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Transition from Flexural−Flow Folding to Flexural−Slip Folding in the Sambagawa Belt

By

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with 11 Text−figures

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Abstract: The styles and physical condition of the folding of the Hijikawa−Oboke phase (Dh phase) have been described and discussed in this paper. The physical condition has been analyzed on the basis of quartz microtextres such as c−axis fabrics and deformation lamellae and of homogenization temperature of fluid inclusion in quartz. When the Dh phase folding occurred in multilayered rock types with extremely thin incompetent layers (films), it shows a transformation from a flexural−flow type during the early stage to a flexural−slip type during the later stage. The flexural−flow folding formed the axial plane cleavage (quartz shape orientation) in competent layers (quartz−rich layers) converging toward the fold core, resulting in the Class 1C type thickness variation for all competent layers, though the thickness variation is as near to Class 1B in the outermost knee and to Class 2 in the fold core. While the flexural−slip folding resulted in the Class 1C thickness variation for the competent layers involved in the outer knee and the fold core and around the inflection points of these involved in the middle knee and in the Class 2−Class 3 thickness variation around the axial zones of these involved in the middle knee. The fault system consisting of R1 set, Y set and P set developed along the layer boundaries and in competent layers during the flexural−slip folding has been also described and discussed, clarifying the relationship between the thickness variation and its related fault system: The Class 2−Class 3 thickness variation is related with the P set (thrust set) which converges toward the top of fold, while the Class 1C thickness variation around the inflection points in the middle knee with the R1 set and Y set.

Contents

I. Introduction

The deformation styles of the Sambagawa schists during the Hijikawa−Oboke phase (Dh phase) folding will be described and discussed in this paper. The geometric and microtextures of the Dh phase folds for pelitic and psammitic schists with quartz seams (and quartz veins parallel to the bedding schistosity) and siliceous schists consisting of quartz−rich layers and mica−rich layers have so far been described and discussed by Hara (1966a, b, c, 1971, 1972), Hara et al. (1968,1975), Hara and Paulitsch (1971), Hara and Tsukuda (1975), Shimamoto and Hara (1976), Hara and Shiota (1978) and Hara and Shimamoto (1984). According to these works, the deformation style of the mica−rich layers during the Dh phase folding is commonly characterized by the formation of crenulation−differentiated crenulation cleavage as axial plane cleavage and that of the quartz−rich layers by the formation of the axial plane schistosity defined by preferred shape orientation of quartz grains (Fig. 1), showing that in these layers occurred such ductile flow during the folding that can be explained in term of flexural− flow. However, microscopic observation of some Dh phase folds indicates that the Dh phase folding occurred in different fashion between its early stage and its later stage: The deformation style during the early stage occurred in a flexural−flow fashion, while that during the later stage did in a flexural−slip fashion.

Such a transition from the flexural−flow type to the flexural−slip type during the Dh phase folding will be described and discussed in this paper on the basis of analysis of two Dh phase folds collected from the Sogauchi nappe in Hachinokawa along the River Kamo just on the south of Iyosaijo. The data for the later stage folding of flexural−slip type must give information available to understand folding mechanism of multilayered rocks.

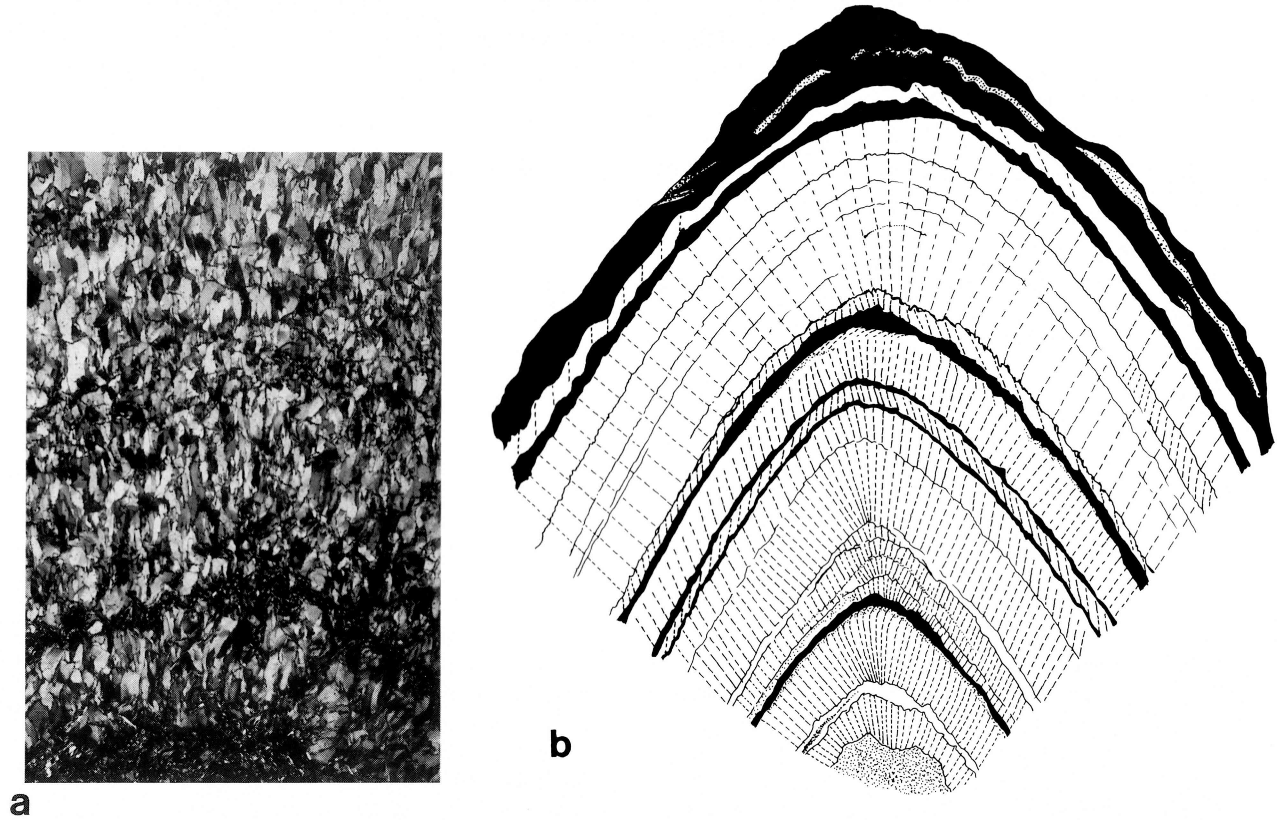

Fig. 1. Quartz shape orientation in a Dh phase fold of flexural—flow type, which has been collected from the Sogauchi nappe developed along the River Kamo in Hachinokawa.
a) Photograph of the axial zone, b) a sketch of quartz shape orientation in quartz—rich layers (competent layers). black layers: flaky mineral—rich layers, white layers: quartz—rich layers, dashed lines: orientation direction of long axes of quartz grains.

Acknowledgements

The authors thank Dr. K. Hoshino of Hiroshima University, who has kindly supported their measurment of the homogenization and freezing temperature for fluid inclusions in quartz. Their works have been partly supported by the Grant in Aid for Scientific Researches of the Ministry of Education of Japan.

II. Folding Style of the Early Stage: Flexural—Flow Folding

The shape orientation of quartz in quartz—rich layers and cleavage orientation in mica—rich layers involved in the Dh phase folds had been analyzed by Hara (1966a, b, c, 1972), Hara et al.(1968), Shimamoto and Hara (1976) and Hara and Shimamoto (1984). Fig. 1 illustrates a typical one of such microtextures. Shimamoto and Hara pointed out that, as assumed by Hara et al.(1968) and Hara (1972), the pattern of shape fabric of quartz in quartz—rich layers as competent layers and the orientation pattern of crenulation—differentiated crenulation cleavage in their host incompetent layers such as pelitic (and mica—rich layers), psammitic and basic schists are comparable with strain picture [orientation pattern of XY plane as the principal axes of strain are X>Y>Z] in buckle folds of competent viscous layers and their host incompetent viscous layers, which was determined by using finite element method. These layers were deformed in a ductile fashion but not by strain concentration along the layer boundaries during the folding, showing that the Dh phase folds so far described belong to the type of flexural—flow fold but not to that of flexural—slip fold. Namely, any fault is not found in the layers involved in these folds as is obvious in Fig. 1.

Deformation style of quartz appears to change distinctly depending upon its deformation condition such as temperature, strain rate and H_2O etc (e.g. Heard & Carter, 1968; AveLallement & Carter,1971; Tullis et al., 1973; Lister & Hobbs, 1980; Bouchez et al., 1983; Hobbs, 1985; Schmid & Casey, 1986). Therefore, the physical condition for the Dh phase folding may be inferred from the deformation style of quartz. Initial quartz grains in the Dh phase folds of quartz veins, which crystallized from vein—filling fluid and are coarse—grained, are changed into dynamically recrystallized fine—grained quartz but some of them are found as relict grains.

Fig. 2 is a microphotograp of such quartz microtextures and also illustrates the c—axis fabric of relict

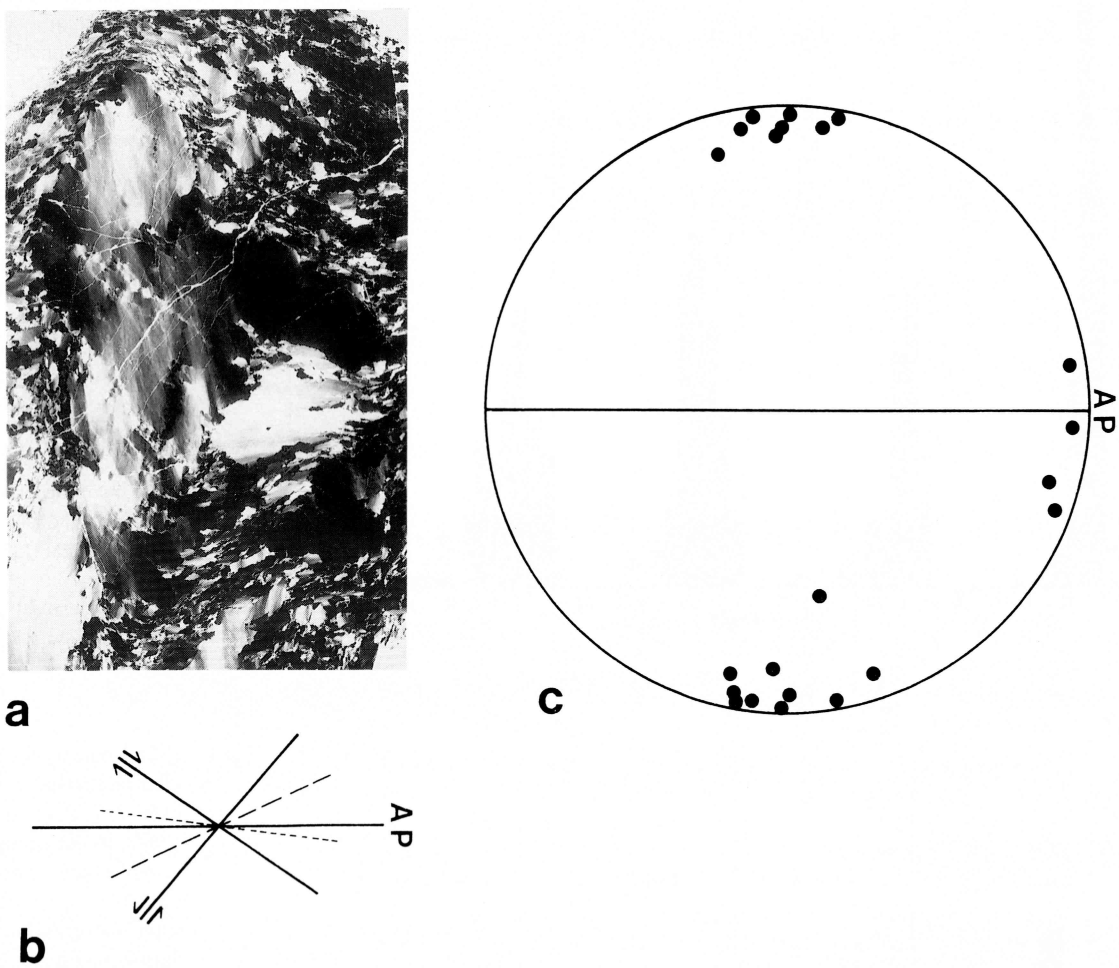

Fig. 2. Orientation data of relict quartz grains in a Dh phase fold collected from the Besshi district along the River Kokuryo, as observed on thin section normal to the fold axis.
a) Photograph of the axial zone in which coarse–grained quartz as relict grains are found together with fine–grained quartz as dynamically recrystallized quartz. b) diagram illustrating the orientation pattern of conjugate shear zones around a relict quartz grain in Fig. 2–a which are defined by preferred shape orientation (dashed lines) of fine–grained quartz. Short dashed line is for right–lateral shear zone and long dashed line is for left–lateral shear zone. c) c–axis fabric for relict quartz grains. AP: axial plane.

vein quartz. The Dh phase fold of quartz vein of this figure is of large interlimb angle (ca.160) and embedded in pelitic schist. Competence difference between quartz vein and pelitic schist is large (Hara et al. , 1968; Shimamoto & Hara, 1976). It would be therefore said that bulk strain of quartz vein of Fig. 2 is fairly small in magnitude. Fig. 2 shows that dynamically recrystallized quartz grains are developed forming two sets of shear zone around a relict quartz grain and that c–axes of relict quartz grains are distinctly regularly oriented in directions normal to and parallel to the axial plane and so to the compression axis during the folding, suggesting that basal plane was the weakest one of active slip systems under physical condition during the Dh phase and the physical condition was near the limit for other slip systems such as rhomb[a] and prism [a] to be active.

Quartz c–axis fabrics in the Dh phase folds of quartz veins, which appeared just before the Dh phase, have also so far been analyzed by Hara and Paulitsch (1971). The interlimb angles are much smaller in Hara and Paulitsch's cases than in the above described case (Fig. 2). Initial vein quartz in the former, which is coarse–grained, is only rarely found, almost being replaced by dynamically recrystallized grains with fine size. The c–axis fabrics of such dynamically recrystallized quartz are commonly referred to type I crossed girdle, except for the case in which basal plane of initial vein quartz is oriented normal and paralled to the axial plane. It would be therefore said that rhomb[a] and prism[a], as well as basal[a], was active during the Dh phase folding but the former was distinctly more hard than the latter.

Deformation lamellae are rarely found in quartz

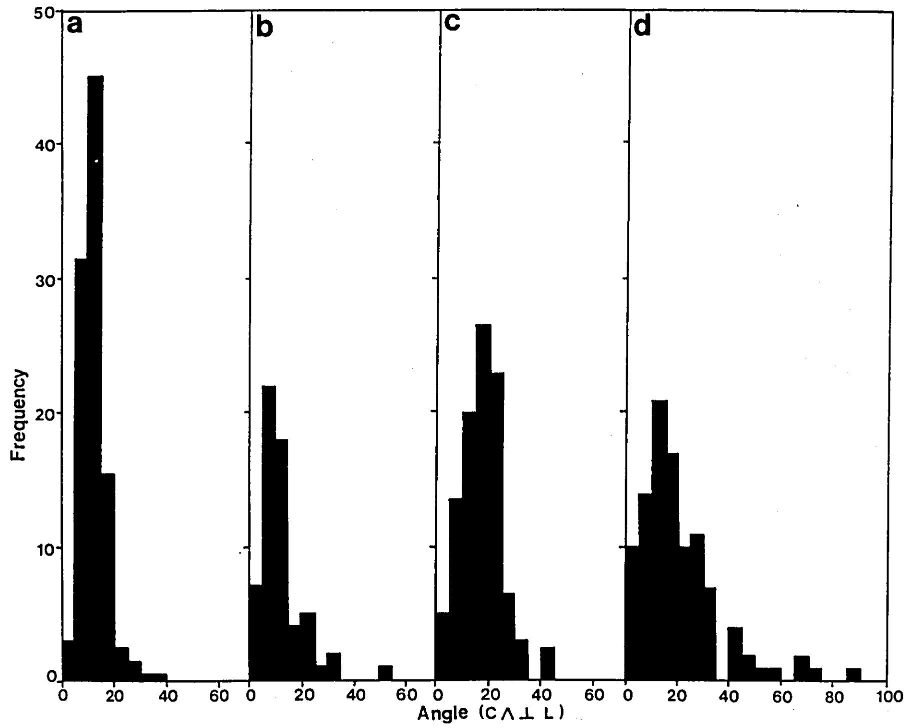

Fig.3. Crystallographic locations (angle between c−axis and pole to lamellae) of deformation lamellae in quartz for various deformation phases.
a) data for quartz with Type III microtextures in siliceous schist of the garnet zone developed along the River Asemi (data for the Sb2−2 phase), b) data for deformation lamellae produced during the formation of the Tsuji overturned fold (data for the Ozu stage) (after Seki et al., 1993), c) data for quartz in the Dh phase folds collected from the Sogauchi nappe along the River Kamo in Hachinokawa, d) Data for quartz in en echelon quartz veins from the Kamidoi district [data for the post−Dh phase after Tsukuda (1976)].

Frequency is given by number of measured grains. For fuller explanation see the Text.

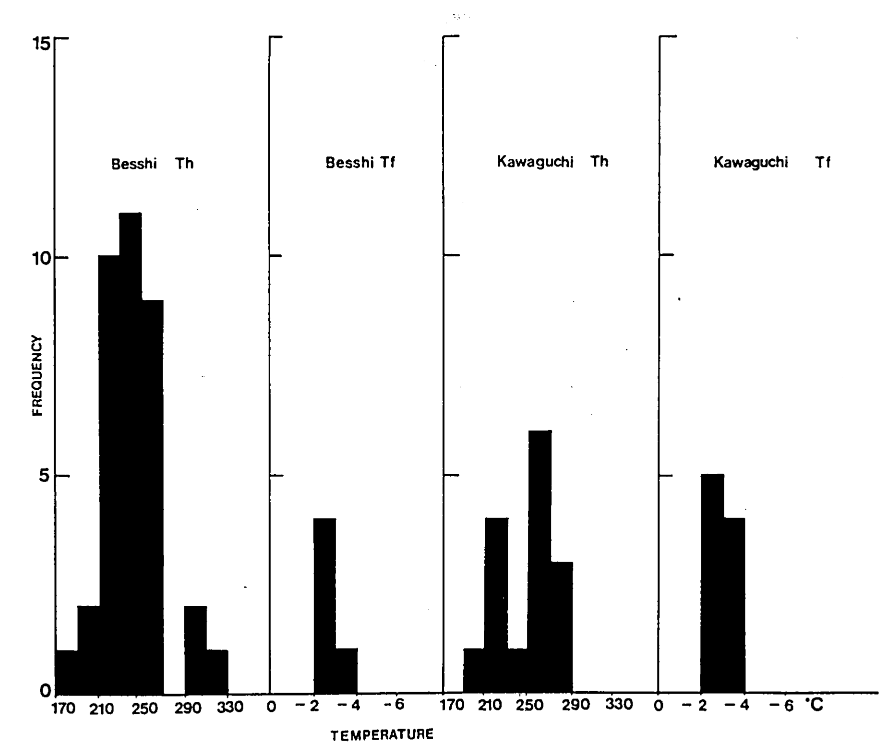

Fig.4. Homogenization temperature (Th) and freezing temperature (Tf) for fluid inclusions in quartz (relict grains) of quartz veins which were produced probably just after the Ozu stage deformation and folded during the Dh phase.

Frequency is given by number of measured grains. Besshi: data from the garnet zone of the Ojoin melange zone in Besshi along the River Kokuryo, Kawaguchi: data from the chlorite zone of the Oboke nappe I in Kawaguchi along the River Yoshino.

grains (both initial vein quartz and dynamically recrystallized quartz) in the Dh phase folds. Fig. 3 is the crystallographic orientation data for the deformation lamellae, showing a marked maximum between 10 and 20 for the angles (Lo) between c−axis and pole to lamellae. From this figure, therefore, it would be said that these for the Dh phase are referred to the type of subbasal I lamellae after AveLallemant and Carter (1971). Deformation lamellae are also rarely found in quartz grains withType III microtextures, which have been assumed by Hara et al.(1992) to have been produced by the Sb2−2 phase deformation. Deformation la-

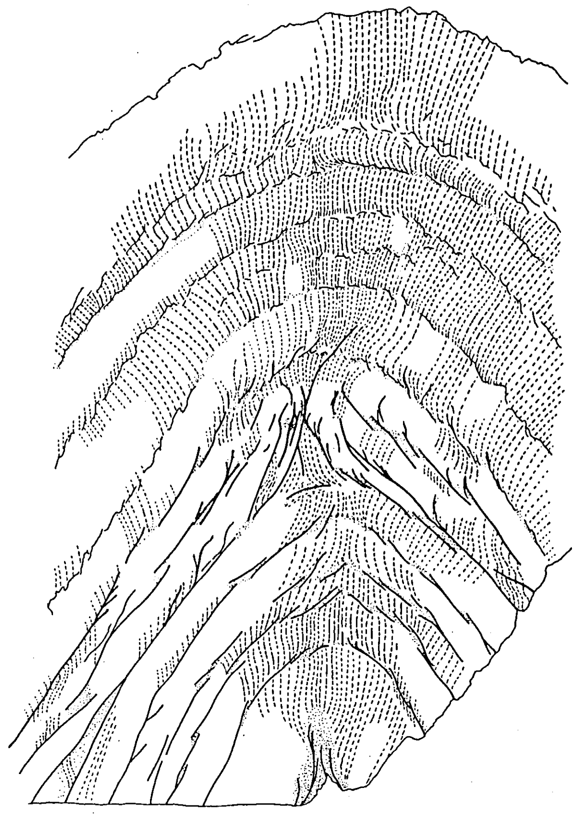

Fig.5. Quartz shape orientation and orientation of dominant faults in a Dh phase fold of flexural−slip type, which has been collected from the Sogauchi nappe developed in Hachinokawa along the River Kamo.
dashed lines: orientation direction of long axes of quartz grains, heavy lines: dominant faults, parts without dashed lines: parts in which preferred shape orientation of quartz disappeared during the flexural−slip folding.

mellae associated with Type III microtextures occur in conjugate sets with a dominant set: The dominant set is synthetic with reference to bulk shear assumed from shape and lattice fabrics (Type II S−C structure) and antithetic set is only rarely found. Fig. 3 illustrates their crystallographic orientation, showing a marked maximum between 5 and 15 for Lo. It is clear that the crystallographic orientation of deformation lamellae is quite different between the Sb2−2 phase and the Dh phase and Lo is smaller for the former than for the latter. Tsukuda (1976) analyzed quartz fabrics such as lattice fabric, shape fabric and deformation lamellae in en echelon quartz veins, which were produced just after the Dh phase folding. The crystallographic orientation data of these deformation lamellae are reproduced in Fig. 3, showing a wide range variation of Lo with a maximum between 10 and 20. It can be said that the Lo shows a clear tendency to increase with the younging of deformation.

In the Sambagawa schists are commonly found the bedding schistosity−parallel quartz veins, which were produced just before the Dh phase folding and after the Ozu stage deformation (Hara et al. , 1968,1992). Fluid incusions are found in quartz grains of such quartz veins. Homogenization temperature (Th) for these fluid inclusions, as well as their freezing temperature (Tf), have been determined to infer the temperature of the Dh phase (Fig. 5). The quartz veins used to determine Th were collected from the garnet zone in the Ojoin melnage zone of the Besshi district along the River Kokuryo, which is placed in the uppermost level of the pile nappes of the Sambagawa schists, and from the chlorite zone in the Oboke nappe I of the Kawaguchi district along the River Yoshino, which is placed in the lowest level (Fig. 5). The chemical composition of the fluid inclusions in question has not been yet determined. Th appears to be ca. 240 in the Ojoin melange zone and ca. 260 in the Oboke nappe I (Fig. 5). It may be therefore roughly said that the Dh phase folding occurred under a little lower temperature in the Ojoin me-lange zone (garnet zone) as the uppermost structural level than in the Oboke nappe I (chlorite zone) as the lowest structural level, showing a downward increase of temperature.

III. Folding Style of the Later Stage: Flexural−Slip Folding

The folding style of multilayerd rocks appears to be

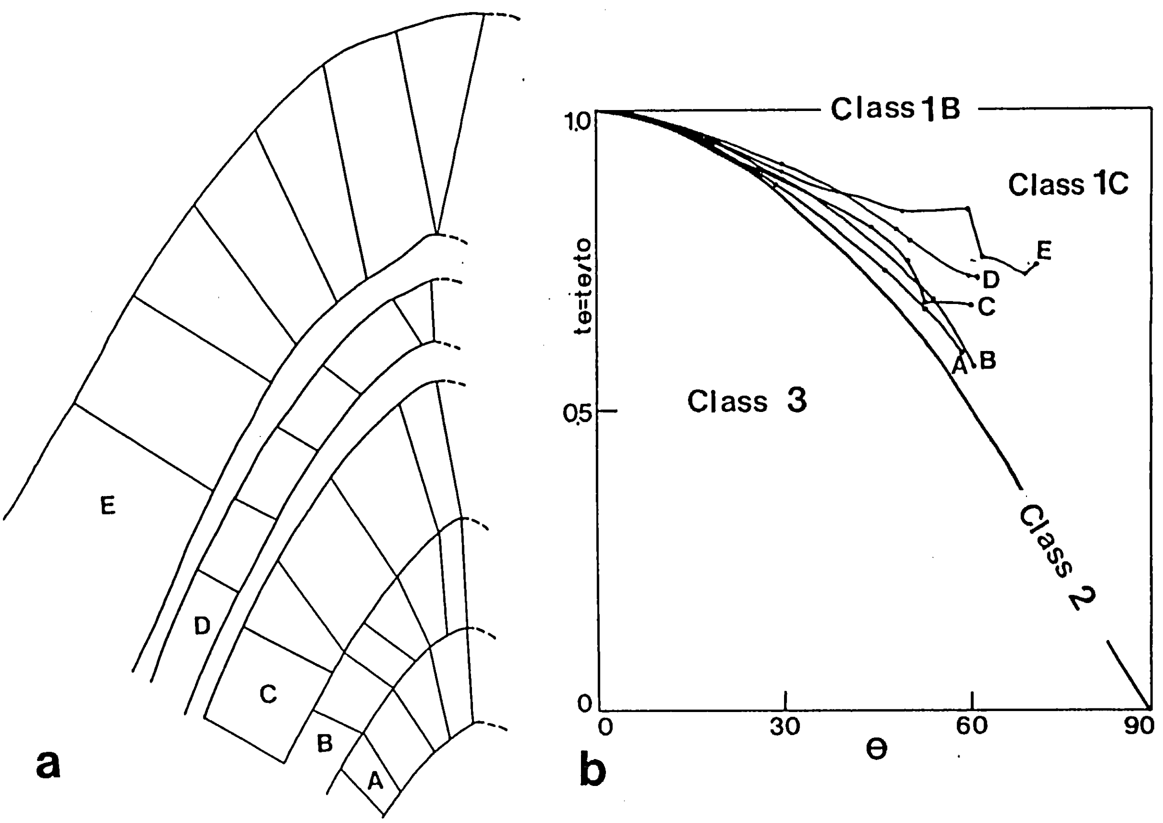

Fig. 6. Dip isogon pattern (a) and layer thickness variation (b) in a Dh phase fold of flexural−flow type shown in Fig. 1. A−E: quartz−rich layers.

controled by thickness ratio and competence difference between constituent competent and incompetent layers, strain rate and stage of fold development etc (e.g. Ramsay, 1974; Price and Cosgrove, 1990). In the Dh phase folds with thick incompetent layers (mica−rich layers) is not found the flexural−slip stage. But it is found in the folds consisting of thick competent layers and extremely thin incompetent layers, showing that a flexural−slip folding occurred only during the later stage. Slip system and associated deformation within competent layers, which appeared during such flexural−slip folding, will be analyzed in this section.

Fig. 5 is a sketch of a Dh phase fold in question. From the shape fabric of quartz in this figure, it can be pointed out that the flexural−flow type folding occurred during the early stage for the formation of the Dh phase fold, forming fan−like arrangement of elongate quartz grains. Most of incompetent layers of the Dh phase fold are extremely thin mica−rich films. Fig. 7 illustrates the dip isogon patterns. The fold is divided into two units with reference to dip isogon patterns, Class 1 unit and Complex unit. The Class 1 unit is placed in the convex side of the fold, while the Complex unit in the concave side. All of the layers involved in the Class 1 unit show the Class 1 type dip isogon pattern and Class 1C type thickness variation (Fig. 7). The thickness variation is as near to the Class 2 for the layer involved in the fold core of the Class 1 unit and to the Class 1B for the layer involved in the outermost knee. While the layers involved in the Complex unit show the complicated patterns of the dip isogon orientation and layer−thickness variation (Fig. 7): The quartz−rich layer A involved in the fold core of the Complex unit shows a bulbous shape with dip isogon pattern of Class 1. The layer B just overlying the layer A shows the Class 2 type dip isogon pattern in the small part around the hinge but the Class 1 type dip isogon pattern in the limbs. All other quartz−rich layers involved in the Complex unit show the Class 2−Class 3 type dip isogon pattern around the hinge but the Class 1 type dip isogon pattern around the inflection point. The area with the Class 2−Class 3 type dip isogon pattern increases toward the outermost knee of the complex unit. The thickness variation around the hinge changes from the Class 1C in the fold core, through the Class 2 in the middle knee, to the Class 3 in the outer knee of the Complex unit. The deformation mechanism, which was responsible for the formation of the fold with the above−described pattern of layer−thickness variation, will be analyzed in the following paragraphs. Fig. 6 illustrates dip isogon pattern and layer−thickness variation for the Dh phase fold of flexural−flow type shown in Fig. 1. For all the layers involved the former is of Class 1 and the latter is of Class 1C, being as near to Class 1B in the convex side, unlike

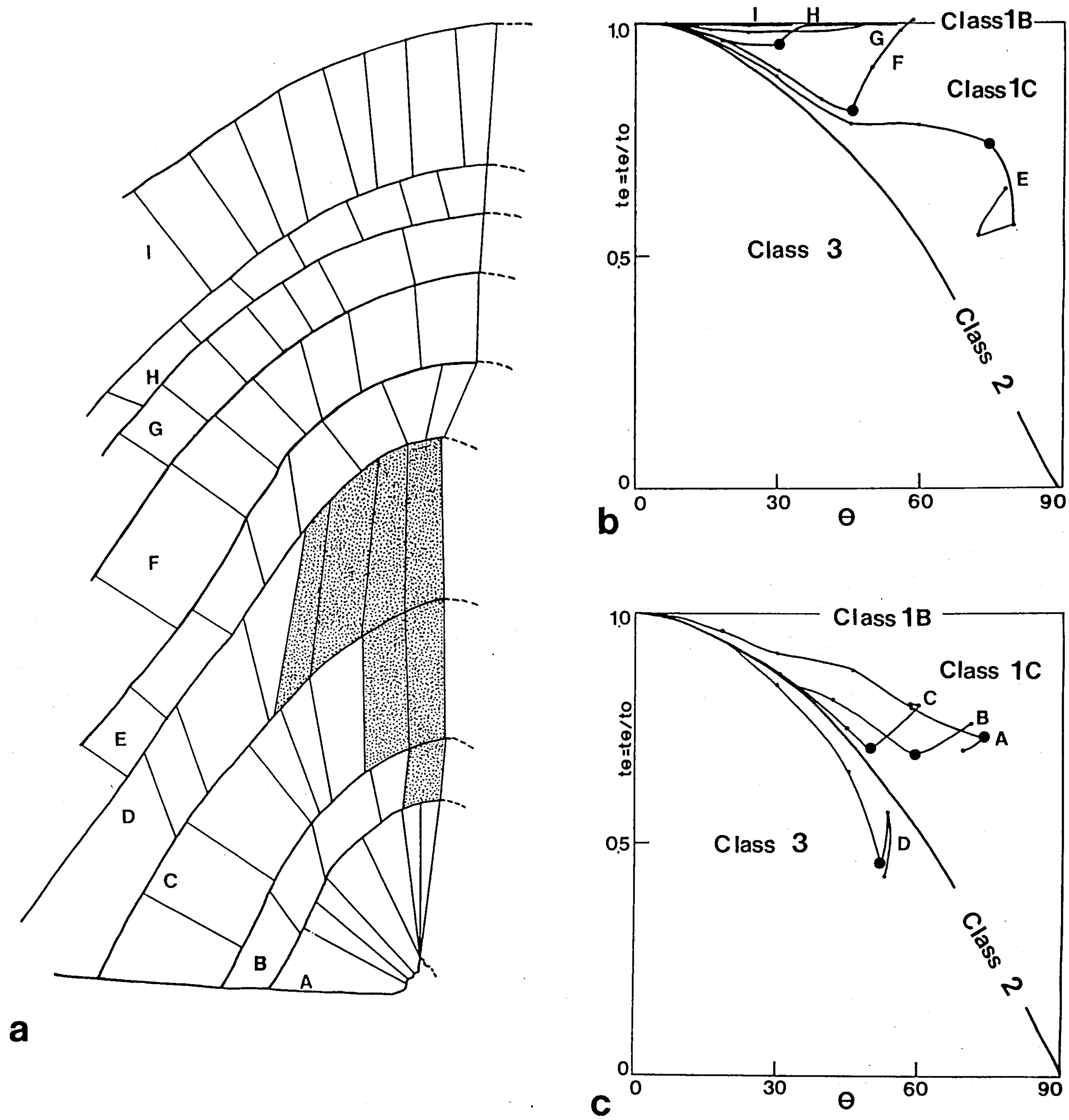

Fig. 7. Dip isogon pattern (a) and layer thickness variation (b and c) in a Dh phase fold of flexural—slip type of Fig. 5. A—I: quartz—rich layers, Layer A—D: complex unit [stippled part: Class 2—Class 3, non—stppled part: Class1], Layer E—I: single unit [Class 1], b) data for layers E—I, c) data for layers A—D.

the case of the flexural—slip type (Fig. 7).

Faults are developed in and around the mica—rich films in the fold limbs (Fig.8) and in quartz—rich and mica—rich films in the fold hinges (Fig. 9). These are especially strongly developed in the layers involved in the middle knee and in the fold core of the layer A.

Faults are shown as zones consisting of minute grains of quartz, mica and opaque minerals (Figs. 8 and 9). Shear sense along the faults is determined from the pattern of shape orientation of mineral grains within and around the zones. Dominant faults traced along long distances and shear sense along them are illustrated in Fig. 10. Most of them on the fold limbs are oriented oblique at small angles to the layer boundaries, being quite rarely parallel to the layer boundaries, but their orientation pattern appears to show a regular fashion. Namely, the faults on the fold limbs appear to be referred to the fault system developed along shear zone, which has been shown by Riedel (1929), Skempton (1966), Tchalenko (1970) and Logan et al.(1979). Thus it would be said that the faults as Riedel shear R1 and as principal dsplacement shear Y are dominant in the part of fold

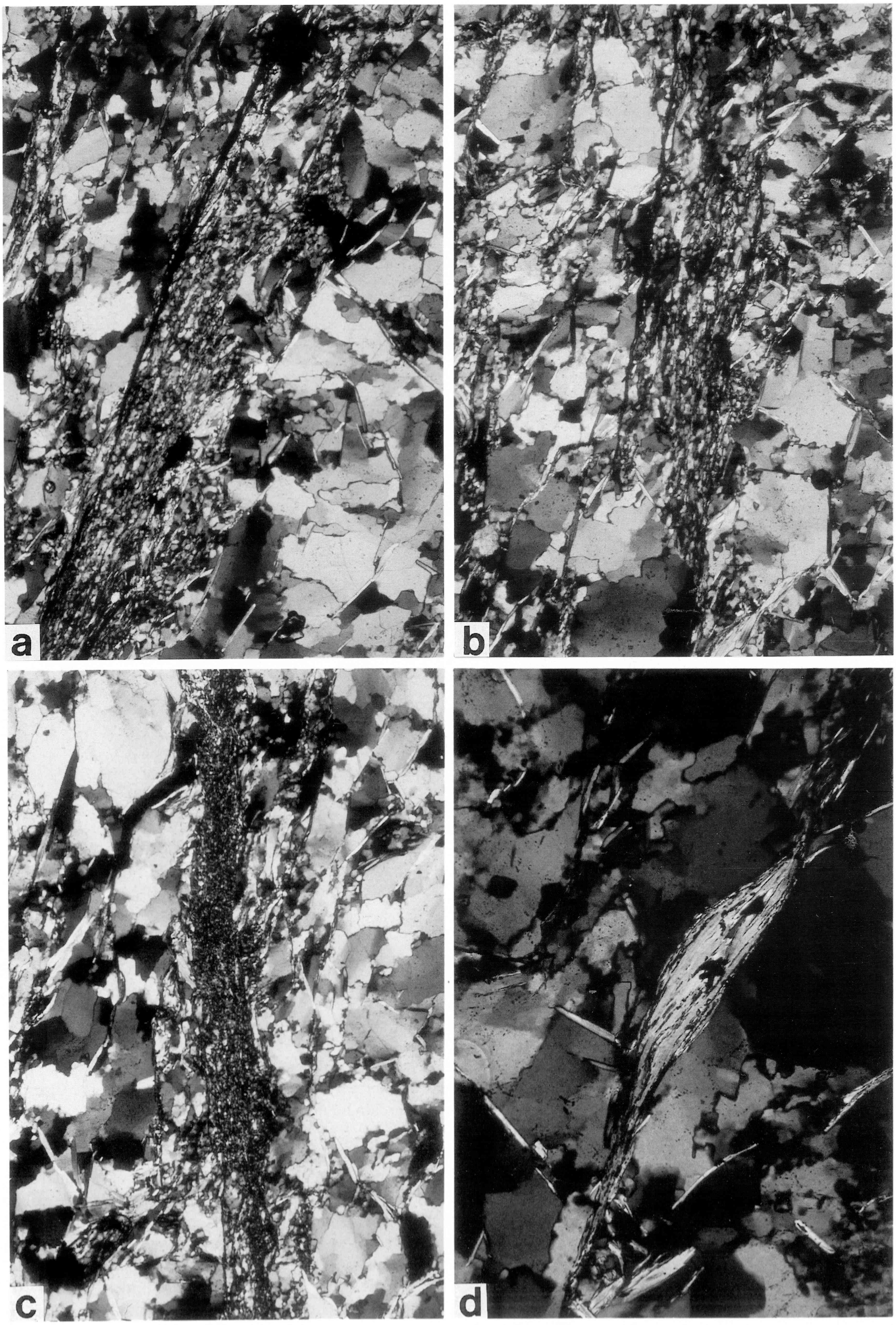

Fig. 8. Various types faults observed in a Dh phase fold of flexural−slip type of Fig. 5.
a) mylonite zone as R1 fault observed in limb, b) mylonite zone developed at the end points of two sets of R1 fault, c) ultramylonite zone as R1 fault observed in limb, d) mica fish along R1 fault.

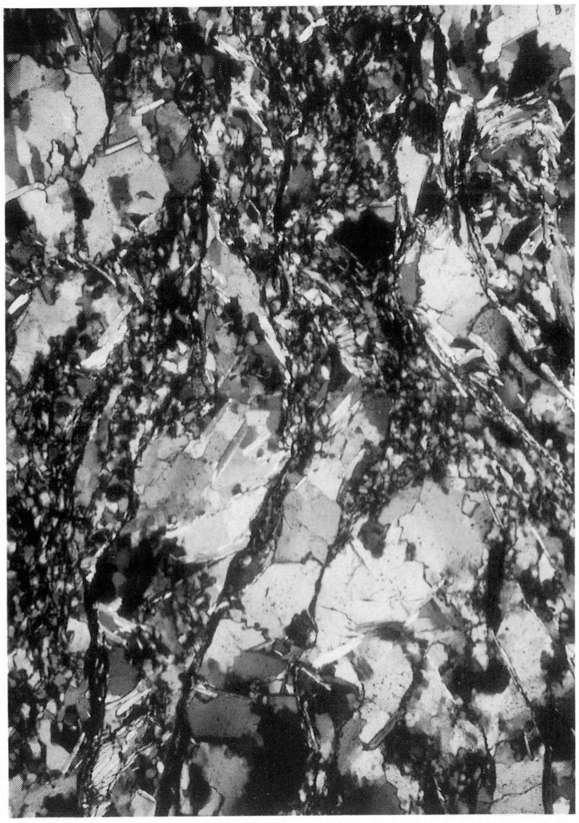

Fig. 9. Mylonite zones as faults converging toward the fold top, which are observed in the middle knee (Fig. 5).

Fig. 10. Orientation pattern and shear sense of dominant faults in the middle knee of a Dh phase fold (Fig. 5) produced during the flexural－slip folding.

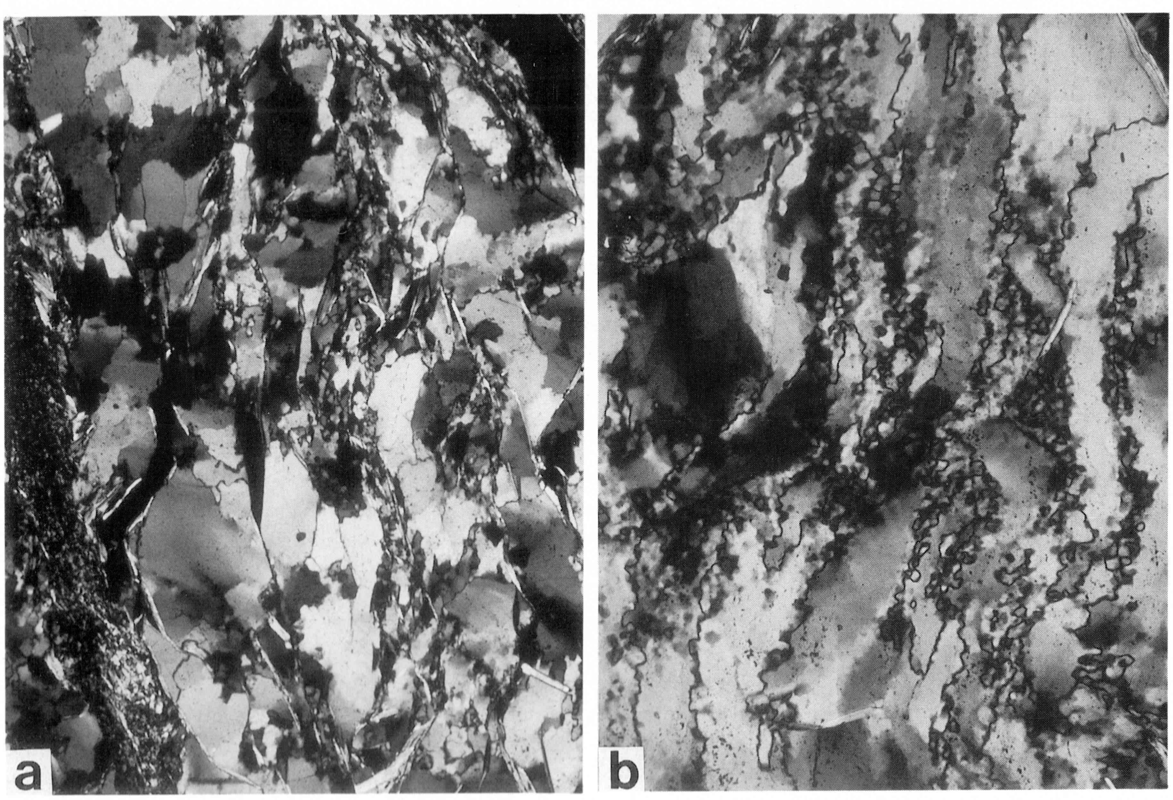

Fig. 11. Minute grains dynamically recrystallized along grain boundaries of quartz in quartz－rich layers of a Dh phase fold of flexural－slip type (Fig. 5).
a) photograph of a quartz－rich layer bounded by R1 falults in limb, b) photograph of axial zone. Quartz grains are strongly elongated parallel to the axial plane.

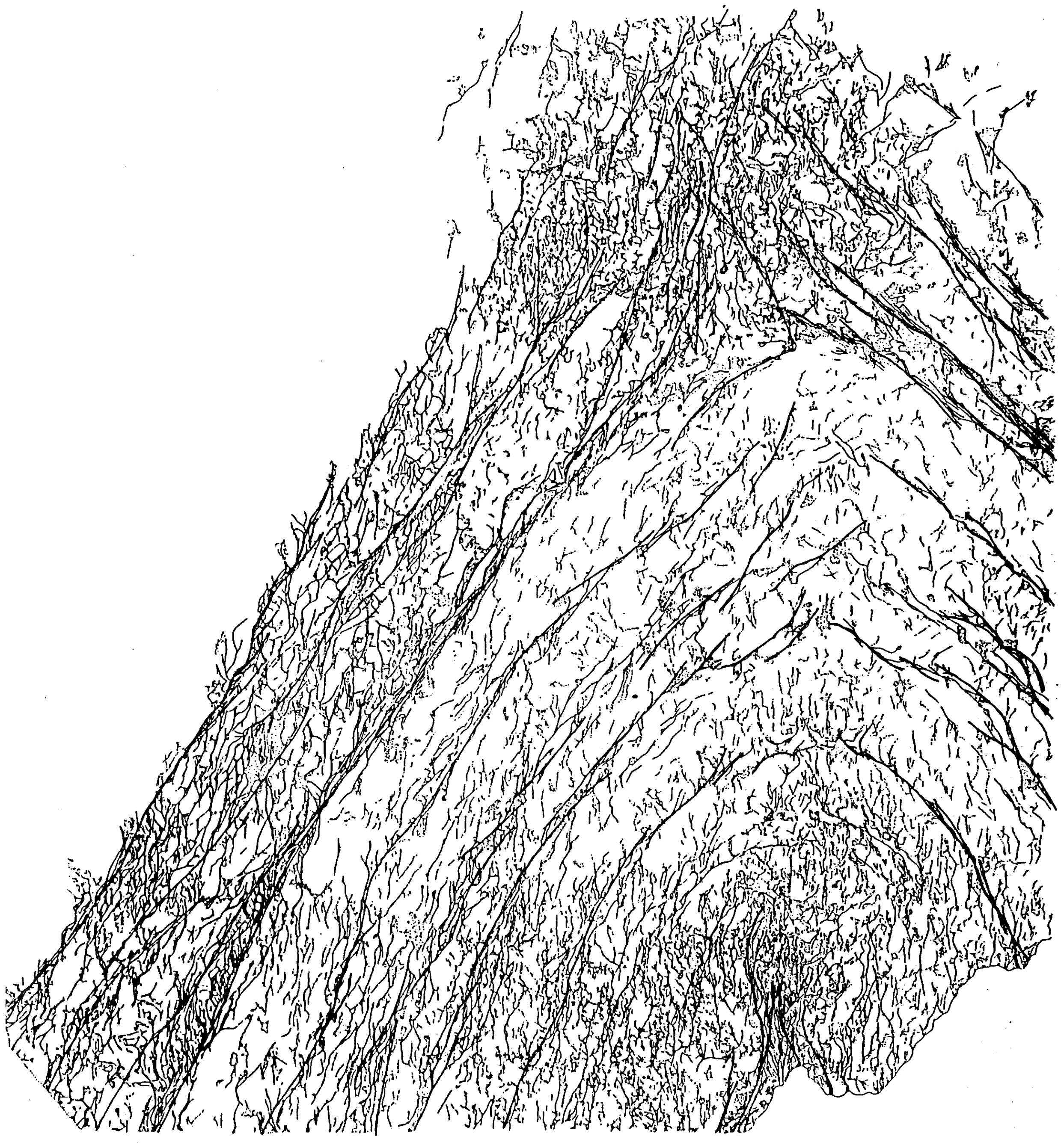

Fig. 12. Distribution pattern of grain−size reduction zones in a Dh phase fold (Fig. 5) produced during the flexural−slip folding. The diagram is for the complex unit and was produced by a detailed sketch of mocrophotographs. The size of the fold as measured along the axial plane is ca.1.5 cm.

limb away from the hinge and these as thrust shear P are dominant in the part of fold limb near and in the hinge.

The P faults in the hinge zones appear to be also developed in arc−like arrangement symmetrically oriented with reference to their axial plane as is obvious in Fig.10. The orientation pattern and shear sense of R1 faults and P faults on both limbs show a symmetrical relation with reference to the axial plane and harmonic relation with the sense of layer−parallel shear, which should have occurred during the folding. It can be therefore said that the flexural−slip during the Dh phase had not occurred only as the layer−parallel faults (Y faults) but also as R1 faults and P faults, unlike the common explanation for the flexural−slip folding in which faulting occurs parallel to the layer−boundaries (de Sitter, 1956). The P faults are dominantly developed in the parts showing the Class 2−Class 3 type thickness variation, showing that such thickness variation is ascribed to the micro displacement of the layers along these faults, i.e. shear folding.

The mode of deformation of the internal parts of individual layers during the flexural—slip folding in question is clearly shown as the development of minute recrystallized grains along grain boundaries of quartz (Fig. 11), which are not in general found in the Dh phase folds of flexural—flow type (Fig.1). That would be understood by the analysis of the pattern of occurrence of such minute recrystallized grains in the fold. Fig. 12 illustrates the distribution of the minute recrystallized grains and also the location of the major faults in the folds. The distribution of such the minute grains shows complicated pattern but not any layer—parallel fashion.

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