Process of Folding to Unfolding of Competent Layer during Progressive Deformation

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with 6 Text-figures and 3 Plates

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Abstract: In progressive non-rotational deformation of a system consisting of incompetent rock and randomly oriented competent layers, the layers, which are inclined at low angles to the plane of the shortest and the intermediate principal axes (Z and Y) of the strain ellipsoid of mean longitudinal strain of the system, are folded and rotated towards either the longest principal axis (X) of the strain ellipsoid or the XY-plane. The folds appear to be generally generated with their axial surfaces normal or subnormal to the layer surface. However, the axial surfaces of folds found on the layers immediately before pass through the surface of no infinitesimal longitudinal strain are oriented in all directions of between the normal to the layer surface and the XY-plane. At this stage, the axial surfaces of the folds which grew in fast rate tend to be oriented approximately parallel to the XY-plane, while those of the folds which grew in slow rate tend to remain in a direction normal or subnormal to the layer surface. After the layers passed through the surface of no infinitesimal longitudinal strain, the fold forms with the axial surfaces normal or subnormal to the layer surface yield to unfolding, while those with the axial surfaces approximately parallel to the XY-plane are not unfolded but yield further to closing. The latter yields to closing even after the layers passed through the surface of no finite longitudinal strain. It has been concluded that it may be frequently difficult to use Talbot's (1970) method for description of strain state.

Contents

I. Introduction

Ramberg (1959), Flinn (1962), Ramsay (1967) and Talbot (1970) assumed that, in progressive non-rotational deformation of a system consisting of incompetent rock and randomly oriented competent layers, the competent layers which cut across the surface of no infinitesimal longitudinal strain and/or lie closer to the axis of maximum compressive stress than this surface, are folded and the other competent layers are extended parallel to the layer surface, often forming boudinage structures, that the competent layers are faster rotated towards either the longest principal axis of the strain ellipsoid of mean longitudinal strain of the system or the plane of the longest and the intermediate principal axes (X and Y) than the surface of no finite longitudinal strain, and that fold-forms of competent layers produced in the earlier stage of deformation are unfolded after the layers passed through the surface of no infinitesimal longitudinal strain and completely unfolded when the layers passed through the surface of no finite longitudinal strain. RAMBERG (1959) experimentally found considerable completeness of unfolding of fold-forms of competent layers during progressive deformation. Then, TALBOT (1970) claimed that, if a system consisting of incompetent rock and randomly oriented competent layers is homogeneously deformed, the surface of no finite logitudinal strain for the mean strain of the system is defined by directions separating between the orientation directions of competent layers showing fold-forms and those of competent layers showing no fold-form, and so that, when poles to folded competent layers and those to competent layers showing no fold-form are together plotted in a diagram, the surface of no finite longitudinal strain can be drawn by a boundary line between the partial area in which the former distributes and the remaining area in which the latter does. However, it does not appear to have yet been generallized that, during the process of deformation in which competent layers folded in the early stage of deformation are rotated towards the surface of no finite longitudinal strain, fold-forms of competent layers are completely unfolded. Based on observations of deformation style of quartz veins in the Sambagawa crystalline schist, therefore, process of folding to unfolding of competent layers during progressive deformation will be examined in this paper.

II. DEFORMATION STYLE OF COMPETENT LAYERS DURING UNFOLDING PHASE

Available data on deformation style of competent layers during the unfolding phase, in which the layers folded in the early stage of deformation are rotated through the surface of no infinitesimal longitudinal strain towards that of no finite longitudinal strain, seems to be obtained from the outcrop (Yukidomari outcrop in the Iyo-Nagahama district, Eheme Pref., Shikoku) in which, in order to understand nature of folding style of multi-layered rocks, geometric properties of folds in the Sambagawa crystalline schist had been examined by HARA *et al.* (1973). The crystalline schist in this outcrocp is basic schist that can be regarded as a multilayered system in which mode of constituent minerals varies more or less from layer to layer and that is associated with quartz veins parallel or subparallel to the layering. The basic schist and quartz veins in this ourcrop are folded in three orders: The folds of the third order (here termed S-fold) are of the minimum order observed in individual layers and the folds formed by the enveloping surface on the S-folds correspond to those of the second order (M-fold)(Plates 9 and 10-a). The folds formed by the enveloping surface on the M-folds correspond to those of the first order (L-fold). The S-folds and the M-folds are referred to as the type of parasitic fold in relation to the L-folds.

As shown in Fig. 1, there is a linear relationship beween arc-length (La) and layer-thickness (T) for the S-folds of quartz veins observed in the hinge zones of the M-folds (HARA *et al.*, 1973). The average La/T ratio is 6. 7. This data appears to be harmonic with BIOT's (1961) and RAMBERG's (1964) prediction that a competent viscous layer in an infinite incompetent viscous medium is folded with dominant wavelength of one order under lateral compression, which depends upon both the viscosity ratio between the former and the latter and the thickness of the former. Fig. 2 illustrates the variation

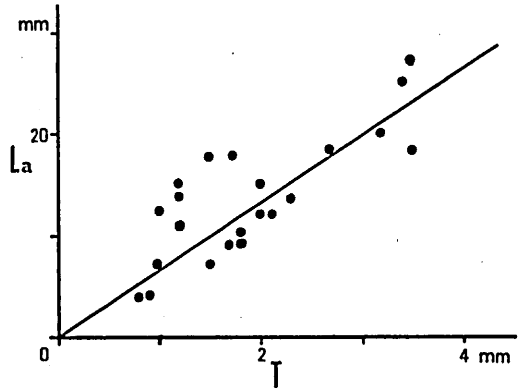

FIG. 1. Diagram showing relationship between length of arc (La) and layer-thickness (T) for the S-folds of quartz veins observed in the hinges of the M-folds.

in the interlimb angle (θ_i) between the S-folds of quartz veins observed in the hinge zones of the M-folds. θ_i is smaller than 120°, showing a marked maximum between 0° and 30°. The minus values of θ_i have been measured from the folds which may be described in term of fan fold (BILLINGS, 1954) in form. Quartz grains in the S-folds of

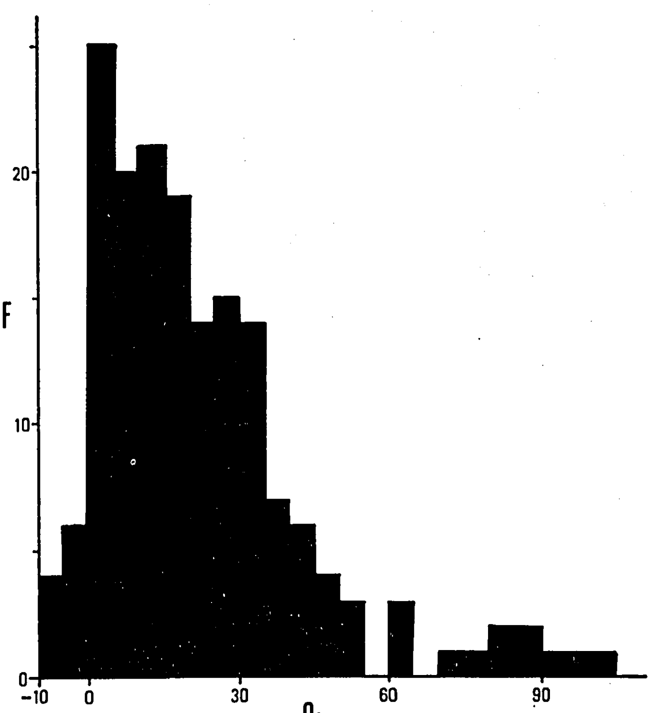

FIG. 2. Histogram showing variation in θ_i between the S-folds of quartz veins observed in the hinges of the M-folds.

quartz veins show perferred dimensional orientation (Plate 10-b). The pattern of dimensional orientation, as observed on the plane nomal to the fold axis, is as to form a fan-like arrangement with convergence towards the innermost knee, that is essentially the same as the cleavage-attitude in buckle fold, according to HARA *et al.*'s (1968) and DIETERICH's (1969) works on strain picture in buckle fold, and correlated with that of Type IV after HARA *et al.*.

The La/T ratios for the S-folds of quartz veins observed on the limbs of the M-folds are very variable, as seen in Fig. 3. This is quite different from the La/T ratios for the

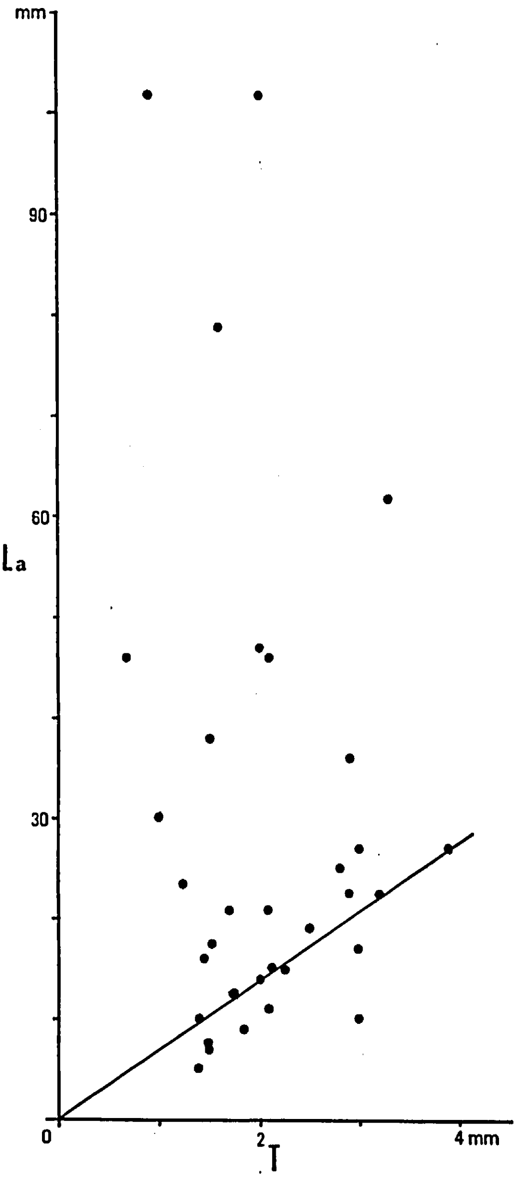

FIG. 3. Diagram showing relationship between length of arc (La) and layer-thickness (T) for the S-folds of quartz veins observed on the limbs of the M-folds.

S-folds of quartz veins (Fig. 1) observed in the hinge zones of the M-folds. θ_l for the S-folds of quartz veins observed on the limbs of the M-folds distributes between −10° and 180° in Fig. 4, showing one maximum between 0° and 40° and one submaximum between 100° and 150°, though θ_l larger than 155° is not plotted in this figure. The S-folds corresponding to the maximum distribution of θ_l show a tendency to have θ_a (=angle between the axial surface of the S-fold of quartz vein and that of the S-fold of the surrounding basic schist) smaller than 15°, while those corresponding to the sub-maximum distribution of θ_l have commonly θ_a larger than 50°. There is a distinct minimum in θ_a between 30° and 45°. The axial surfaces of the S-folds (=strain-slip cleavage) of the basic schist would be regarded as to be parallel to the XY-plane of mean strain in the system concerned, based on HARA *et al.* (1968). The axial surfaces of the S-folds with θ_a larger than 50° are commonly inclined at high angles to the enveloping surface of the folded quartz veins. The pattern of the dimensional orientation of quartz grains in the S-folds having θ_a smaller than 30° is essentially the same as that in the S-folds of quartz veins observed in the hinge zones of the M-folds, as is obvious in comparison of Plates 10–b and 11–a. While the dimensional fabric of quartz grains in many of the S-folds of quartz veins having θ_a larger than 60° is quite different from that in the S-folds having θ_a smaller than 30°, as shown in Plate 11–a and b. Quartz grains in the former show strongly undulatory extinction and fragmentation, destroying their radial arrangement around the knee. The S-folds having θ_a smaller than 30° and those having

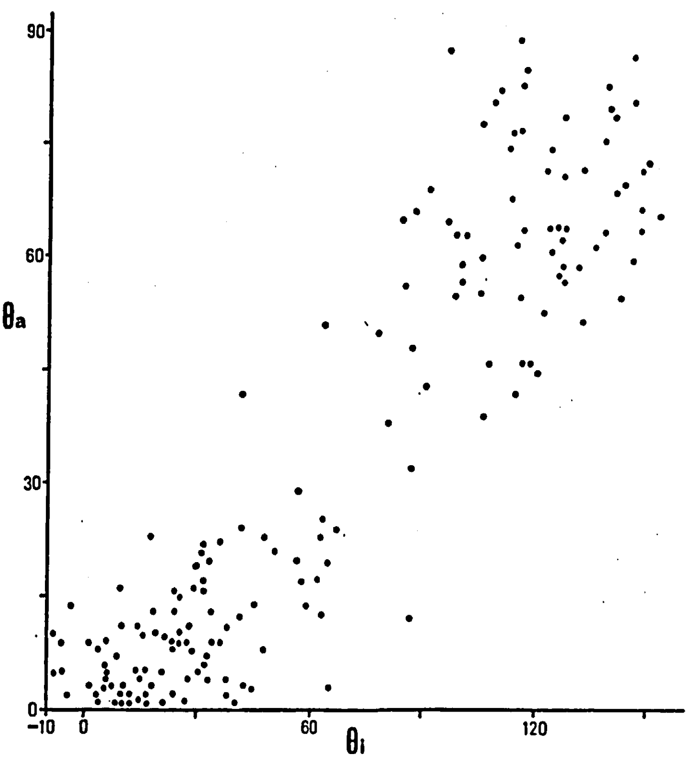

FIG. 4. Diagram showing relationship between θ_l and θ_a for the S-folds of quartz veins observed on the limbs of the M-folds.

θ_a larger than 60° are commonly together found on the same quartz vein. On the limbs of the M-folds, the folded quartz veins alternate frequently with the quartz veins showing no fold-form (Plate 10–a). The former is parallel to the latter. The quartz veins, which do not show any fold-form on the limbs of M-folds, are intensely folded in the hinge zones of the M-folds, like in the case of the folded quartz veins on the limbs of the M-folds. Quartz grains in the planar quartz veins on the limbs of the M-folds show strongly undulatory extiction and fragmentation, destroying original preferred dimensional orientation.

In Fig. 5, poles to quartz veins (if folded, pole to the enveloping surface) on the limbs of the M-folds, which have been measured in a small domain (ca. 1 m^2) of the Yukidomari outcrop, are plotted with reference to their deformation style. Two poles with same

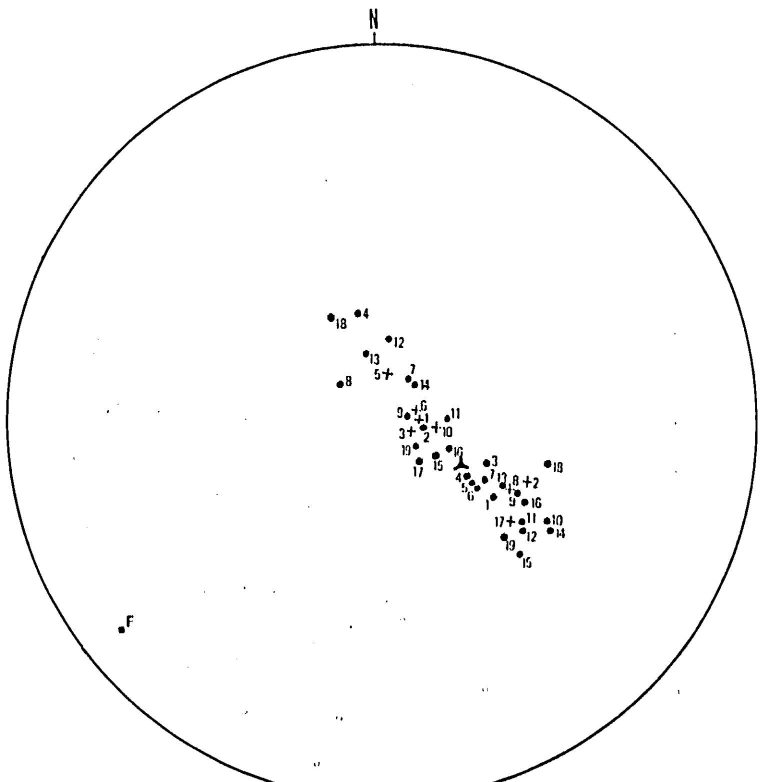

FIG. 5. Diagram for poles to quartz veins observed on the limbs of M-folds in the small domain of the Yukidomari outcrop which are plotted with reference to their deformation style. F: axis of M-fold. Triangle: pole to axial surface of M-fold. Crosses: poles to planar quartz veins. Dots: poles to folded quartz veins.

number in this figure correspond to two limbs of one M-fold for one quartz vein respectively. Therefore, the angle between two poles with same number can be regarded as the interlimb angle of one M-fold. The M-folds in the hinge zone of one L-fold generally form a fold group, in which the axial surfaces are parallel to each other and fold-forms can be frequently traced through distance of a few meters along the axial surfaces. The data of Fig. 5 has been measured from such the fold group developed in the hinge zone of one L-fold. Poles to quartz veins showing fold-forms and those to quartz veins showing no fold-form together distribute in the same parts of Fig. 5.

In this small domain of the Yukidomari outcrop there are no fold and boudinage structures, whose axes are oblique to the axes of the folds in question and which are of the same generation as the latter. However, the planar quartz veins on the limbs of M-folds and of S-folds appear to show frequently boudinage structures whose axes (neck lines) are parallel or subparallel to the axes of those folds (Plate 9 and 10–a). If quartz veins were extended in a direction parallel to the fold axis during the long history of the deformation related to the formation of the S-folds, therefore, boudinage structures, whose axes are normal to the fold axis, should be formed on them. It could be said that quartz veins in this domain were only slightly or not extended in a direction parallel to the fold axis during the folding. Now, it would be concluded that the shape (k-value) of the strain ellipsoid of mean strain in this domain is described in term of $0 \ll k \leqslant 1$ and that the shortest principal axis (Z) of the strain ellipsoid is normal to the axial surfaces of the M-folds and the intermediate principal axis (Y) parallel or subparallel to the fold axis. From Fig. 5, the interlimb angles for the M-folds in this domain are very small (18° to 57°) and so the folds will be referred to as the type of the close-tight fold (cf. FLEUTY, 1964). Namely, quartz veins plotted in Fig. 5 (=limbs of the M-folds) are oriented at angles much larger than 45° to the Z-axis and parallel or subparallel to the Y-axis. It could be therefore said that those veins must have already passed through the surface of no infinitesimal longitudinal strain. While the quartz veins in the hinge zones of the M-folds are placed closer to the Z-axis than to the surface of no infinitesimal logitudinal strain. Such the difference in strain condition between the quartz veins in the hinge zone and those on the limbs of the M-folds would be related to the above-described difference in deformation style between the former and the latter. Now, following points would be concluded. Most of S-folds of quartz veins having θ_1 larger than 120° and θ_a larger than 60° (Fig. 4) on the limbs of the M-folds would be referred to as the type of partially unfolded fold, and most of planar quartz veins, which do not show any fold-form, to as the type of completely unfolded fold. This conclusion appears to be supported by the above-mentioned nature of the dimensional fabric of quartz grains in them (see Plate 11–a and b). The S-folds of quartz veins having θ_1 smaller than 90° and θ_a smaller than 30° observed on the limbs of the M-folds in which the dimensional fabric of quartz grains have the same nature as that in the S-folds of quartz veins observed in the hinge zones of the M-folds would be referred to as the type of active closing fold. According to RAMBERG's (1959), FLINN's (1962), RAMSAY's (1967) and TALBOT's (1970) assumption that, during progressive deformation, fold-forms of competent layers produced in the earlier stage of deformation are completely unfolded when passed through the surface of no finite longitudinal strain, the partial areas in Fig. 5, in which poles to the completely unfolded quartz veins distribute, must be regared as the over all extension field occupying between the XY-plane and the surface of no finite longitudinal strain. Their assumption suggests that there should be no possibility that, on parallel competent layers in homogeneously deformed domain which are oriented in the over all extension field, planar parts (=completely unfolded folds) are together found with active closing folds and opening folds. Now, it can be pointed out that the present data is quite not harmonic with RAMBERG's, FLINN's, RAMSAY's and TALBOT's assumption mentioned above, and that deformation style of quartz veins during the unfolding phase (=deformation phase after passed through the surface of no infinitesimal longitudinal strain) is more complicated than what they assumed.

III. DISCUSSION

What does it mean that, on parallel quartz veins which are of the same generation and deform under the same stress condition, active closing folds are together found with opening folds (and completely unfolded folds), that, on one quartz vein whose general trend drawn by the enveloping surface is straight, active closing folds are together found with opening folds, and that one quartz vein, whose general trend drawn by the enveloping surface is straight, is divided into folded part and planar part? Such the question will be replaced by the following terms: How are quartz veins folded during the folding phase (=deformation phase before pass through the surface of no infinitesimal longitudinal strain)? And how are fold-forms of quartz veins, produced in the earlier stage of deformation, unfolded during the unfolding phase?

Folding style of quartz veins developed during the folding phase has been briefly examined by HARA *et al.* (1968), describing the relationship between θ_i and θ_a for the folds of quartz veins in the psammitic schist of the Koboke district, which are oriented parallel to the Y-axis for the mean strain of the system concerned and at angles of 50°–60° to the XY-plane. This relationship is reproduced in Fig. 6.

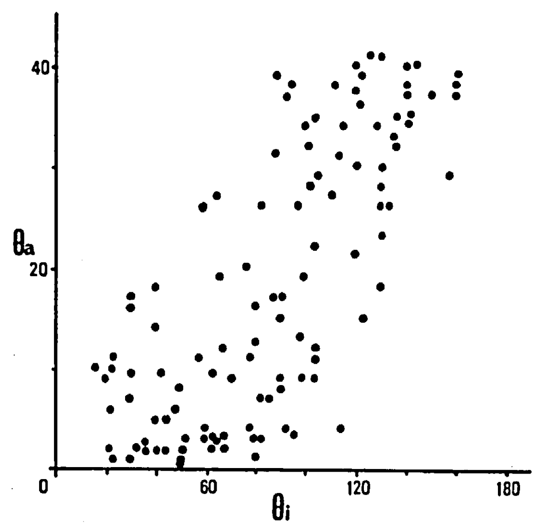

Fig. 6. Diagram showing relationship between θ_i and θ_a for the folds of quartz veins in the psammitic schist of the small domain of the hinge zone of the Koboke syncline, whose enveloping surfaces are inclined at angles of 50°–60° to the XY-plane.

Fig. 6 indicates that θ_a is not constant but between 40° and 0°. Namely, the axial surfaces of the folds of quartz veins are neither always normal to the layer surface nor parallel to the XY-plane, but they are oriented in all directions of between the normal to the layer surface and the XY-plane. Roughly speaking, however, θ_1 the larger, θ_a the larger. And the axial surfaces of the folds of quartz veins with the largest value of θ_1 are oriented approximately normal to the layer surface, while those of the folds with the smallest value of θ_1 are approximately parallel to the XY-plane. The orientation directions of the axial surfaces of the fold found on one quartz vein are not always constant, showing co-existence of folds with the axial surfaces normal to the layer surface and those with the axial surfaces parallel to the XY-plane. However, on some quartz veins are predominate the folds with the axial surfaces normal to the layer surface, while on some others are predominate the folds with the axial surfaces parallel to the XY-plane. Those facts may suggest that the quartz veins are initially folded with the axial surfaces normal to the layer surface and, though the axial surfaces are generally rotated towards the XY-plane during progressive deformation, those of the folds which grow in fast rate are so faster rotated. However, Fig. 6 also indicates that the axial surfaces of some folds are still oriented normal to the layer surface even when θ_1 became 80°. Therefore, an alternative interpretation on Fig. 6 is that folds which grow in slow rate are initially formed with the axial surfaces normal to the layer surface, while folds which grow in fast rate have their axial surfaces parallel to the XY-plane even in the initial stage of folding. However, the former interpretation on Fig. 6 appeats to be rather harmonic with the result of GHOSH's (1966) simple shear experiments.

How are quartz veins, which during the folding phase were folded in such a fashion as mentioned above, deformed during the unfolding phase? If the axial surfaces are parallel to the XY-plane when quartz veins pass through the surface of no infinitesimal longitudinal strain, they should remain in a direction parallel to the XY-plane during the unfolding phase. Then, the folds should be still closing but not unfolded. The folds would be actively closing still after the quartz veins passed through the surface of no finite longitudinal strain. On the other hand, if the axial surfaces are normal to the layer surface even when quartz veins pass through the surface of no infinitesimal longitudinal strain, the folds should be unfolded during the unfolding phase, because of compressive strain normal to the axial surfaces. Therefore, the folds may be completely unfolded when the quartz veins pass through the surface of no finite longitudinal strain. If the axial surfaces are oriented in a direction intermediate between the XY-plane and the normal to the layer surface when quartz veins pass through the surface of no infinitesimal longitudinal strain, the folds would be slower unfolded during the unfolding phase than the folds with the axial surfaces normal to the layer surface. Thus, it can be concluded that it is not generallized that all fold-forms on quartz veins produced in the earlier stage of deformation are completely unfolded when pass through the surface of no finite longitudinal strain.

On quartz veins in the Koboke outcrop, which are parallel to the Y-axis and in a direction intermediate between the surface of no infinitesimal longitudinal strain and that of no finite longitudinal strain, are found both close fold-forms and open fold-forms (see Fig. 2 of HARA *et al.*, 1968). Even on quartz veins close to the surface of no finite longitudinal strain which is assumed by TALBOT's method are found close folds. If fold-forms on quartz veins would be completely unfolded when pass through the surface of no finite longitudinal strain, θ_1 should show a distinct tendency to increase towards this surface. This trend is not found in the data of Fig. 2 of HARA *et al.* (1968).

The above-described evidences and considerations are quite harmonic with the data from the Yukidomari outcrop. Thus, it can be pointed out that deformation style of competent layers produced during the unfolding phase is controlled by that of them produced during the folding phase. For example, if folds of competent layers were predominantly developed with their axial surfaces parallel to the XY-plane of the system concerned during the folding phase, on those layers would predominantly occur active closing of those folds even after those layers passed through the surface of no infinitesimal logitudinal strain and further through that of no finite longitudinal strain. Therefore, it would be said that TALBOT's (1970) method for description of strain magnitude may not be always usefull.

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EXPLANATION OF PLATE IX

Photograph of S-folds and M-folds (in reverse). Active closing folds, partially unfolded folds and boudins are observed on quartz veins. X 4.

EXPLANATION OF PLATE X

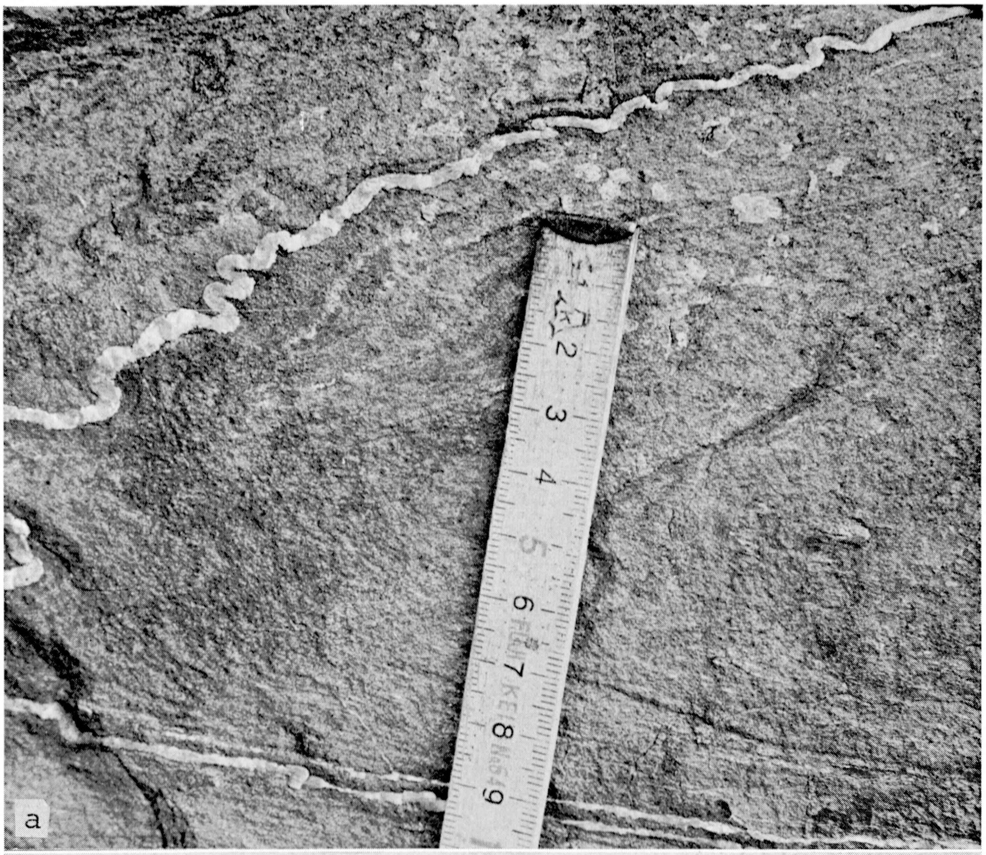
FIG. a. Photograph of S-folds and M-fold. One of quartz veins on the limb of M-fold is partially unfolded but the other is completely unfolded.

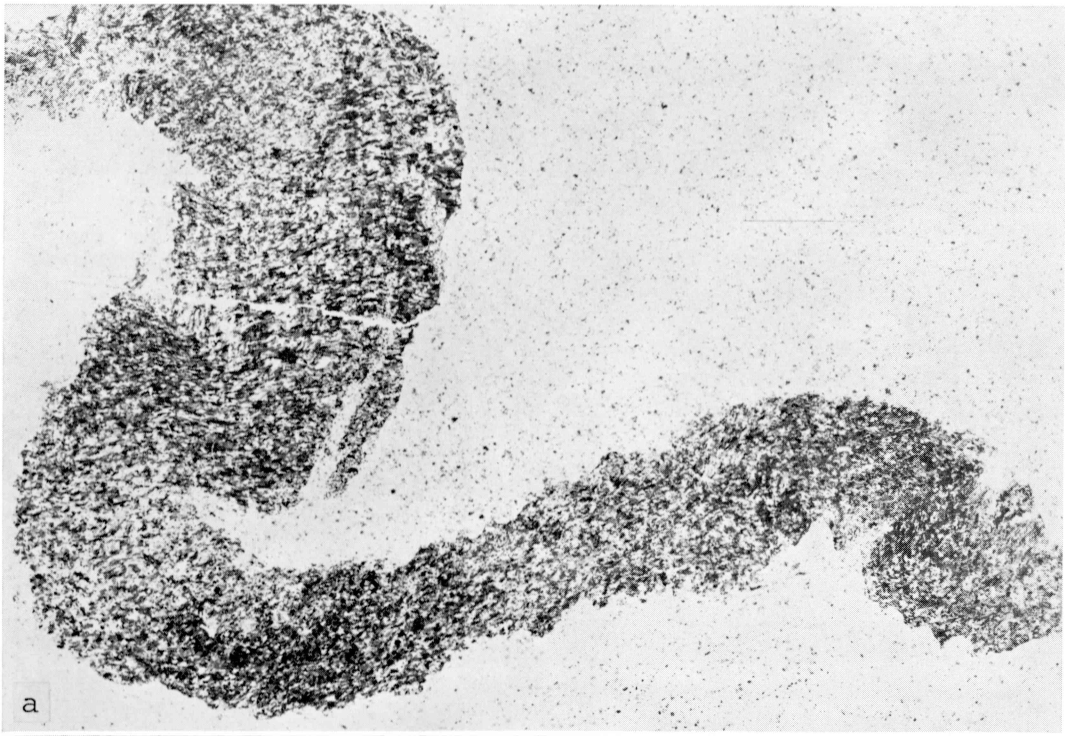
FIG. b. Dimensional orientation of quartz grains in the fold of quartz vein found in the hinge of M-fold (in reverse). X 20.

EXPLANATION OF PLATE XI

FIG. a. Dimensional orientation of quartz grains in the active closing fold and partially unfolded fold of quartz vein found on the limb of M-fold (in reverse). X10.

FIG. b. Dimensional orientation of quartz grains in the partially unfolded fold of quartz vein (in reverse). X 20.

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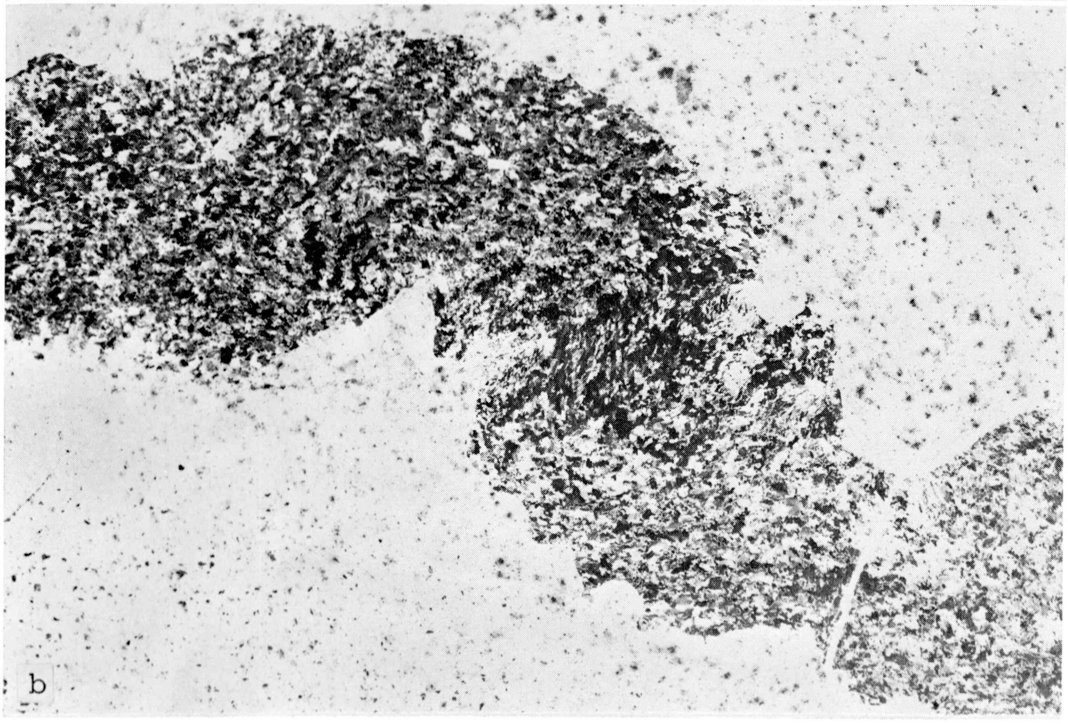
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