

By

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with 2 Tables, 9 Text-figures, and 4 Plates

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Abstract: The structural features of a "concentric" fold of a multilayered system consisting of alternating quartz-rich layers and mica-rich layers have been analysed in detail, with regard to the strain distribution and the nature of behaviour of rock material in all the layers involved in the system. On the basis of obtained data, the strain distribution and geometry of the "concentric" folds of multilayered rocks have been discussed, and a new kinematic and geometric model of "concentric" folding of multilayered rocks has been proposed. In order to understand physical conditions in which the "concentric" folding can occur in multilayered rocks, some schematic patterns of flexural folding of multilayered rocks odserved in nature have been also examined with reference to mutual relationships between them.

CONTENTS

I. INTRODUCTION

In flexutral folding of multilayered systems consisting of alternating competent layers and incompetent layers, generally, where the competent layers are widely spaced, these layers tend to be independently folded in a disharmonic fashion, while, where the competent layers are fairly closely spaced, these layers show a tendency to buckle in phase with one another. And, where the competent layers are much closely spaced, such folds as described in terms of parallel or concentric fold appear to be formed in the system. In other multilayered systems may develop such pattern of flexural folding as characterized by the deformation of the systems which resembles pure bending of a homogeneous plate (flexural folding of Type II by HARA, 1966c).

The folds of concentric type cannot persist through the whole thickness of a multilayered system which is thicker than a certain limit, and they die out upward and downward. Their radius of curvature decreases toward the core of the fold, where complex minor folds and thrusts are often developed. From such geometrical characters of the concentric folds, it can be inferred that, where the competent layers in a multilayered system are closely spaced and the folding of concentric type is developed, the stress and strain pictures in the competent layers change from the convex zone to the concave zone of the system, unlike the case in that, where the competent layers are widely spaced and the folding of concentric type is not developed, those pictures are more or less of the same character for all of the competent layers.

The concentric folds of multilayered rocks have been so far described and discussed by many authors, since van HISE (1894) proposed to distinguish concentric folds from other types. An ideal geometric model of the concentric fold supported by many authors (e.g., ICKES, 1923; NEVIN, 1949; BILLINGS, 1952; de SITTER, 1956; HILLS, 1963; TURNER and WEISS, 1963; DONATH *et al.*, 1964) is drawn in terms that the folded layers are in parallel curves, retaining constant thickness throughout the fold, and in the core of the fold where they can no longer fold under the condition of parallelism maintaining their original length complex minor folds and thrusts are often developed. de SITTER (1956) assumed that any curve is formed by three circles, while MERTIE (1940 and 1947) regarded the curves as parallel involutes. However, most concentric folds of multilayered rocks show geometrical features not strictly compatible with the above-described ideal model (e.g., RAMSAY, 1961 and 1962). RAMBERG (1963b, p. 13) says, "this sort of fold style is physically unrealistic and must be considered a purely geometric demonstration used to show that the thickness over which concentric folding may persist is limited." Detailed examination of the layer-thickness distribution of the concentric folds of multilayered rocks was done by RAMSAY (1962). He described three concentric folds on two of which the variation in the whole thickness of the concentrically folded multilayered system was examined and on one of which the thickness-variation of only a fraction of the layers involved in the system was done, showing the conclusion that the folded layers are thickened in the fold hinges and thinned on the fold limbs before the systems have reached a condition of maximum shortening by flexure alone. In order to understand the geometry of the concentric folds of multilayered rocks, it must be important to determine in what fashion the nature of thickness-variation changes when passing from the layer involved in the convex zone to that in the concave zone of the fold.

An ideal kinematic model of the concentric folding of multilayered rocks supported by many authors (e.g., ICKES 1923; NEVIN, 1949; BILLINGS, 1952; de SITTER, 1956; HILLS, 1963; TURNER and WEISS, 1963; DONATH, *et al.*, 1964) is illustrated in terms that the concentric folding of multilayered rocks is due primarily to flexural-slip on the layerboundaries, though the folded layers may be under buckling conditions, each developing an individual neutral surface. DONATH *et al.* (1964, pp. 45, 53–54 and 51) 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 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. ...... The geometry of the flexural-slip fold is that of the parallel or concentric fold." However, our present knowledges on the concentric folds of multilayered rocks, with reference to the stress and strain distribution and the nature of behaviour of rock material in all the layers involved in the system, do not seem to be always adequate for rigorous treatments of the mechanisms which produced those folds. In flexural folding of multileyered rocks generally, where competent layers involved in the system are much closely spaced, folds of concentric type are formed in the system, while, where compentent layers are widely spaced, these layers tend to be independently folded in a disharmonic fashion. Therefore, the development of the concentric fold in multilayered rocks appears to be generally related to a unique stress distribution that is developed only where the competent layers involved in the system are much closely spaced but not where these are widely spaced. Such a unique stress distribution may be usually developed in multilayered rocks in which flow occurred within layers, as well as where flow within layers is negligible, owing to a combined action of competent layers involved in the system, only if theses layers are much closely spaced. The solution of the mechanism of concentric folding of multilayered rocks appears to require first the determination of stress and strain distribution and that of the nature of behaviour of rock material in the natural folds of concentric type.

In this paper, the structural features of a concentric fold of a multilayered system consisting of alternating quartz-rich layers and mica-rich layers will be analysed in detail, with regard to the strain distribution and the nature of behaviour of rock material in all the layers involved in the system. On the basis of obtained data, the strain distribution and geometry of the concentric folds of multilayered rocks will be discussed.

Acknowledgement: The author is especially indebted to Prof. G. Kojima for the review of the manuscript.

II. Analysis of Strain Distribution and Geometry

The fold in question is taken from a specimen of the "black schist" which was found in the Sambagawa crystalline schist of the Sazare district, Centrail Shikoku. The rock involved in the specimen is a multilayered system consisting of alternating quartz-rich layers and mica-rich layers. The profile of the fold in question and its environs observed within the specimen is shown in Fig. 1. The quartz-rich layers involved in the member I (Fig. 1), which are much closely spaced, are folded in phase with one another. Also those involved in the member II, which are much closely spaced, show a tendency to fold in phase with one another, although some layers involved in the concave zones of the folds show second-order minor folds. The folds of the member I and those of the member II, which are enclosed in thick mica-rich layers, are independently developed in a disharmonic fashion. The fold examined in the following paragraphs corresponds to a portion of the folds of the member I (Fig. 1).

The rock (member I) involved in the fold in question is a multilayered system made of alternation of three quartz-rich layers (b, d and f in Fig. 2) and two mica-rich layers (c and e), that is enclosed in thick mica-rich layers (a and g), (Plate 11). Both quartz-rich layers and mica-rich layers contain quartz, muscovite, chlorite and carbo-

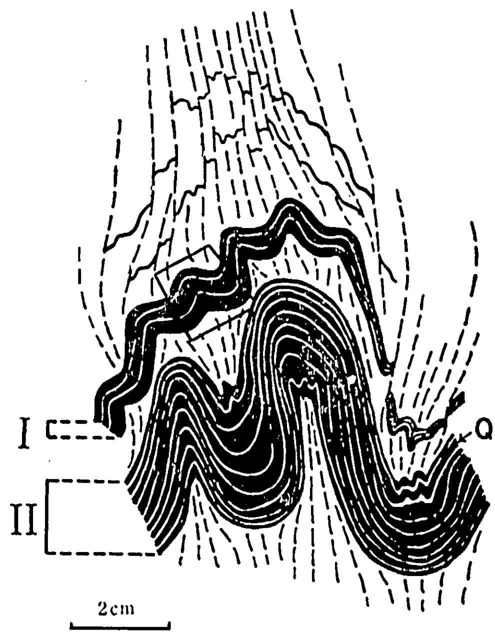

FIG. 1 Profile of the described fold and its environs.
I and II: member I and member II.
broken lines:transversal cleavages in the mica-rich layers.
Q: quartz-rich layers.
▭: the fold described in this paper.

naceous matter as constituent minerals. In the former, quartz is the main constituent mineral (more than 70 per cent in volume), while, in the latter, muscovite and chlorite flakes are predominant (more than 85 per cent in volume). The average thickness of the mica-rich layer e through the fold is less than one fifth of that of the quartz-rich layer f and that of the quartz-rich layer d. The average thickness of the mica-rich layer c is less than one fifth of that of the quartz-rich layer d and one eighth of that of the quartz-rich layer b. Detailed observation indicates that the quartz-rich layer d is fairly mica-rich along a very thin zone (layer d_3) in its middle horizon, by which it may be separated into two quartz-rich layers d_1 and d_2 (Fig. 2).

Some characters of the fold in question are enumerated as follows: 1) The hinge line is straight. 2) The axial surface is slightly curved. The fold is termed nonplane cylindrical fold with reference to its geometric property (TURNER and WEISS, 1963). 3) The form is asymmetrice bilaterally across the axial surface (Fig. 2). The fold has a monoclinic symmetry. 4) Fold-style changes from the layer involved in the concave zone of the fold to that in the convex zone, as will be described in the later pages. Around the hinge I, the angle between the limbs increases from the layer f (convex zone) toward the layer b (concave zone), while around the hinge II it is approximately consistent from layer to layer. 5) Mica and chlorite flakes in the quartz-rich layers and micarich layers are generally oriented parallel to the layer surface, showing a distinct

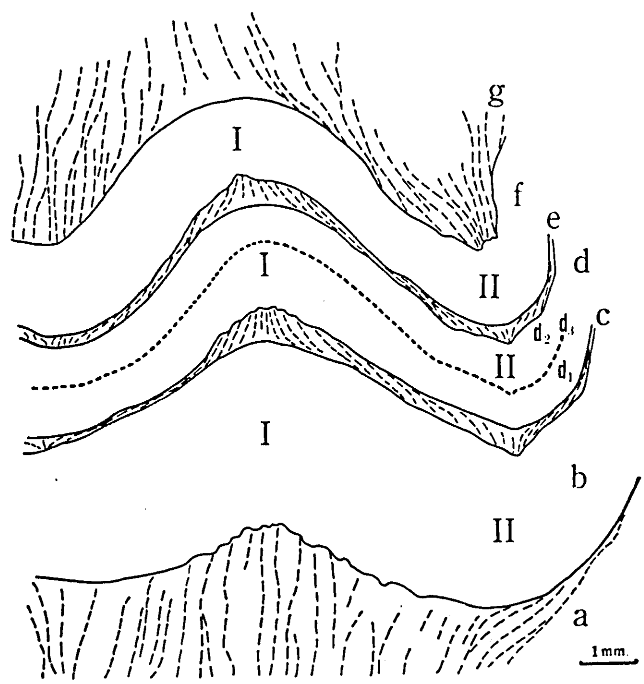

FIG. 2 Schematic sketch of the fold on the plane normal to the fold axis.
a, b, c, ...: names of layers
I and II: hinge I and hinge II
dash lines: transversal cleavages in the mica-rich layers.

schistosity. In the mica-rich layers are found transversal cleavages which are displayed as a combination of discrete surfaces of microfault and crincles of the schistosity surface (correlated with the cleavage of Type III in HARA, 1966a). The attitude of the cleavage surfaces in the fold is shown in Fig. I and Plate 11. The cleavage-attitude in the fold hinge corresponds approximately to the Type B of the author's classification (HARA, 1966a). In the fold limbs of the mica-rich layers c and e, the cleavage surfaces tend to be oriented at low angles to the layer boundaries.

Fig. 3–a, b and c shows the variation in thickness of the quartz-rich layers b, d and f as measured in a direction parallel to the axial surface, respectively. There is a distinct decrease in thickness toward the hinges I and II for all of the quartz-rich layers and the minimum thickness is at both hinges. Detailed observation indicates that at the hinge I this nature of the thickness-variation shows a tendency to become progressively distinct from the layer b to the layer f, while at the hinge II it tends to become progressively distinct from the layer f to the layer b. Therefore, it can generally be said that the above-described nature of the thickness-variation shows a tendency to become progressively distinct from the layer involved in the concave zone to that in the convex zone of the fold.

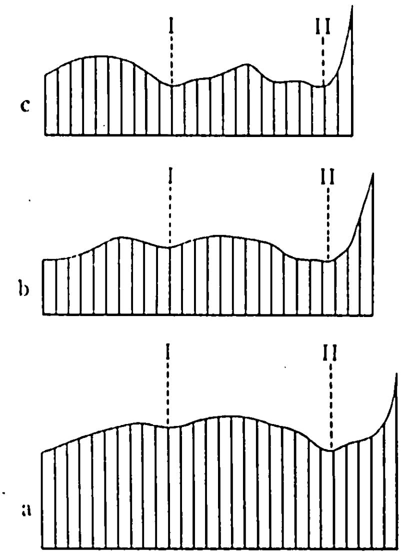

FIG. 3 Graphic representation of the variation in thickness of the quartz-rich layers shown in FIG. 2, measured in a direction parallel to the axial surface. a: layer b. b: layer d. c: layer f.
I and II: positions of hinges I and II.

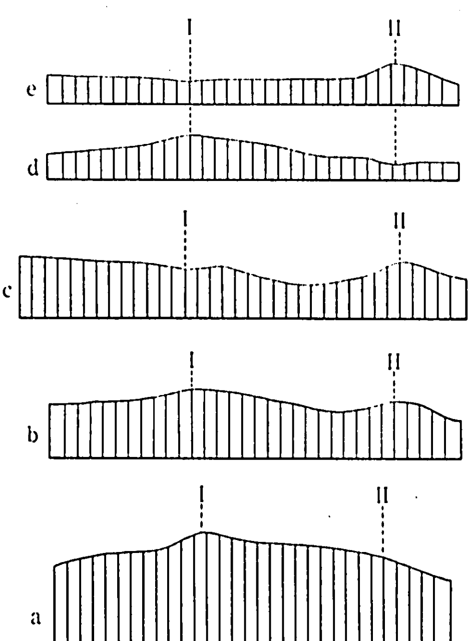

FIG. 4 Graphic representation of the variation in thickness of the quartz-rich layers shown in FIG. 2, measured at right angles to the layer surface. a: layer b. b: layer d. c: layer f. d: layer d_1. e: layer d_2.
I and II: positions of hinges I and II.

Fig. 4–a, b and c shows the variation in thickness of the quartz-rich layers b, d and f as measured at right angles to the layer surface, respectively. The thickness of the layer f is at a maximum at the hinge II and at a minimum at the limb lying between the hinges I and II. Furthermore, Fig. 4–c shows that there is a small but distinct decrease in thickness toward the hinge I. Therefore, it can be pointed out that the nature of the thickness-variation is quite different between the hinges I and II. The thickness of the layer d is not constant throughout the fold, showing maximum values at the hinges I and II (Fig. 4–b). At the hinge I, the nature of the thickness-variation of the layer d (Fig. 4–b) is quite different from that of the layer f (Fig. 4–c). The layer d may be divided into two layers d_1 and d_2. Fig. 4–d and e shows the variation in thickness of the layer d_1 and that of the layer d_2, respectively. The thickness of the layer d_2 which is close to the layer f is at a minimum at the hinge I and reaches a maximum at the hinge II. While, the thickness of the layer d_1 is at a maximum at the hinge I and reaches a minimum at the hinge II, unlike the case of the layer d_2. Fig. 4–a shows the variation in thickness of the layer b. There is a distinct increase toward the hinge I.

Now, it comes into question whether the nature of the variation in thickness of the quartz-rich layers b, d and f, shown in Fig. 4, was the result of variation in the initial thickness of these layers or produced by deformation which accompanied the development of the fold. This problem will be discussed after the dimensional fabric of quartz in those layers will have been analysed in the following paragraphs.

Dimensional fabric of quartz in the quartz-rich layers b, d and f was analysed, with

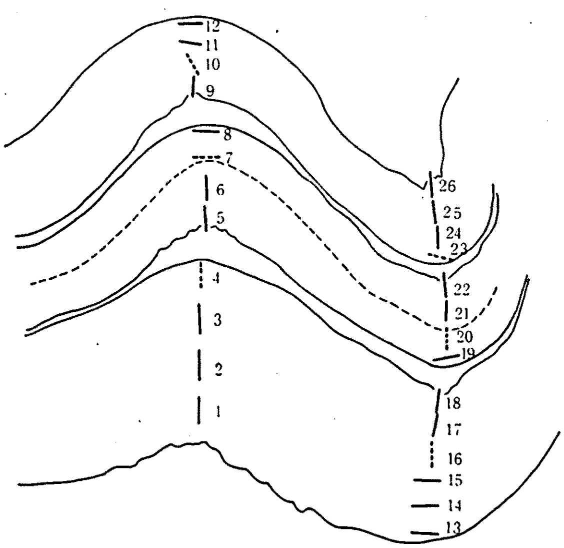

Fig. 5 Directions of quartz grain orientation at 26 positions in the quartz-rich layers b, d and f.
Dotted lines: directions of quartz grain orientations which is not statistically significant.

regard to the strain and movement pictures in the deformation related to the formation of the fold in question, according to the method of analysis used in the previous papers (HARA *et al*,, 1966; HARA, 1966b and c). The grain orientation on the plane normal to the fold axis was examined at 26 positions which are located at the hinges I and II, as shown in Fig. 5. The result is illustrated in Fig. 5 and Table 1.

Table 1 Summary of grain-orientation data

Position No.	Vector Magnitude (%)	Probability	Significant
1	69.2	$<10^{-10}$	Yes
2	63.6	$<10^{-5}$	Yes
3	47.4	$<10^{-4}$	Yes
4	18.4	>0.10	No
5	47.8	$<10^{-4}$	Yes
6	34.4	<0.01	Yes
7	16.4	>0.20	No
8	37.6	$<10^{-3}$	Yes
9	39.2	$<10^{-3}$	Yes
10	9.0	>0.60	No
11	30.2	<0.02	Yes
12	60.2	$<10^{-5}$	Yes
13	49.6	$<10^{-5}$	Yes
14	53.6	$<10^{-5}$	Yes
15	33.2	<0.01	Yes
16	11.8	>0.40	No
17	24.4	<0.05	Yes
18	44.6	$<10^{-4}$	Yes
19	25.2	<0.04	Yes
20	16.6	>0.20	No
21	30.2	<0.02	Yes
22	37.4	$<10^{-3}$	Yes
23	12.2	>0.40	No
24	37.6	$<10^{-3}$	Yes
25	61.6	$<10^{-5}$	Yes
26	64.0	$<10^{-5}$	Yes

Fig. 5 shows that the pattern of the grain orientation throughout the fold is not homogeneous. At the innermost zone of the hinge I for the layer f, the long axes of quartz grains are preferably oriented parallel to the axial surface, while at the middle to outer zone they show a preferred orientation parallel to the layer surface (Plate 14). Between the former and the latter zones the grain orientation is not statistically significant. While, at the hinge II for the same layer the long axes of quartz grains are generally preferably oriented parallel to the axial surface, though at the outermost zone the grain orientation is not statistically significant. At the middle to inner zone of both hinges for the layer d, the long axes of quartz grains are preferably oriented parallel to the axial surface, and at the outermost zone they show a preferred orientation parallel to the layer surface (Plate 13). Between the former and the latter zones the grain orientation is not statistically significant. At the hinge I for the layer b the long axes of quartz grains are generally preferably oriented parallel to the axial surface, though at the outermost zone the grain orientation is not statistically significant (Plate 12). While, at the middle to outer zone of the hinge II for the same layer the long axes of quartz grains are preferably oriented parallel to the layer surface, though at the inner zone they show a preferred orientation parallel to the axial surface, and between the former and the latter zones the grain orientation is not statistically significant.

At the hinge I as well as the hinge II, there are distinct differences in the pattern of grain orientation between the quartz-rich layers b, d and f. However, it can be pointed ont that in each of those layers is commonly found a portion where the grain orientation is not statistically significant and the locality of this portion shows a tendency to change regularly from the inner zone to the outermost zone of the hinge when passing from the layer f to the layer b at the hinge I or from the layer b to the layer f at the hinge II.

The quartz dimensional fabric in question will also be interpreted according to the rule used in the previous papers (HARA, 1966 b and c), that was established with reference to the date and idea given by OFTEDAHL (1948), FAIRBAIRN (1950), FLINN (1956), BRACE (1955 and 1961), TURNER and WEISS (1963) and CARTER, CHRISTIE and GRIGGS (1964). The directions of grain orientation (vector mean) and their normals, so far as they are statistically significant, at any position on the plane normal to the fold axis are regarded as representing the directions of the principal strain axes X (maximum) and Z (minimum) respectively. Then, the preferred orientation of the long axes of quartz grains parallel to the layer surface at the outer zones of the hinges for the individual quartz-rich layers (positions 8, 11, 12, 13, 14, 15 and 19) and that parallel to the axial surface at the inner zones (positions 1, 2, 3, 4, 5, 6, 9, 17, 18, 21, 24, 25 and 26) indicates the development of the tension zone and the compression zone, respectively, during the folding, and the portions (positions 4, 7, 10, 16, 20 and 23), where the grain orientation is not statistically significant, coincide with the locality of the neutral axis.* On the basis of the pattern of quartz dimensional fabric

* According to RAMBERG (1964), under lateral compression, competent layer embedded in incompetent layer shortens by two unlike mechanisms: 1) by buckling (buckle shortening) and 2) by uniform strain along the layer (layer shortening). Buckle shortening and layer shortening take place simultaneously but usually with different rates. The ratio between the rates of the former and the latter increases rapidly as the amplitude increases. At the early stage of deformation, the layer shortening may be more predominant than the buckle shortening. The tensile stress will not be developed at the convex zone of the fold until the buckle shortening will become significant. Strictly speaking, therefore, the locality of the neutral axis at the final stage of the deformation related to the formation of the fold in question does not coincide with a portion showing random dimensional orientation of quartz developed between portions showing preferred dimensional orientation of quartz parallel to and normal to the layer surface at the fold hinge, but it appears to be within the portion showing preferred dimensional orientation of quartz normal to the layer surface.

shown in Fig. 5 and Table 1, thus, it can be pointed out that during the folding related to the fomation of the fold in question the quartz-rich layers b, d and f were under neutral surface conditions, each developing an individual neutral surface. This conclusion appears to be also derived from the cleavage-attitude on the fold limbs of the mica-rich layers c and e (cf. BAYLY, 1965). The boundaries between the buckled quartz-rich layers and the mica-rich layers are not referred to the displacement discontinuities but to the strain discontinuities.

The locality of the neutral axis shows a tendency to change regularly from the inner zone to the outer zone of the hinge when passing from the layer f to the layer b at the hinge I or from the layer b to the layer f at the hinge II. This fact will be interpreted as to reflect that, during the folding of the multilayered system consisting of the layers b to f as a unit, layer-parallel compressive stress acting at the hinge zones tended to increase progressively from the convex zone to the concave zone of the system, showing a combined action of the layers involved in the system.

The strain pictures developed in the quartz-rich layers b, d and f during the folding, which is inferred from the dimensional fabric of quartz, appear to correspond fairly well to the nature of the variation in thickness of those layers though the fold described in the preceding pages. For the layer f, the nature of the thickness-variation that there are a maximum thickness at the hinge II and a small but distinct decrease toward the hinge I corresponds to the strain and movement pictures that, whereas the hinge II corresponds almost as a whole to the compression zone (preferred orientation of the long axes of quartz grains parallel to the axial surface), at the hinge I prevails the tension zone (preferred orientation of those axes parallel to the layer surface). For the layer d_2, the nature of the thickness-variation that the thickness is at maximum at the hinge II and at a minimum at the hinge I corresponds to the strain and movement pictures that, whereas the hinge II corresponds wholy to the compression zone, at the hinge I develops the tension zone, For the layer d_1, the nature of the thickness-variation that the thickness is at a minimum at the hinge II and at a maximum at the hinge I corresponds to the strain and movement pictures that, whereas at the hinge II develops the tension zone, the hinge I corresponds wholy to the compression zone. For the layer b, the nature of the thickness-variation that there is a distinct increase in thickness toward the hinge I corresponds to the strain and movement pictures that, whereas at the hinge II develops the tension zone, the hinge I corresponds almost as a whole to the compression zone. It seems probable that the minimum thickness at the limb between the hinges I and II for the layer f and the distinct decrease in thickness from the hinge II toward the right limb for the layer b reflect the result of variation in the initial thickness of those layers.

If the initial grain orientation of quartz in the quartz-rich layers b, d and f was not at random but showed a certain unique pattern, the strain and movement pictures mentioned in the preceding paragraphs must be newly redrawn. Also in this case, however, it can be safely pointed out that during the folding of the multilayered system in question the quartz-rich layers were under neutral surface conditions, each developing an individual neutral surface, and that layer-parallel compressive stress acting at the hinge zone showed a tendency to increase progressively from the convex zone to the concave zone of the system, showing a combined action of those layers.

In the fold of the member II, though the quartz-rich layers involved show a tendency to fold in phase with one another, some of them involved in the concave zone show second-order minor folds (Fig. 1). Those folded quartz-rich layers are under neutral surface conditions, each developing an individual neutral surface, judging from the dimensional fabric of quartz in those layers, though the fabric data is not shown in this paper. About analogous pattern of heterogeneously layered fold RAMBERG (1964, p. 325) says, "during the large-scale folding of the multilayer as a unit, layer-parallel compressive stress affects the layers in the concave regions of the complex. The stress increases from the middle of the complex toward its concave surface……In the central part of the buckling multilayer, layer-parallel compressive stress is too low to generate second-order buckling. …… As the compressive stress increases from layer to layer toward the concave surface, the possibility arises that the stress will become strong enough to generate short-wavelength individual buckling of layers in the concave portion……" Also the fold pattern of the member II will be well explained by Ramberg's terms cited above.

Thus, it will be inferred that, only if competent layers involved in a multilayered system, where flow may occur within those layers or it may be negligible, are much closely spaced, generally, analogous pattern of the stress and strain distribution is also equally developed in the system, owing to a combined action of those layers. Such pattern of the stress distribution appears to correspond clearly to the general geometric character of the concentric folds that the folds cannot persist throughout the whole thicknes of a multilayered system which is thicker than a certain limit. Namely, increase in the layer-parallel compressive stress toward the concave zone of the fold induces corresponding decrease in the radius of curvature of the folded layers. It will be stated that the development of the concentric fold in a multilayered system is generally related to that of a unique stress distribution such as progressive increase in the layer-parallel compressive stress toward the concave zone of the system, and so that the folded layers are not generally in parallel curves but the nature of thickness-variation changes from the layer involved in the convex zone to that in the concave zone in a manner corresponding to the unique stress distribution, though the layers involved in the concave zones may develop second-order minor folds. Under the physical conditions where flexural folds, except for kink bands, can be formed in multilayered rocks, flow appears to occur within layers.

On the basis of the above-described data for the present specimen, here, another model of concentric folding of multilayered rocks will be proposed as follows: During the folding of multilayered rocks as a unit, the folded competent layers involved in the system are under neutral surface conditions, each developing an individual neutral surface. At this time, layer-parallel compressive stress acting at the hinge zones shows a tendency to increase progressively from the convex zone to the concave zone of the system, showing a strain picture such that, whereas in the competent layers involved in the concave zone prevails the compression zone, in these in the convex zone prevails the tension zone. Owing to such stress-strain picture, the distribution of layer-thickness such as shown idealy in Figs. 6 and 7 must be formed in the fold. Generally, folded layers are not in parallel curves. The distribution of layer-thickness in the fold tends to change regularly from minimum to maximum at the hinge when passing from the layer involved in the convex zone to that in the concave zone of the fold. Increase in the layer-parallel compressive stress toward the concave zone of the fold result in corresponding decrease in the radius of curvature of the folded layers or in the formation of complex minor folds and thrusts in the core of the fold. Therefore, the term concentric is inapplicable. The mechanism of flexural folding of multilayered rocks in question may be regarded as a combination of the Type I and Type II of flexural folding (cf. HARA, 1966c). For convenience' sake, the flexural folding of this type will be designated Type Ic. Broadly speaking, the distribution of layer-thickness in the flexural fold of Type Ic appears to be similar to that of the flexural fold of Type II, if in the concave zone of the former one the folded layers do not show second-order minor folds and if the flexural folding of Type II can give large deformation a multilayered system. Therefore, it must be very difficult to determine whether any flexural fold is referred to the Type Ic or the Type II of flexural fold on the basis of observation of its cross-sectional shape. Because, in the flexural folding of Type Ic of a multilayered system, the folded competent layers involved are under neutral surface conditions, each developing an individual neutral surface, they appear to be commonly in slightly disharmonic condition, although they show a tendency to develop in phase with one another. While, because the flexural folding of Type II of a multilayered system resembles pure bending of a homogeneous plate, the layers in-

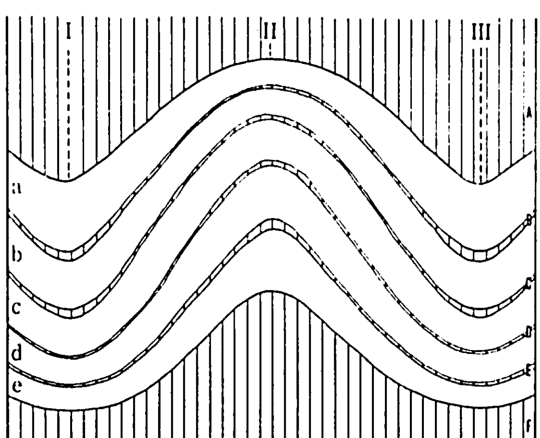

FIG. 6 An ideal distribution of layer-thickness in the fold formed by the flexural folding of Type Ic.
a to e: names of competent layers. A to F: names of incompetent layers. I, II and III: hinge I, hinge II and hinge III.

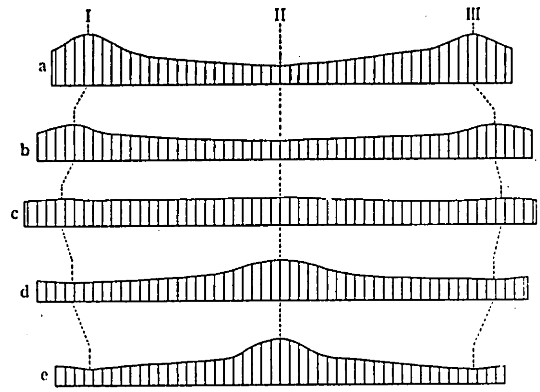

FIG. 7 Graphic representation of the variation in thickness of the competent layers shown in FIG. 6, measured at right angles to the layer surface.
a to e: names of layers.
I, II and III: positions of hinges I, II and III.

volved in the system are strictly conformablly folded in phase with one another, only if at the initiation of folding they are strictly conformable. This point will be very useful to distinguish the flexural fold of Type Ic from the flexural fold of Type II. In order to understand the nature of the flexural folding of Type Ic in multilayered rocks, furthermore, it is important to determine the controlling factors which govern whether competent layers involved in the concave zone of the system show second-order minor folds or not (instead, those layers are considerably thickened at the hinge zones).

When competent layers involved in a multilayered system are much closely spaced, generally, the flexural folding of Type Ic is developed in the system, while, when those layers are widely spaced, those layers tend to be independently folded in a disharmonic fashion. What causes are related to determine whether competent layers involved in a multilayered system are independently folded in a disharmonic fashion or these layers buckle in phase with one another have been discussed by RAMBERG (1961, 1963a and 1964) and CURRIE *et al.* (1962) on the theoretical and experimental viewpoints. According to RAMBERG, "the aformentioned unlike behaviour of multilayers is due to interference between the buckling layers, and this interference is determined by the extent to which the fields of contact strain and stress of neighbor competent layers penetrate one another. Now the width of the contact strain along a buckling sheet in a infinite medium equals about one wavelength λ_∞. ...... Thus if the spacing is greater than $2\lambda_\infty$ the interference should be completely negligible and each competent layer should buckle as if surrounded by an infinite medium. At decreasing spacing the interference will increase in significance, the layers should show increasing tendency to buckle in phase with one another, and that part of the buckling resistance which is caused by the contact strain in the incompetent set of layers should diminish (1963a, p. 493)". A photoelastic study on this problem by CURRIE *et al.* (1962) appears to give a result compatible with that of Ramberg. Here, it comes into question whether, as soon as competent layers involved in a multilayered system buckle in phase with one another, the stress and strain distribution corresponding to the flexural folding of Type Ic is developed in the system or that is not practically developed until the competent layers are so much closely spaced that the fields of contact strain of these layers penetrate much deeply one another. Namely, the extent to which competent layers involved in a multilayered system are closely spaced when the flexural folding of Type Ic is developed in the system must be calculated.

In the present specimen, the folds of the member I and those of the member II, different two systems of flexural folding of Type Ic, are independently developed in a disharmonic fashion (Fig. 1). The fomer and the latter are bounded by the mica-rich layer a, which is much thicker than any of the mica-rich layers involved in the individual fold systems. The member II is much thicker than the member I, and the length of arc of the folds of the member II is much larger than that of the folds of the member I (Fig. 1). While, in the specimens previously described by the author (1963 and 1964), some different systems of flexural folding of Type Ic show a tendency to develop in phase with one another. In the specimen described in 1964, the fold I (fold A+fold B, involving the layers b to r in Plate 34–1, 1964) and fold II (fold C, involving the layers t to z and overlying several layers in Plate 34–1, 1964) correspond to different two systems of flexural folding of Type Ic, judging from the fold style of individual layers involved, the distribution of layer-thickness, the cleavage-attitude and the lattice and dimensional fabric of quartz. The former and the latter are bounded by a mica-rich layer (layer s in Plate 34–1, 1964), which is much thicker than any of the mica-rich layers involved in the individual fold systems. The whole thickness of the layers involved in the fold I is nearly equal to that of the layers involved in the fold II. It is more probable that, in the specimen described in 1963, the fold I and fold II correspond to different two systems of flexural folding of Type Ic, though in the previous papers (HARA, 1966a and b) the author pointed out that those folds correspond to different two systems of flexural folding of Type II. However, it is clear that the stress distribution which developed through the fold I and fold II during the deformation related to the formation of deformation bands in quartz corresponds to that for the flexural folding of Type II (cf. HARA, 1963, Plate, 54–4). The fold I, fold II and surrounding unfolded systems are bounded by mica-rich layers, which are much thicker than any of the mica-rich layers involved in each of those systems. Those two examples appear to indicate conditions in which the flexural folding of Type Ic can penetrate through many layers of a multilayered system in a harmonic fashion. It is important to determine the controlling factors which govern whether different systems of the flexural fold of Type Ic are independently developed in a disharmonic fashion or conformablly developed in phase with one another.

Finally, some schematic patterns of flexural folding of multilayered systems consisting of alternating competent layers and incompetent layers, that have been induced from the observation of natural flexural folds, will be briefly sketched, although those patterns may have been so for described by many authors. Such pattern that the flexural folding of multilayered systems occurs by the neutral surface folding having the neutral axis within the individual competent layers involved respectively was designated Type I (HARA, 1966 a, b and c). The flexural folding of Type I is commonly developed in the following three patterns. In the first pattern, the competent layers involved in the system are independently folded in a disharmonic fashion, and they are under neutral surface condition, each developing an individual neutral surface. This pattern of flexural folding will be named Type Ia. In the second pattern, the competent layers involved are conformablly folded in phase with one another, and they are under neutral surface condition, each developing an individual neutral surface. The stress and strain distribution developed during the folding is more or less uniform from layer to layer, unlike the case of the flexural folding of Type Ic. This pattern of flexural folding will be named Type Ib. The flexural folding of Type appears to be essentially the same as the similar folding of the second kind theoretically given by BIOT (1965a). The third pattern corresponds to the Type Ic of flexural folding discussed in the preceding paragraphs. The transition of flexural folding of Type Ia, through Type Ib, to Type Ic appears to be controlled by the spacing between the competent layers combined with the competency differences between these layers and neighbour incompetent la ers (cf. RAMBERG, 1961, 1963a and 1964). Where different systems of flexural folding of Type Ic are formed in a multilayered system, they may show a tendency to develop conformablly in phase with one another (Fig. 8) or they may be independently developed in a disharmonic fashion. (Fig. 1) The former pattern is named Type Ic–c, and the latter pattern Type Ic–d.

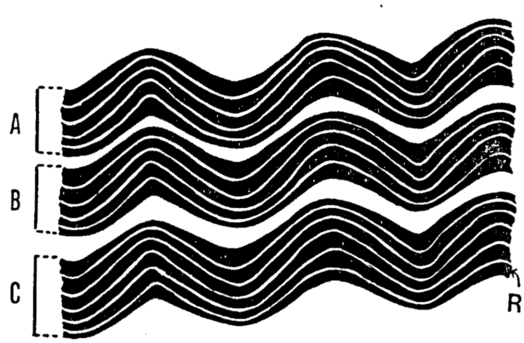

FIG. 8 Schematic diagram showing the flexural fold of Type Ic–c A, B and C: different three systems of flexural fold of Type Ic.
R: competent layers.

The flexural folding in some multilayered systems may be characterized by neutral surface folding having a neutral axis in a unit comprising several competent layers and incompetent layers, that resembling pure bending of a homogeneous plate. This pattern corresponds to the flexural folding of Type II (HARA, 1966c), and is essentially the same as the similar folding of the first kind theoretically given by BIOT (1965a). BIOT discusses the controlling factors which govern the first and second kinds of similar folding. According to him (pp. 257–258), the transition from one to the other "is controlled by the relative magnitudes of the three viscosity coefficients ...... of the competent layer, the incompetent layer, and the embedding medium." Also the transition from the Type Ib or Type Ic of flexural folding to the Type II of flexural folding will be equally explained by BIOT's terms cited above. In the specimen previously described by the author (1963, Plate 54–4), different two systems of flexural folding of Type II show a tendency to develop in phase with one another. This example appears to indicate a condition in which the flexural folding can penetrate through many layers of a multilayered system in a harmonic fashion. This pattern of the flexural folding of Type II will be named Type IIc. Different systems of flexural folding of Type II may be also independently developed in a disharmonic fashion. This pattern will be named Type IId.

Thus, six principal types of flexural folding of multilayered systems consisting of alternating competent layers and incompetent layers can be designated as shown in Table 2. The buckling stress which needs for a competent layer to buckle with a charcteristic wavelength will show different intensity when the types of flexural folding of the competent layer are different. It will gradually change when the type of folding of the competent layer change from Type Ia to Type IIc (in the descending flexural order in Table 2).

Table 2 Principal types of flexural folding

- Type I
  - Type Ia
  - Type Ib
  - Type Ic
    - Type Ic-d
    - Type Ic-c
- Type II
  - Type IId
  - Type IIc

For explanation see text.

Now, it can be pointed out that, where the flexural folding is penetrative through many layers of a multilayered system in a harmonic fashion, it occurs by either one of the Type Ib, Type Ic (Type Ic or Type Ic–c) and Type II (Type II or Type IIc) of flexural folding or one of their combinations (Type Ib+Type Ic (Type Ic or Type Ic–c), Type Ib+Type II (Type II or Type IIc), Type Ic (Type Ic or Type Ic–c)+Type II (Type II or Type IIc) and Type Ib+Type Ic (Type Ic or Type Ic–c)+Type II (Type II or Type IIc)). CURRIE *et al.* (1962) found flexural folds with wavelengh of several kilometers. Therefore, it may be said that the above-described patterns of flexural folding in multilayered systems occur in scales ranging from several millimeters to several kilometers.

Geometries of the incompetent layers interspaced between the competent layers showing the flexural folding of Type Ia are commonly complex, and any axial surface may not be always determined in such a geometric manner that it is the surface passing through the hinge lines on successive folded surface (Turner and Weiss, 1963). Analogous pattern of fold geometry may be also equally developed for the incompetent layers interspaced between different systems of flexural fold of Type Ic (in the case of Type Ic-d), between these of Type II (in the case of Type IId), between flexural fold of Type Ic and that of Type II and between flexural fold of Type Ic (or Type II) and that of Type Ib. While, it is clear that the incompetent layers involved in the system showing the Type Ib and Type Ic of flexural folding are folded in phase with the neighbour competent layers, and, then, that the thickness distribution of the confined incompetent layers is usually heterogeneous through the fold but it tends to show a certain regular pattern.

Geometries of confined incompetent layers in flexural folds of Type Ic and Type Ib which are observed in nature are of various patterns, strictly speaking. Although the author cannot perfectly arrange all of those fold geometries into some distinct patterns, some of them appear to be grouped into three principal patterns and many of remaining others appear to be regarded as representing intermediate patterns between those principal patterns. Fig. 9 shows schematic skecth of the three principal patterns.

In the first principal pattern (Fig. 9-a), the confined incompetent layers are thickened at the hinges and thinned on the limbs. This pattern of fold geometry is quite similar to that of similar fold defined by Bhattacharji (1958). It is further defined as follows according to his terms (1958, p. 656): The fold geometry becomes "more and more pronounced as the following relations of the radii of curvature of the upper surface (R_u) and the lower surface (R_l) of a layer show":

Anticlinal part	Synclinal part
R_u tends to O	R_u tends to ∞
R_l tends to ∞	R_l tends to O

In this paper, however, this pattern of fold geometry of the confined incompetent layers will be named Pattern I.

In the second principal pattern (Fig. 9-b), the confined incompetent layers are thinned at a hinge (e.g. anticlinal part) and gradually thickened from the limbs toward its just neighbour hinges (e.g. synclinal part). This pattern of fold geometry is quite similar to that of flowage fold and reverse flowage fold defined by Bhattacharji (1958). Because his geometric classification on the folds of incompetent layers is partly based on the geographic attitude of them, the flowage fold is distinguished from the reverse flowage fold. According to him (1958, pp. 656-657), namely, the flowage fold geometry "becomes more and more pronounced as the following relations of R_u and R_l show":

$$\begin{matrix} R_u \text{ tends to } \infty \\ R_l \text{ tends to } O \end{matrix} \quad \text{for anticlinal and synclinal parts}$$

A fold geometry produced when the flowage fold is rotated through 180° is referred to that of the reverse flowage fold. When folds of flowage type and reverse flowage type are of small-scales (scales of hand specipem), the author considers that the former is essentially the same as the latter, with regard to similarity in the cleavage-attitude (=movement picture) between folds of both types that is shown in the later page. When folds of flowage type and reverse flowage type are of large-scales, however, it is not clear whether the former is essentially the same as the latter or not. In this paper the patterns of fold geometry in question will be collectively named Pattern II, for convenience' sake.

In the third principal pattern (Fig. 9-c), the confined incompetent layers are thickened on the limbs and thinned at the hinges, contrary to the case of Pattern I. This

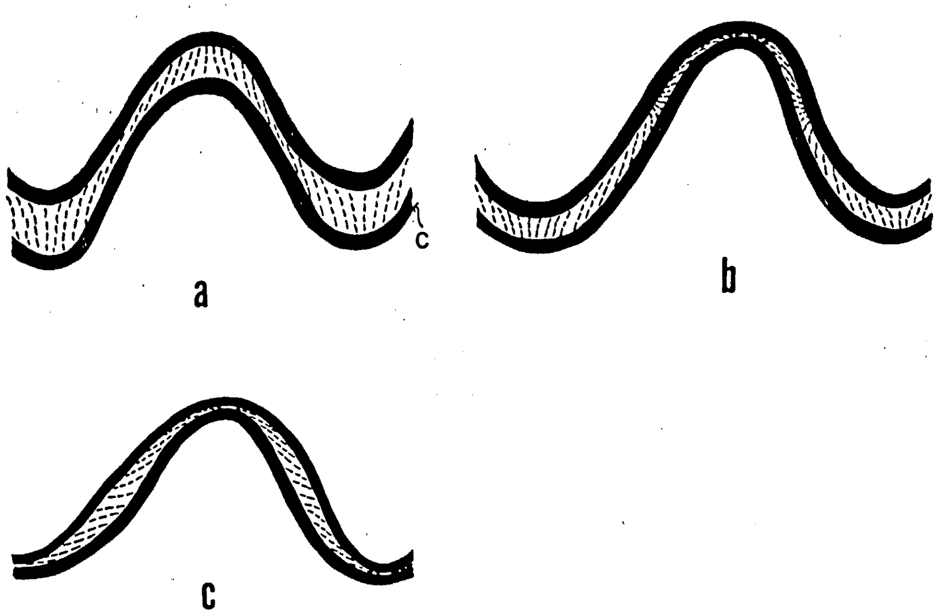

FIG. 9 Mutual relations between the cleavage-attitude and fold geometry of the confined incompetent layers:
a) fold geometry of Pattern I and cleavage-attitude of Type X, b) fold geometry of Pattern II and cleavage-attitude of Type Y, and c) fold geometry of Pattern III and cleavage-attitude of Type Z. For fuller explanation see the text.
C: competent layers. dash lines: cleavage surfaces in incompetent layers.

pattern of fold geometry is quite similar to that of reverse-similar fold defined by BHATTACHARJI (1958). It is further defined as follows according to his terms (1958, P. 657): The fold geometry "becomes more representative as the following relations of the radii of curvature of the upper (R_u) and lower (R_l) surfaces show":

Anticlinal part	Synclinal part
R_u tends to ∞	R_u tends to O
R_l tends to O	R_l tends to ∞

In this paper, however, this pattern of fold geometry will be named Pattern III.

Analogous patterns of fold geometry, Patterns I, II and III and intermediate patterns between these principal patterns, may be also equally developed for the incompetent layers confined between different systems of flexural fold of Type Ic (in the case of Type Ic–c), between these of Type II (in the case of Type IIc), between flexural fold of Type Ic (or Type II) and that of Type Ib and between flexural fold of Type Ic and that of Type II.

The fold geometry of Pattern I of the confined incompetent layers has been so far described by many authors, while the fold geometries of Pattern II and Pattern III have not been observed in natural flexural folds, so far as the author knows. The fold geometry of Pattern II appears to be similar to that of "flowage fold" by BAHN (1931) and that of "suprataneous fold" by NEVIN (1949). However, the former must be distinguished from the latter. This is because the former is only for passive folding of the confined incompetent layers that is controlled by relative patterns of buckle folding of the neighbour two competent layers, but such controlling factor of the formation of fold is not for the latter. The fold geometry of Pattern II has been experimentally produced by BHATTACHARJI (1958). The Pattern II and Pattern III of fold geometry of the confined incompetent layers have been observed in some natual flexural folds by the author *et al.* (1967).

It is clear that different patterns of fold geometry mentioned above indicate those of passive fiow of material of confined incompetent layers in folding. Three patterns of migration of incompetent material through fold which correspond respectively to the three principal patterns of fold geometry were roughly assumed by BHATTACHARJI (1958). Generally, style of passive deformation of confined incompetent layers in folding may be clearly understood by analysis of types of cleavage and orientation patterns of the cleavage of particular type in any fold, in addition to analysis of thickness distribution of those layers.

Orientation patterns of cleavages of various types (containing those of the axial surfaces of parasitic folds) in incompetent layers interspaced between the buckled competent layers have been so far examined by many authors (e.g. WILSON, 1946; NEVIN, 1949; BILLINGS, 1952; SITTER, 1956; WILLIAMS, 1961; HILLS, 1963; KIRILLOVA, 1965). However, mutual relation between the cleavage-attitude and fold geometry of the confined incompetent layers in flexural folds does not seem to have been yet described and discussed. So far as the author has examined in the literature, the cleavage-attitudes in the confined incompetent layers, which have been reported by many authors, appear to be for these showing the fold geometry of Pattern I, and they, regardless of types of cleavage, all appear to be arranged into a single pattern that the cleavage surfaces show a fan-like arrangement the apex of which is directed toward the top of hinge (Fig. 9–a). In this paper, this pattern of cleavage-attitude in the confined incompetent layers will be named Type X. The author (1966a and b) has previously examined the cleavage-attitudes in the confined incompetent layers showing the fold geometry of Pattern I, especially these within the hinge zones, and indicated three different types, Type B, Type C and Type D. However, two of those three types, Type

B and Type C, may be contained within the Type X of cleavage-attitude. While the cleavage-attitude of Type D may not be contained within that of Type X. In this case, the folds of neighbour competent layers show a broad crestal zone, and that of the upper competent layer is fairly broader than that of the lower competent layer (HARA, 1966a, Fig. 2-c, and 1966b, Fig. 9). Strictly speaking, therefore, the fold geometry of the confined incompetent layers in question may not be referred to that of Pattern I, but it will be referred to one of the intermediate patterns between the fold geometries of Pattern I and other principal patterns.

Attitude of minor folds in a fold of "flowage type" was shown by NEVIN (1949, Fig. 55). This is essentially the same as the cases of "flowage folds" described by BAIN (1931), and is quite different from the cleavage-attitude of Type X.

However, the cleavage-attitude in the confined incompetent layers showing the fold geometry of Pattern II, which will be induced by observations of some flexural folds by the author *et al.* (1967), is quite different from the orientation pattern of minor folds in folds of "flowage type" described by NEVIN (1949) and BAIN (1931). The former is of such pattern as schematically shown in Fig. 9-b. This pattern of cleavage-attitude will be named Type Y. While, the cleavage-attitude in the confined incompetent layers showing the fold geometry of Pattern III, which will be induced by observations of some flexural folds by the author *et al.* (1967) is of such pattern as schematically shown in Fig. 9-c. This pattern of cleavage-attitude will be named Type Z. Coexistence of the Type X, Type Y and Tyoe Z of cleavage-attitude in the confined incompetent layers in the same flexural fold has been recognized. The cleavage-attitudes of those three types will be in detail described and discussed in separate paper by the author *et al.* (1967).

The flexural folds of Type Ic of the member I are associated with microfaults which are oriented parallel to their axial surfaces and to the transversal cleavages in the mica-rich layers (Fig. 1). The microfaults developed in the flexural folds of Type Ic are essentially the same as the cleavage structures previously described in term of S_{2_q}-cleavage (HARA, 1966a and b), which are developed in the flexural folds of Type Ia and Type Ib. It seems probable that, though genetic relationship between the flexural fold (Type Ia, Type Ib or Type Ic) and associated axial plane microfault is not strictly apparent, the latter was produced in the course of fold development (HARA, 1966b). The geometric and genetic relationships between the small-scale flexural folds and associated axial plane microfaults mentioned above appear to be essentially the same as those between the large-scale flexural folds and associated thrust faults examined by CURRIE *et al.* (1962). In order to understand the nature of the flexural folding of multilayered rocks, it will be very important to clarify the genetic relationship between the flexural folding and associated axial plane faulting.

Generally, the flexural folding of multilayered rocks appears to occur either in a single set with parallel axial surfaces or in pairs with mutually inclined conjugate axial surfaces. The former is the case such that the axial surfaces of resulting folds are oriented normal to the axis of the principal compressive stress acting within the system, while the latter is the case such that they occur as conjugate sets symmetrically oriented at moderate angles to the axis of the principal compressive stress (e.g., conjugate folds, JOHNSON, 1956; kink bands, PATERSON and WEISS, 1962 and 1966, and HARA, 1965), where the layering is initially oriented parallel to the axis of the principal compressive stress and normal to the axis of the principal tensile stress. All the patterns of flexural folding of multilayered rocks considered in the preceding pages correspond to those occurring in the former condition. While, our present knowledges on the flexural folds which are developed in the latter condition, with reference to the stress and strain distribution and the nature of behaviour of rock materials in all the layers involved in the system, do not seem to be always adequate for rigorous treatments of the mechanisms which produced those folds. Where the flexural folding occurs in pairs with conjugate axial surfaces, generally, the competent layers show a tendency to fold in phase with one another, regardless of the spacing between them, unlike the case that in the flexural folding in the single sets of parallel axial surfaces, generally, only where the competent layers are closely spaced, these tend to fold in phase with one another. The controlling factors which govern for the competent layers to buckle conformablly in phase with one another must be quite different between the former and the latter conditions. According to the knowledge on the conjugate kink bands experimentally given by PATERSON and WEISS (1962 and 1966), the kink bands grow in width by lateral migration of their boundaries, with increasing deformation. While, for the flexural folding of a multilayered system occurring in the single sets with parallel axial surfaces appears to be generally more or less retained a linear relationship between the length of arc (nearly equal to the initial fold wavelength) and thickness of the buckled competent layers, according to detailed observations of natural flexural folds by CURRIE *et al.* (1962) and the present author *et al.* (1967). This fact is strictly compatible with the information on the relationship between the initial wavelength and thickness of buckled competent layers embedded in incompetent layers theoretically given by BIOT (1957, 1961, 1964 and 1965a and b), RAMBERG (1960, 1961, 1963a and 1964) and CURRIE *et al.* (1962). Therefore, it may be said that the nature of the flexural folding of multilayered systems occurring in pairs with conjugate axial surfaces is essentially different from the natures of the flexural folding of Type Ia, Type Ib, Type Ic and Type II, which were mentioned in the preceding pages, and that the former type of flexural folding cannot involve the latter types of flexural folding, which are commonly taking place in the single sets with parallel axial surface.

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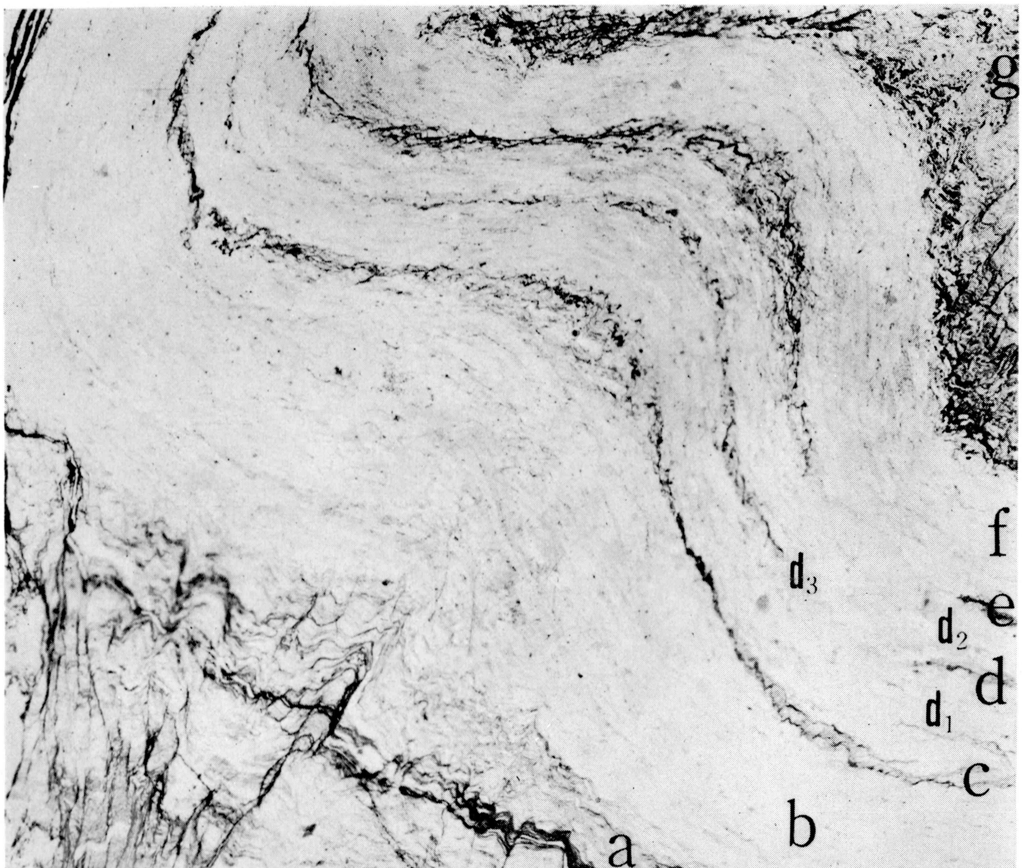
Explanation of Plate XI

Profile of the fold described in this paper.

a, b, c,...... : names of layers. Lower nicol only.


g
f
d_3
e
d_2
d
d_1
c
b
a
1mm

Explanation of Plate XII

Dimensional orientation of quartz at the hinge I for the quartz-rich layer b. Crossed nicols.


0,5 mm

Explanation of Plate XIII

Dimensional orientation of quartz at the hinge I for the quartz-rich layer d. Crossed nicols.


0,5 mm

Explanation of Plate XIV

Dimensional orientation of quartz at the hinge I for the quartz-rich layer f. Crossed nicols.


0,5 mm