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Kink band structures in the Orlica Mts, Middle Sudetes

ABSTRACT: The nature and development of kink bands are considered under the terms of structural factors active during the deformation. These factors control the attitude of the kinked zone as well as the kink surface. Both, flexural slip and simple shear appear to develop the kink band structures. The two mechanisms often operate together or flexural slip can be replaced by simple shear at a later stage of the inception of kink fold, especially of the low angle one. It is concluded that penetrative kink bands development is a total effect of a number of small distortions arranged parallel to planes of maximum shearing stresses.

INTRODUCTION

Metamorphic rocks of the Orlica Mts consist mainly of schists occasionally intercalated with marbles and of pelitic slates. Several phases of deformation were recorded in these rocks (Żelaźniewicz 1972). One of the phases referred to as F_5 produced small fold structures of particular interest. The folds are intimitely associated with the two types of strain-slip cleavages described by Knill (1960). Different forms of these small folds belong, on the whole, to the structures commonly known as kink bands. Owing to the common structural origin of the variants one is able to trace the variations in a mechanism of development and an overall attitude of the kink structures depending on local structural conditions. Valid factors describing structural conditions of the kink band formation seem to be: structural level, pressure-temperature parameters, state of external and especially local stresses, degree of competence, kind of rock materials and changes of their properties during deformation, initial textural properties of rock before kinking, character of lamination and layering, thickness relationships between layers and/or laminae (number of foliation units per thickness of individual layer), t/l and l_s/l_l ratios as well as α angle between deformed S-surface (foliation, schistosity, etc.) and active kink surface or bounding surface (Fig. 1).

MAIN FEATURES OF KINK FOLDS

Dewey's (1965) and Ramsay's (1967) terms are followed in the geometrical description of kink bands. Kink folds are generally the asymmetrical folds and, therefore, the terms: short and long limbs are commonly used. However, the width of kink bands, examined by the author, is not seldom greater than the distance between them; as a result, they often do not represent the true short limbs. Hence the author keeps the words: "long" and "short" in quotation marks and understands the "short" limbs as those which suffered a distinct external rotation. It must be also noticed that kink surfaces rarely occupy an exact bisecting position between the two limbs, and at best they commonly merely approximate it.

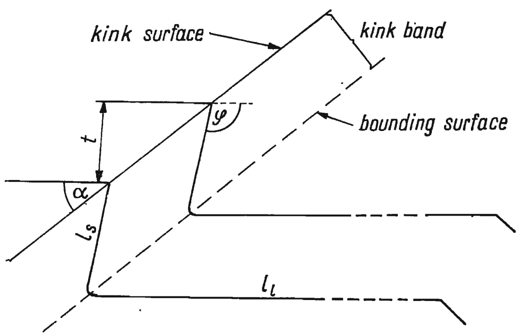

Fig. 1

Terminology of kink bands

One can commonly note a slight difference in colour between "short" and "long" limbs if they are seen in a section cut perpendicular to kink axes. Kink bands appear as zones of a somewhat different shade and these zones are bounded by kink surfaces. One can expect the existence of small difference in mineral composition between two limbs. Low angle kink bands occurring in pelitic slates — phyllites were examined under the microscope. The observations have shown that the "short" limbs are often richer in quartz than the "long" ones. Quartz grains dimensions are either the same in both limbs or larger in the "short" ones. This enrichment often results in more distinct lamination within the "short" limbs due to the alternating quartz and mica laminae. It clearly suggests that dilation occurs within kinked zones. Nevertheless, quartz grains in both limbs are markedly needle or spindle--shaped and they display an undulatory extinction proving the strain (Fig. 2 and Pl. 1). In many instances, however, there is no evidence of any mineral composition difference between two limbs. Turner & al. (1954, 1956) published the photographs of kink bands produced in calcite and enstatite crystals: they show the same phenomenon of the variable shade between the both limbs as it is commonly seen in the cut handspecimens or the thin-sections. This clearly suggests that not merely compositional changes cause the effect of the shade differences.

Since kink bands suffered volume increase one has to assume a migration of silica from "long" limbs to "short" ones to take place during the deformation. Such a migration starts simultaneously with the beginning of external rotation of the "short" limbs and favours the low-angle kink folds. Owing to this a great deal of strongly strained quartz grains appear to be generated within kinked zones. There is one more proof of the silica migration. In voids produced at the hinge zones of kink folds quartz concentrations occur (Figs 2, 5 and Pls 2—3). The quartz grains which crystallized in these voids have usually the appearance of large porphyroblasts that are either strain-free or nearly unstrained. This clearly shows that a distinct dilation can also occur along axial surfaces.

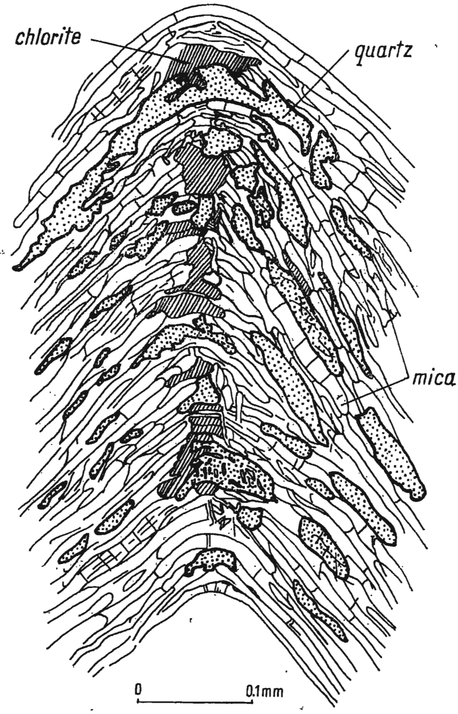

Fig. 2

Relationships and characteristic appearance of a kink surface zone

Dilation within kink bands suggests extension acting perpedicularly to the "short" limbs. In high-angle kink folds where the layer thickness remains constant throughout the fold, the dilation fissures can occur within kinked zone. Such fissures are usually filled up with mineral material migrated from the neighbourhood and to some extent from the "long" limbs which results in unstrained quartz or calcite veinlets in more calcareous slates (Fig. 3). This is possible to occur where the l_s/l_l ratio is low, that is, where the "short" limbs are much shorter than the "long" ones. If the kinked zones are wide, the volume increase can be very hard to detect or it does not exist at all since active tension stresses are too small to open

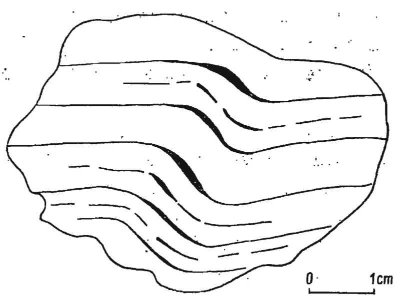

Fig. 3

Dilation veinlets resulted from extension acting across the band in a high angle kink fold

up the rock material across the layers. This depends, then, on the structural conditions dominating while kinking deformation affects the rocks.

As it was mentioned above, dilation shown by the voids development adjacent to margins of kink bands commonly occurs in low angle kink folds examined by the author. Small quartz concentrations were produced there. Observation under the microscope shows that, in thinly laminated slates, they have an appearance of saddle reefs arranged along transverse axes (*sensu* Hills 1963) in narrow zones, darker when nicols are crossed. So, mineralogically these zones differ slightly with the limbs. It is clearly seen that the zones of saddle reefs arrangements, best developed where $\varphi > 90°$, are generally impoverished with other minerals, especially mica ones. That is why, in places where foliae are usually only parted and their continuity is sufficiently maintained, strain may, or may not, be discontinuous across axial surfaces to kink folds. Strain discontinuity, therefore, appears not seldom to be alternated with strain continuity along these surfaces.

It is obvious that the kink folds featured like those above described have to originate in high structural level but under still metamorphic conditions. This view is supported both by the occurrence of quartz recrystallization and alternation of biotite into chlorite. Such an alternation commonly takes place at the margins of the kink bands. One can observe the continuous passage of biotite into chlorite there. This zone of transformation is strictly fixed to the hinge zones of kink folds (Fig. 2 and Pl. 2). Small cataclasis often occurs in these zones. New crystallizing tiny flakes of chlorite or sericite tend to be parallel to the axial surfaces of kink folds (Fig. 2). Such a tendency is limited, however, by a pre-existing frame made of unchanged minerals during this deformation and influencing the orientation of *(001)* planes. In thinly laminated phyllites where an actual amount of volume increase is very small, the existing mineral setting makes new crystallizing flakes adjust to itself and to crystallize mimetically. But where even a small cataclasis is involved and voids at the hinges are relatively larger the minute flakes readily arrange parallel to the axial surfaces. They often have an appearance of inclusions in quartz grains produced there.

It is obvious that occasional new chlorite growth may also occur in those "short" limbs which suffer a distinct volume increase but, clearly, this is not frequent to observe.

Many observations similar to those above were made also by Dewey (1969).

Spatial orientation of the axial surfaces to kink folds (F_5) is considerably constant throughout the Orlica Mts in spite of changes in the main foliation attitude (Żelaźniewicz 1972). Moreover, these surfaces appear to be conjugate. Following Johnson (1956), Ramsay (1962), Dewey (1966, 1969), Roberts (1966) and others, one can assume that the kink surfaces represent the planes of maximum shearing stresses related to externally applied forces. So, new crystallizing tiny, sericite or chlorite flakes tend to grow parallel to these planes according to the mechanism suggested by Gonzalez-Bonorino (1960). Nevertheless, apparent shortening and tightening of individual kink fold involve local compressive stress which, action more or less perpendicularly to their axial surfaces, influences the new mineral growth. too. The two mechanisms facilitate the mineral conversions in the zones of axial surfaces to kink folds.

The commonly accepted view states that kink folds are developed by external rotation of the "short" limbs, and "long" limbs generally preserve the pre-existing attitude of the layering. Kink surfaces usually tend to occupy the rough bisecting position between two limbs. It must be noted, however, that this is usually far limited and α angle and especially φ angle are strongly variable within kink folds. As it was stated previously, the regional attitude of the axial surfaces of kink folds can be considered, on the whole, as spatially constant. It seems likely that conjugate F_5 kink bands in the Orlica Mts can be interpreted as due to external compressive stresses (basement shortening) normal to the direction of the primary banding. It is obvious that local compressions in foliation were derived from those stresses enabling δ_2 to lie in the foliation and modifying kink surfaces attitude. Penetrative conjugate paths of weakness with fairly constant orientation were born throughout the rock domains. These paths were convenient to shear failure to have occurred regardless of considerable local distortions of the foliation by earlier foldings. However, it seems clear that it is these distortions that determine the inclination of the kink surfaces to the dominant foliation. That is why, the α angle can assume different values, usually low but sometimes high in such distorted places.

In the Orlica Mts all the kink bands show the reverse sense of external rotation. The author did not succeed in finding out normal kink folds envisaged by Dewey (1965). Therefore, in the present paper, the term "kink band" covers only the term "reverse kink band" of Dewey.

Dewey (1965) has classed the kink bands in four geometric categories differing considerably from each other by strain and mechanism of deformation. The kink folds, examined by the author, correspond approximately to his types, both the segregation kink bands and pelitic strain bands. The author does not however attempt to distinguish them so distinctly; in his opinion many transitions depending on given structural conditions can be traced here.

In order to exactly describe the strain and mechanism of development, detailed observations are required especially in the fold hinges.

The variation in the appearance of the hinge zones of low angle kink folds, traced along the transverse axes, is presented in Pls 2—3. The saddle reef mineral concentrations are best developed if the interlimb angle is small. Mica flakes do not continue across kink surface. They are broken and displaced at the point of maximum curvature. Therefore, strain is regarded to be discontinuous across axial surface. With the increasing interlimb angle values saddle reefs become more flattened in their shapes and some mica flakes begin to bend at the hinge zone. Then, strain starts to be partly continuous instead of totally discontinuous across axial surface.

If $\varphi < 2\,(90—\alpha)$ or $\varphi < 90°$, mica flakes frequently may be merely slightly bent and not broken tracing the curvature but this strongly depends also on the t/l ratio. In high angle kink folds saddle reefs do not essentially occur. Nevertheless, the "short" limbs may occasionally suffer volume increase under those circum-

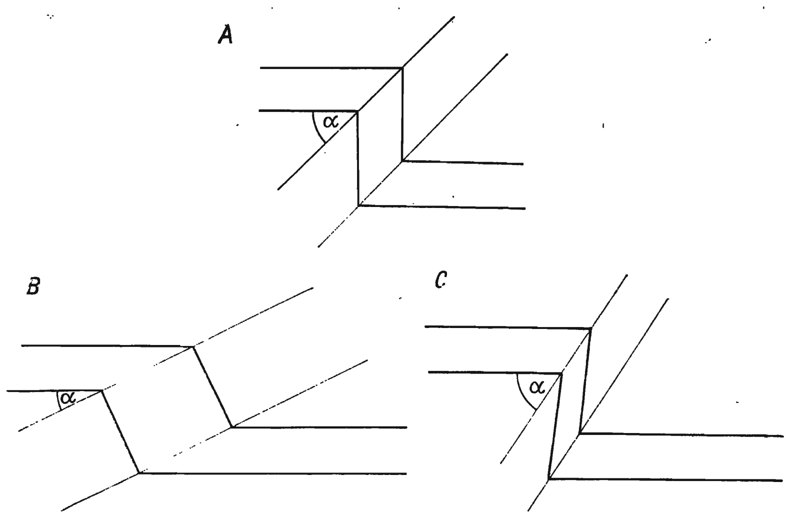

Fig. 4

Dependence of layer thickness in a kink band on size of α and φ angles stances, accompanying by dilation veinlets production. Strain depending on other structural conditions can be perfectly continuous.

Dilation adjacent to kink surfaces is largest where interlimb angle takes the lowest values. Dilation normal to the band is most frequent if $\varphi > 2(90—\alpha)$. Where $\varphi < 2(90—\alpha)$ volume increase within kinked zone may, or may not, occur depending on structural factors, mainly: structural level, n/t as well as the l_s/l_l ratio. One can often observe no marked mineral difference between "long" and "short" limbs, that is, volume increase, if any, is hardly detectable. This is governed by the number n of foliation units per thickness t of a given layer (Dewey 1965), and by the interlimb angle value as well as by the l_s/l_l ratio — n is very large and $l_s/l_l \approx 1$.

It must be also noted that kink band may suffer volume decrease resulting in pelitic strain band, the type of kink bands envisaged by Dewey (1965). Possibility of the occurrence of either volume increase or decrease within "short" limbs depends on φ and α angle values; Fig. 4 clearly shows that this takes place because φ can range from $2(90—\alpha)$ up to $90—\alpha$. It is obviously limited or additionally controlled by pressure-temperature parametres. Apparent volume decrease occurs where φ takes values less than $2(90—\alpha)$. Considerable differences in the orthogonal thickness of the same layer distributed in the two kink fold limbs appear where α is small (less than 45°). If α is limited between 45—90° the mentioned thickness differences are not so distinct. It is clear that the layer thickness is comparable merely when kink surface becomes a bisector. However, this is considered as rather special case. Since the φ angle is variant within an individual kink band one can expect that thickness increase where $\varphi < 2(90—\alpha)$ has to be compensated by decrease of thickness where $\varphi > 2(90—\alpha)$. Therefore, one kink band can be composed of both thickened and thinned layers. Thus, as individual kink band can appear as the combination along its length of the two separate Dewey's types — segregation band and pelitic strain band. Owing to this phenomenon the total effect of the deformation may show no bulk changes throughout the whole rock domain. As usually such a pure geometric simple relationship gets more complicated due to obliteration and prevention action of other structural factors. Nevertheless, it is clear that the possibility of segregation of mineral material does exist, as well as direction of silica migration (either to or from kink band) are considerably governed, among others, by the α and φ angle of external rotation.

MECHANISM OF KINK FOLD DEVELOPMENT

Careful analysis of the changes of interlimb angle values within individual kink folds suggests that the deformation initiates at those places where causative stresses start to be relieved by strain and themselves die out along certain distance. Stresses can concentrate in any available point within the rock but related strain makes the most of the presence of the paths of weakness.

It seems that the stress couple acting obliquely to foliation appears to be the essential cause of kink band development. Such a view is supported by Gilman's (1968) observations concerning the kink bands developed in response to the syngenetic expansion of carbonate concretions and produced in enclosing sediments where shear couple appears to have operated. These kink bands occur around the thin edge of the discus-shaped concretions. Gilman noticed that the α angle ranges from 44° to 90°

along the length of kink band and the lower angles are formed near the edge of the concretion. This shows that the largest φ angle is generated near the point of stress storage. Dewey (1969) also recorded that α and φ very along the same band. Close examination of kink bands shows that the interlimb angle usually varies gradually within them. The differences observed may reach even 60° (Fig. 5).

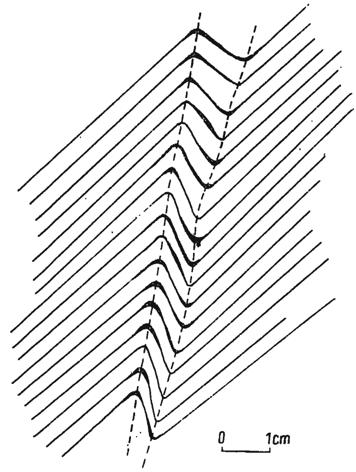

Fig. 5

Variation in interlimb angle along the length of a kink band and saddle reefs occurrence

Ramsay (1967) states that the development of the folds is controlled by two types of shear strain — internal shear strain and shear strain on the layer boundaries. Relative importance of these two types varies during the folding. The total strain increments on the limbs of the structure have maximum values at the start of the folding (threshold value) and at the end of the folding (locking value).

From the start of the folding rotation of the "short" limbs proceeds toward a certain point, the point of locking-up. If the external stresses keep a high value, there are two distinct points where further rotation is prohibited. The first is a point where $\varphi = 2\ (90—\alpha)$ and the other absolute one where $\varphi = 2 \cdot 90—\alpha$ which practically is never reached. However, an actual prohibition of this rotation strictly depends on the concrete structural conditions. One can often observe kink bands to have $\varphi \neq 2\ (90—\alpha)$. Ramsay (1967) explains the phenomenon by means of the external stress value and the amount of the t/l ratio. Dewey (1965) states that the point where further rotation of the "short" limbs is prohibited depends largely on the type of kink band structures, that is, on the mechanism which causes the deformation to exist.

Before folding can start the initial strain threshold must be overcome which is localized within the layers (Ramsay 1967). Applied stresses have to overcome the material resistance as well as inertia to give rise the fold. Therefore, it recquires maximum shear strain value at the start of the folding. Stress may, or may not, be only partly relieved by this strain. If it happens, the rock material is forced to produce a slight curvature — wave instability or buckles — in these places where a given layer stops to be statistically homogenous. Owing to infinitely large incremental shear strain the φ angle rapidly grows up to $\varphi > 2\,(90—\alpha)$ as quick as several foliation units become involved in the fold (Fig. 6 and Pl. 4, Fig. 1). Kinked zone margins simultaneously start to migrate away. "Short" limbs tend to rotate toward position where $\varphi = 2 \cdot 90—\alpha$. This rotation is commonly arrested at any point but the φ value essentially does not exceed 160°. Owing to this, stress becomes relieved to a certain degree but remains still to act. Now the φ values decrease more or less toward approximately $\varphi = 2\,(90—\alpha)$. This is one of the two points of distinct prohibition of the external rotation. Next, stress may, or may not, store partly within this portion of the developed kink band where φ reaches or strongly approximates $2\,(90—\alpha)$ value. If stress is still sufficiently large it can start to be relieved more rapidly again magnifying the φ value, $\varphi > 2\,(90—\alpha)$. This phenomenon may repeat several times but usually

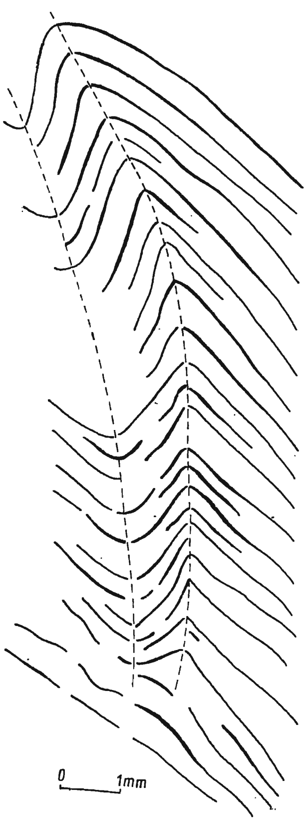

Fig. 6

Inception of a kink band

does not so because the deformation is arrested and it depends on local stress value. The process finishes when stress becomes too small to do that. Then, small stress concentration in a point where $\varphi \approx 2\,(90—\alpha)$ solely suffices in order to tend to diminish φ angle to zero along certain distance due to infinitely large incremental shear strain before the locking-up is achieved. The ideal process described above usually fails at any moment controlled by general state of the structural conditions operating during the kink fold development.

Figures 5 and 6 show the variation in the total strain effect througout the kink folds. It was shown above that kink band starts to develop and dies out along certain distance by approach of the φ value to zero. This sometimes may be impossible for several reasons and therefore rupture appears to occur along kink surface. Strain becomes entirely discontinuous across it. If total strain discontinuity takes at the beginning of the deformation the φ angle is commonly small and strain results in joint drag formation. Every next kink fold developed on relatively higher structural level may, or may not, be produced. Therefore an individual kink band can be regarded as zone where local stresses to cause it are completely relieved. Total penetrative deformation can be considered to be composed of a great deal of small distortions controlled by a sum of many such local stress fields.

As it was stated above the interlimb angle is variable troughout the kink fold. That is why, the kink surfaces practically never occupy an exact bisecting position. One can say that only α angle values are fairly constant but not always along the length of a kink band. Thus the kink surfaces usually maintain the static material positions and divide the interlimb angles into two unequal parts. The smaller angle of the two lies close to the "long" limbs. Therefore, an axial plane to a kink fold may be regarded as a bisector only as a special case. Moreover, if frequency of bands per unit of length is high, and the l_s/l_l ratio approximates 1, the attitude of foliation within "long" limbs becomes slightly variant. It may change about 10° providing occasional small rotation of these limbs, too. Sense of the rotation seems to be opposite to that shown by "short" limbs.

The orthogonal layer thickness as well as fold shape vary throughout the fold. The overall geometry of the kink folds, examined by the author, is not exactly that of the similar type suggested by Ramsay (1967).

It is clearly seen that the "long" limbs are rarely completely unstrained. However, strain is relatively very small. Sometimes one can observe clear evidence of the strain the "long" limbs have undergone. In pelitic slates — phyllites commonly built up of alternating very thin quartz and mica laminae, occasionally there occurs a much thicker (10 or more times) quartz lamina which was primarily enriched in quartz. Where such a lamina is surrounded by mica laminae a competence difference there arises. The lamina in Fig. 7 tapers toward adjoining hinge zones. Its thickness and attitude prevent it from solution and segregation. The lamina discussed occurs in the "long" limb which underwent strain during kink fold development. This strain was marked here by drag fold inception within the tapering lamina (Fig. 7 and Pl. 5, Fig. 1). The drag fold shows the sense of relative movement. Axial plane to this fold corresponds to adjacent kink surfaces. The drag fold in thicker quartzose lamina caused the development of open fold in the mica surroundings. This fold dies out sideways to a distance of the tenfold thickness of the quartzose lamina. This seems to be a reliable proof of the slip action along foliation within "long" limbs. Such a slip movement influences and is connected with partial quartz solution as well as quartz migration mentioned above. It seems obvious that this process is associated with and compensated by gliding along (*001*) mica planes within more micaceous laminae. Such a minute gliding must exist between most mica flakes. However, occasionally, much larger mica flakes occur commonly not free to move. Then, they become strained due to stretching which results in tension fissures perpendicular to their (*001*) planes (Pl. 5, Fig. 2).

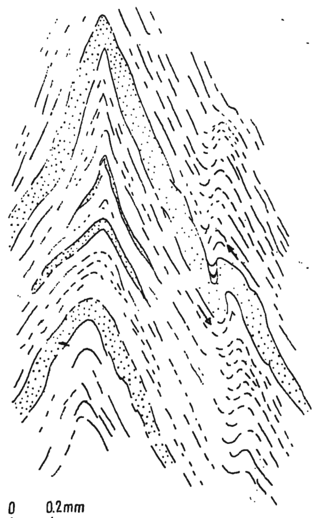

Fig. 7

Drag fold development due to slip in kink fold limbs

It is clear that the flexural slip is the mechanism employed, and almost completely accomplished by slip on the layering (and on foliae) as well as shear occurring internally within the layer. There are several lines of evidence that flexural slip appears to have been the important mechanism in the development of the investigated kink folds.

Following Dewey (1965), one can assume that constant thickness of a layer during flexural slip deformation regarded as discontinuous simple shear on the variant foliation must involve gliding of varying magnitude on kink surfaces. Moreover, the width of kink band changes depending on α and F (thickness of individual foliation unit). The axial surfaces to kink folds appear to be planes of shear during continuous simple shear which results, ideally, in folds of perfectly similar shape.

Flexural slip and continuous simple shear are for the most part hard to differentiate. The methods were described by Ramsay (1962) and Dewey (1965) but they may be used only under certain, not commonly fulfilled, conditions.

As presented above, flexural slip was the important mechanism responsible for the development of kink folds in the Orlica Mts. They often have, however, non-planar foliation in their limbs, kink surfaces usually do not bisect the interlimb angles and orthogonal thickness of layers throughout the folds is frequently variant. (Pl. 6, Fig. 1). Thus, it is clear that flexural gliding mechanism was influenced and got more complex due to other factors.

Close examination of the shape of "short" limbs makes it apparent that they often assume a more or less marked S-shape. In Fig. 8 is shown that stresses responsible for external rotation of "short" limbs result generally in coupled movements operating on each kink surface. These movements control the shape of "short" limbs, that is, the shape of foliation within kink bands. Such structures could develop only at a late stage of the formation of kink bands due to shear action on kink surfaces just after setting up the layers into fixed position within kinked zone (by arrest of further rotation depending on structural conditions) but before stresses became completely relieved. In the "short" limbs a number of S-shaped fissures occur which parallel foliation and assume the form of tension gashes. The gashes bear witness of volume increase within the kinked zone. These fissures are filled up with quartz and/or opaque minerals. The sense of movement declared by the sigmoidal forms is the same as that shown by external rotation of "short" limbs. This suggests

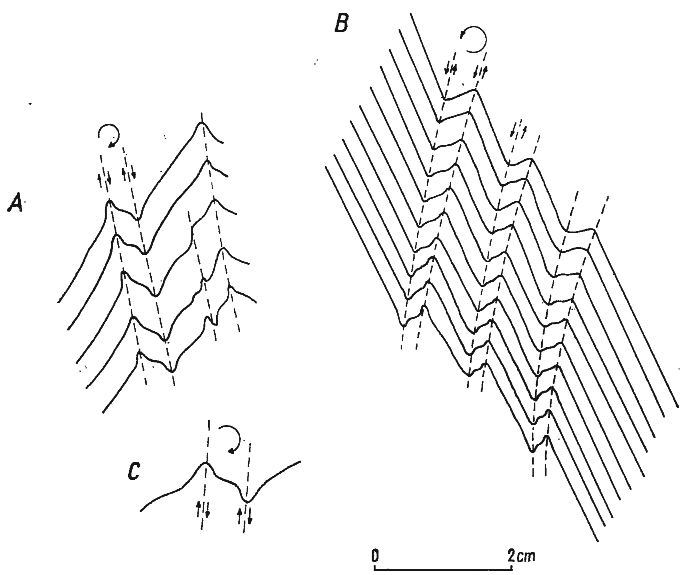

Fig. 8

S-shaped foliae within kink bands due to simple shear of kink surfaces that the movement on kink surfaces becomes accelerated at a late stage of the deformation. It was previously stated, following Ramsay (1967), that the total strain increments on the limbs reach, among others, maximum values at the end of the folding. At the very moment "short" limbs fall into the locking-up position. If this happens to a low angle kink fold some planes of movement arise convenient for still existing stresses to be relieved. Slip on the layers boundaries in such a fold, particularly if it is supported by competence difference, passes into slip along axial surfaces in high portions of the low angle fold at the end of its development.

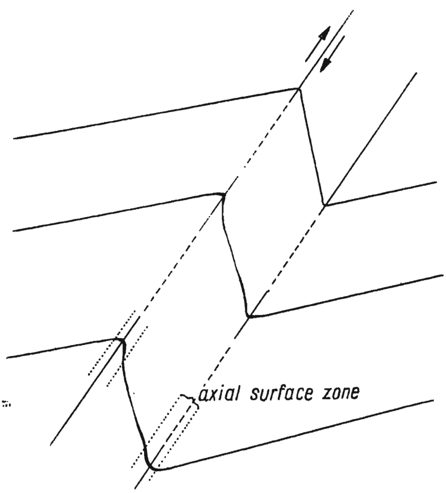

Fig. 9

Development and roundness of a kink surface zone due to movement acceleration in a late stage of deformation and small amount of rotation of portions of foliae immediately to the kink surface

The acceleration of movement is also accentuated by roundness of hinge zones (at least on microscopical scale). Let us now consider what happens to a layer (lamina) in the hinge zone. A slightly more speedy movement on kink surfaces makes a layer in a "short" limb assume a sigmoidal form. It seems that one movement couple causes the ends of the layer within a kink band to migrate toward axial surfaces. The same sense must be shown by rotation which necessarily has to affect the adjoining end of the layer in the "long" limb (Fig. 9). For this reason, a slight roundness of the hinge zone is produced (Pl. 6, Fig. 2). Moreover, in the hinge additional very small folds are occasionally developed and strain may be continuous across the axial surface (Pl. 6, Fig. 3). They produce the axial surface zone of a certain width and marked out by strong curvature of a layer (lamina). The axial surface to this kink fold occupies here a more or less median position between two limbs. The zone, among others, is composed of mentioned above almost above almost strain-free quartz grains and minute new chlorite or sericite flakes.

A structure as shown in Fig. 10 can be produced due to differences in the layer competence. The core of the fold is made up of a slightly more competent layer and orthogonal thickness is roughly constant throughout the fold. The less competent layers outside the core have another thickness. Owing to this, the t/l ratio decreases and shortening is facilitated too since the competence differences are commonly associated with changes in this ratio. The hinges become angular and the limbs tend to converge diminishing the acute angle between them. The width of the axial surface zone tends to be reduced to zero being replaced by a single median slide plane. The small central double fold can be crenulated and chlorite felt may occur to mark shear plane. The structure under discussion seems to be produced at first by flexural slip mechanism and later by simple shear on kink surface at a late stage of deformation. This simple shear appears to be continuous throughout the core which is built up of more competent layers and becomes discontinuous sideways. Mica flakes are broken at the hinge which is apparent under high magnification. The fine chlorite felt, occasionally associated with a slightly later produced thin quartz veinlet, bears witness of the passage of gliding on layers during flexural slip to simple shear on the axial surface to kink fold (Pl. 4, Fig. 2).

If the competence of layers which make up the fold is fairly con-

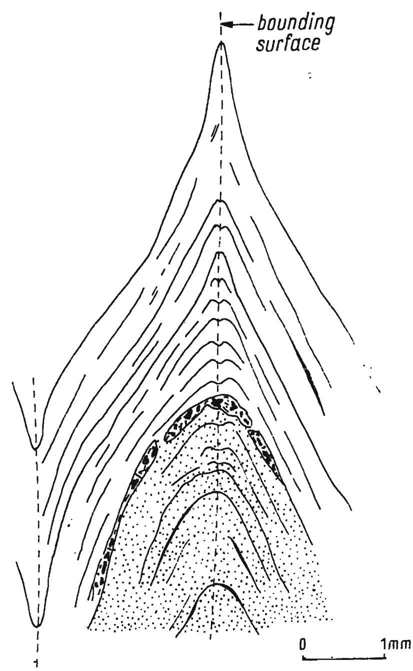

Fig. 10

Variation in style of the same kink band depending on the competence of involved layers. Transition from a flexural slip mechanism in a more competent layer to a simple mechanism in a less competent one accompanied by changes in orthogonal layer thickness throughout the kink fold

stant, very weak sigmoidal forms can be solely attained. Strain in such a case is variant. Continuous strain alternates with prevailing discontinous strain depending on the structural conditions in any given point of the structure when it is traced along transverse axis.

It is clear that the geometry of kink bands largely depends on the initial angle made by deformed pre-existing foliation and the plane of weakness resulted from externally applied stresses and destined to become a kink surface. This angle undirectly controls the amount of rotation of the "short" limb.

As it was stated previously φ is variable within kinked zone. One can easily notice that the dying out of kink band often takes place where a little more competent layer, traced by an increase of the t/l ratio, has to be overcome by deformation. Then, the φ angle tends to diminish to zero since material resistance becomes too great to relieve the local stresses by deformation.

It seems to be a well established notion that in the kink bands developed in laminated slates under the discussed conditions strain continuity or discontinuity across kink surface is controlled by φ angle, t/l and n/F ratios. Moreover, the magnitude of shear strain which relieves stress along axial surface is not constant throughout the deformed portion of rock.

Sometimes one can observe a structure as that shown in Fig. 11. Most of the small kink folds are fairly constant in their attitude and sense of rotation. Stress is continuously dissipated by a plastic yield strain. However, particular folds which differ from the common kink folds occasionally occur. Strain appears here to be perfectly discontinuous across axial surfaces, and interlimb angles simultaneously become very small. Geometry of these folds attains the symmetrical appearance. No longer limbs are discernable and foliation in no limb coincides with the attitude of foliation in "long" limbs of the neighbourhood. It seems that much greater movement was acting along the axial surface. Such a structure dies out very quickly sideways bearing witness of rapid and merely local stress relief. This employs cataclasis and even brecciation to produce

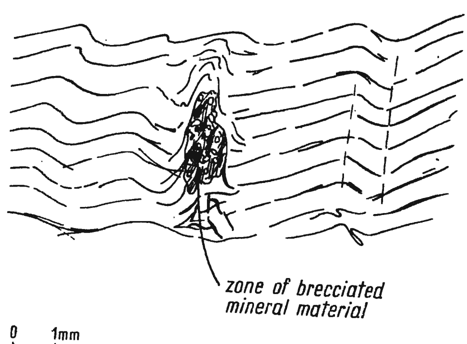

Fig. 11

Development of a minute zone of brecciation due to rapid but very local stress relaxation along a kink surface

zones of crushed mineral material. The zones are strongly elongated along axial surfaces and composed of randomly oriented small sericite flakes and small quartz grains (Pl. 7). Strain-free quartz porphyroblasts, biotite plates as well as occasional chlorite ones are rare and occur against that background. Large concentrations of opaque minerals can be often observed. This phenomenon seems to occur at a late stage of the deformation and corresponds to the movement acceleration mentioned above. The author reached the conclusion that local stress storage had been rapidly relieved by a strong cataclasis and brecciation and later the obvious pressure decrease resulted in growth of strain-free quartz grains and biotite or chlorite flakes.

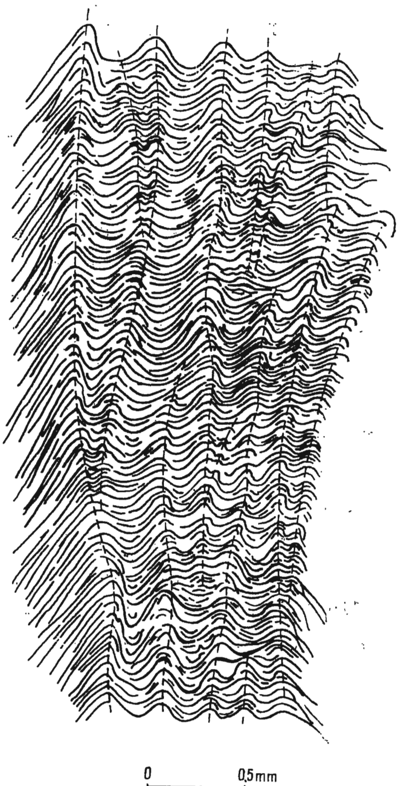

Fig. 12

Pattern of kink surfaces distribution throughout the kinked rock seen in cross section

A phenomenon like that described above confirms the notion about an unequal disposition of stress and strain throughout the rocks affected by kinking. This unequal stress-strain disposition surely governs also the occurrence frequency of kink bands and their width within the rocks. The mechanism employed here seems to be similar to that one which controls distribution of joints or zones of "gleitbretter" throughout the rock domains.

In the author's opinion, the investigated kink folds were developed both by the mechanism of flexural gliding and that of simple shear along axial surfaces. Moreover, they appear to be closely connected. At a late stage of deformation, the initial flexural slip can be replaced by a variant simple shear. This is possible in the kink bands affected by strong rotation. Simple shear strain may, or may not, be continuous across a kink surface depending only on specific structural conditions. Discontinuous simple shear, however, appears to be totally prevalent. Within an individual kink fold the two types of simple shear can be observed. These kink bands are not too frequently bounded by planes of total strain discontinuity. The above discussion points out that flexural slip may be the mechanism of deformation, even where the kink surface does not bisect the angle between "long" and "short" limbs. So, any corolary based upon unsufficient detailed analysis and concerning this problem appears to be plausible.

Both field and thin-section examinations of rock to be kinked show the pattern of kink surfaces distribution throughout the rocks. Kink surfaces apparently seem to move toward one another where the a angle value changes or the kink band dies out. According to the opinion expressed previously, the penetrative character of the kinking deformation seems to be effected by a summing up of a number of small relieving local stresses. Each of them is relieved by development of an individual kink band regardless of the scale being a micro or macro one. In the section normal to the kink axis one can observe the transverse axes to converge and diverge (Fig. 12 and Pl. 8, Figs 1—3). Every individual fold may be considered as due to relaxation of each individual stress field. Every small fold results from any small movement. In place where one deformation generated by this movement dies out the other folds begins to develop simultaneously (Pl. 8, Figs 2—3). The scale of this process varies within a very broad range depending on the competence and cohesion displayed by the rock. The frequency of closely spaced planes of movement intensity also appear to be important here.

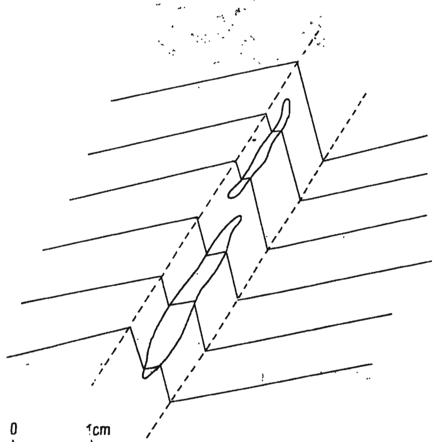

Fig. 13

Appearance of zones of foliae cut off by kink surfaces but unaffected by external rotation and occurring within a "short" limb

Within "short" limbs much smaller zones often occur where orientation of foliation corresponds to the attitude of foliation in "long" limbs (Fig. 13). These domains usually lens out within the main kink band.

This proves that the "short" limbs, treated as a whole, do not rotate "en masse" during deformation. Hence, zones free of rotation appear within "short" limbs. The view about the total summary effect of the minute displacements seems to be reliably supported. Therefore, in any one environment kink bands can vary in width since their nucleation is controlled by the mode of stress relaxation throughout the kinked rock domains.

It is obvious that the rock masses are unequally divided into a great number of zones where the movements concentrate. The width of such zones is strongly variable. Strongly strained zones referred to as "short" limbs appear often to be wider than unstrained ones (or weakly strained) commonly regarded as "long" limbs. Therefore, the terms: "short" and "long" bearing on limbs may to some extent be misleading (Fig. 14).

It seems interesting to trace the behaviour of kink bands where deformation affects a more competent and much thicker layer. The style of deformation of the calcite layer in Fig. 14 differs from the style of adjacent kink bands. Thinner mica and quartz laminae adjoining the layer tend to fit into its boundaries. Therefore, kink bands vanish in the immediate neighbourhood of the layer. Due to the intervening calcite band the movements which generally result in kink bands become resolved in a number of more minute displacements on more closely spaced planes close to the layer (Pl. 8, Fig. 1). These planes are very weakly fanned. This is controlled by the curvature of the carbonate layer and action of the buckling component. It bears one more evidence of significant role played by the competence differences between deformed

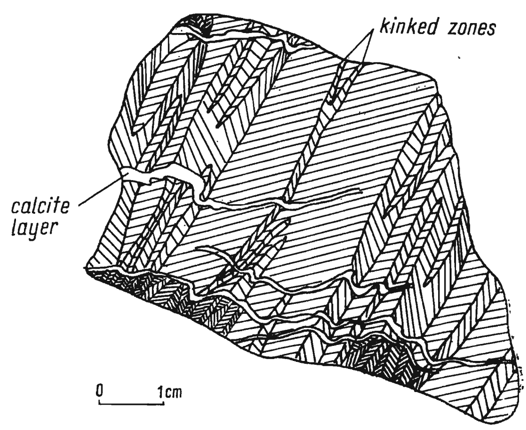

Fig. 14

Variation in appearance and width of zones of externally rotated foliae; variation in style of kink folds depending of lithology and thickness of kinked layers

layers in the course of kink band structures development while local stresses are relieved.

The kink bands, examined by the author, are sometimes accompanied by second order structures. They assume the form of very fine wrinkles which consistently cut the first order kink axes at an angle of about 20°. This also proves that simple shear on kink surfaces takes part in kink bands development.

The author hopes that this paper has shown how the development of kink band structures, their geometry and character are the function of both the intervening structural conditions and the mechanisms employed to deform the rock. An actual attitude of any kink band results from one of a great deal of various possible arrangements of the above discussed factors.

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A. ŻELAŹNIEWICZ

FAŁDY ZAŁOMOWE W METAMORFIKU GÓR ORLICKICH

(Streszczenie)

Rozwojem oraz własnościami fałdów załomowych (ang. *kink bands, joint drags*) rządzi zespół czynników określających strukturalne warunki deformacji. Poza parametrami charakteryzującymi środowisko tektoniczne istotne są tu: litologia, miąższość lamin oraz wielkości t/l, l_s/l_l, kąt α (fig. 1 i 4). Stałość przestrzennej pozycji foliacji w skrzydłach dłuższych, różnice mineralne i miąższościowe między obydwoma skrzydłami oraz specyficzne stosunki w strefie powierzchni osiowej należą do bardziej charakterystycznych cech deformacji typu fałdów załomowych (fig. 2—5 oraz pl. 1—3). Fałdy te powstawać mogą dzięki wyginaniu lub ścinaniu. Przeważnie oba te mechanizmy współdziałają ze sobą lub nakładają się wzajemnie (fig. 6—10 oraz pl. 4—6). Wyginanie w późniejszych stadiach deformacji może być zastąpione przez ścinanie proste wzdłuż powierzchni osiowej, szczególnie w fałdach o małym kącie między skrzydłami (fig. 6 i 8 oraz pl. 4 i 6). Fałdy załomowe są wynikiem deformacji przekraczalnej (Teisseyre 1971) i mogą być uważane za sumaryczny efekt rozładowań małych lokalnych pól stressów, kontrolowany przez rozkład w skale powierzchni inicjalnych odpowiadających płaszczyznom największego ścinania w zewnętrznym polu stressów, gdy δ_2 jest równoległa lub prawie równoległa do deformowanej powierzchni metamorficznej (fig. 11—14 oraz pl. 7—8).

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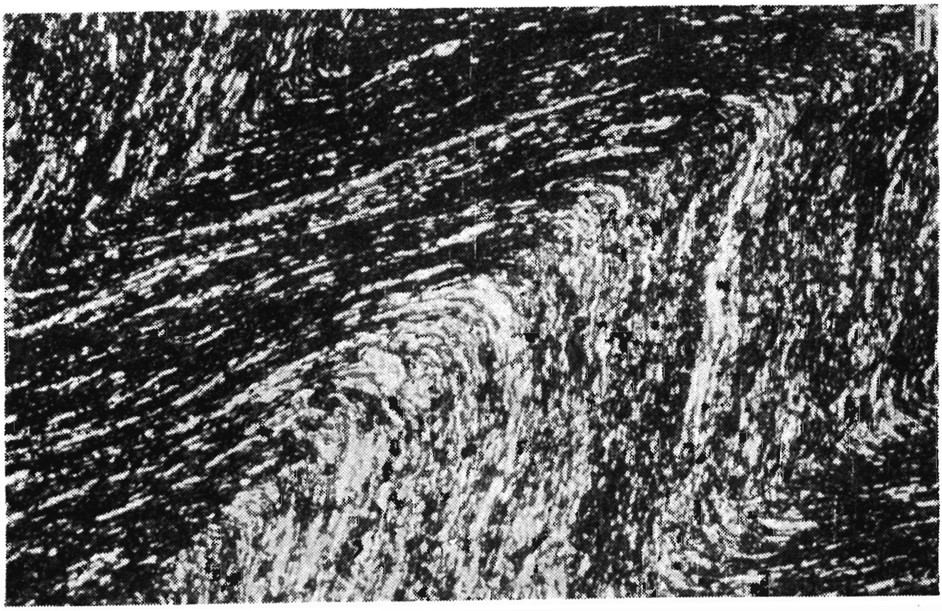
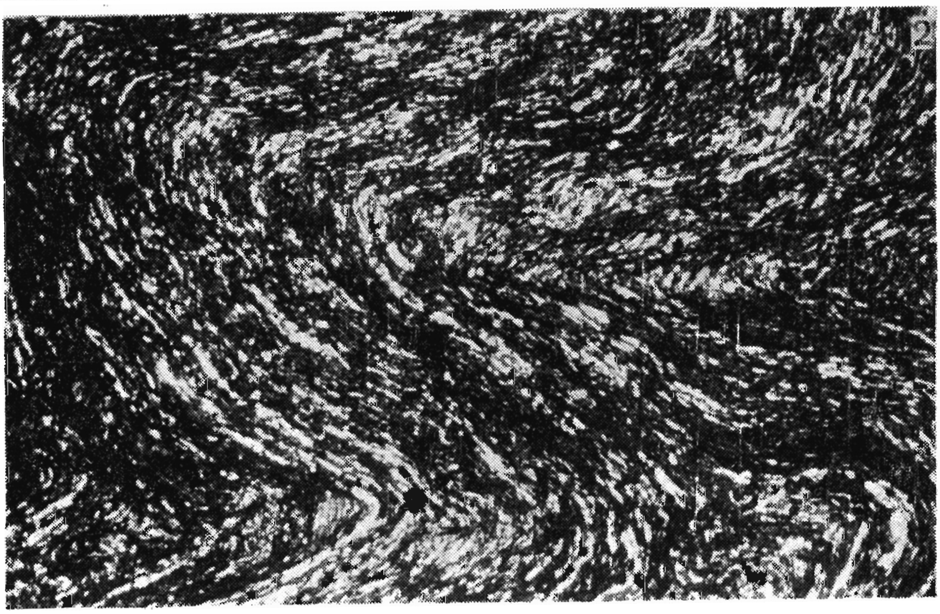
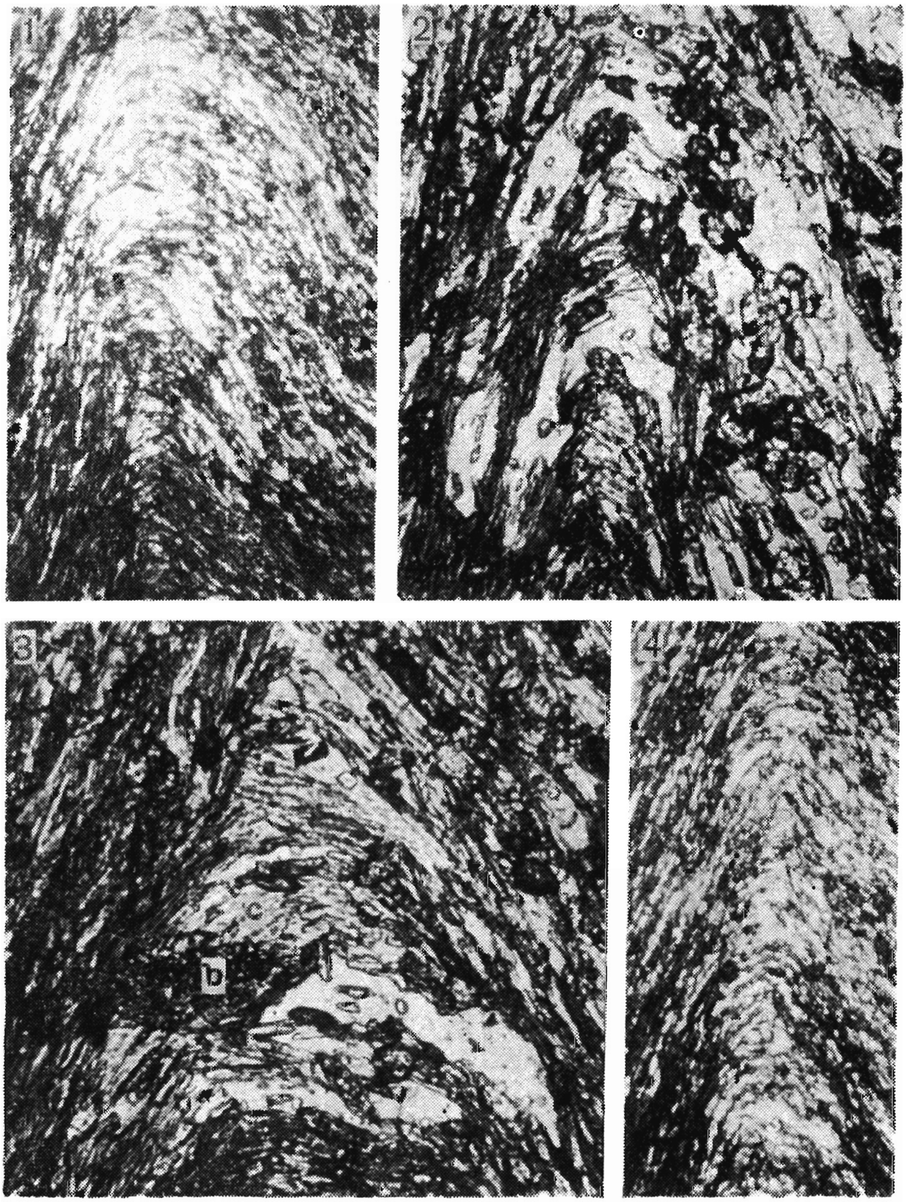




Main features of "short" limbs of kink folds developed in slates

1 — Mineral and colour differences between "short" and "long" limbs. Quartz is segregated within the kink band which suffered volume increase. Without analyser. Field of view 1.5 mm wide.

2 — Non-planar bounding surface. Both φ and α angles are variant along the length of kink band. Kink surfaces move away from each other but the length of foliation cut off by them is roughly constant. Foliae within kink band are distinctly curviplanar. Without analyser. Field of view 1.5 mm wide.



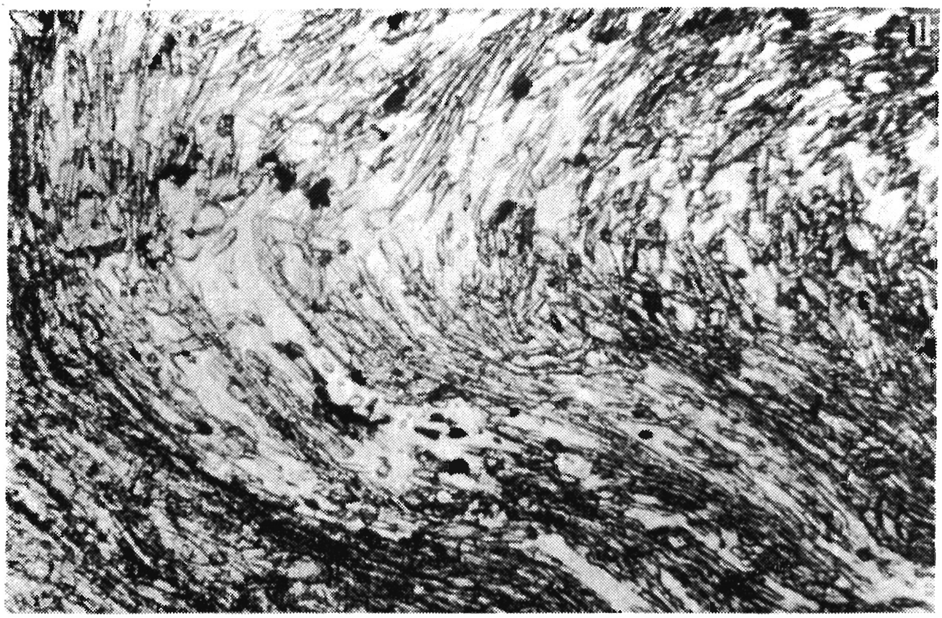
Saddle reefs development in voids produced in hinges of kink folds ("short" limbs are constantly on the right hand sides of the photographs)

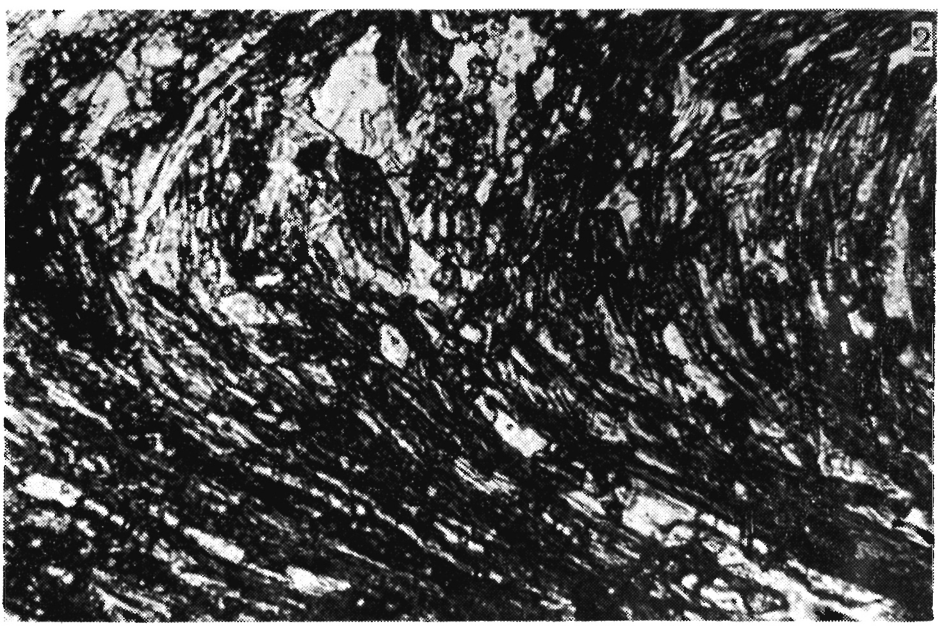
1 — Unequal distribution of quartz saddle reefs along the length of kink surface within the same layer. Without analyser. Field of view 0.6 mm wide.

2 — Voids between parted foliae of low angle kink fold filled up with quartz and chlorite. Without analyser. Field of view 0.25 mm wide.

3 — Continuous passage and alternation of biotite (*b*) into chlorite (*c*) strictly fixed to voids developed in the hinge. Without analyser. Field of view 0.3 mm wide.

4 — Uninterrupted development of saddle reefs between parted foliae along kink surface while strain continuity is generally maintained across it. Without analyser. Field of view 0.37 mm wide.

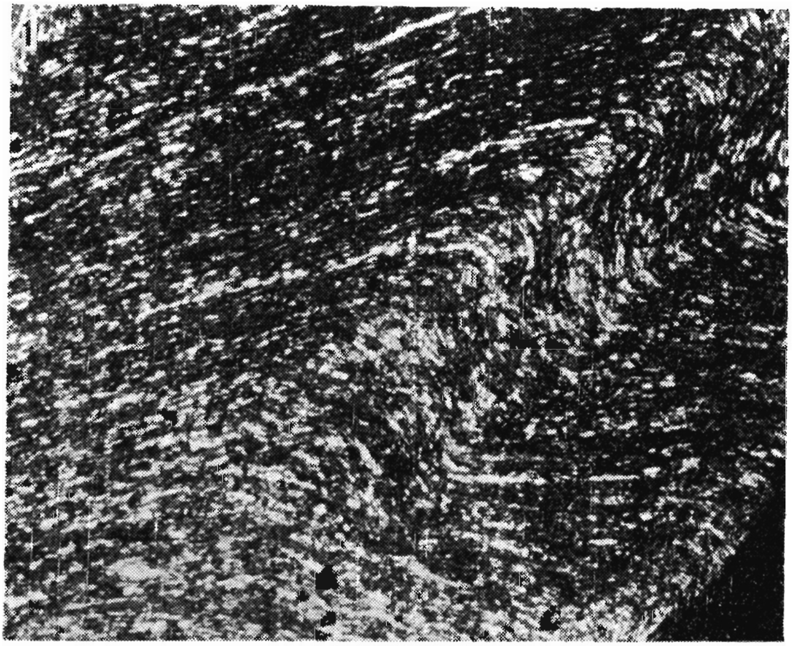




State of strain across kink surface

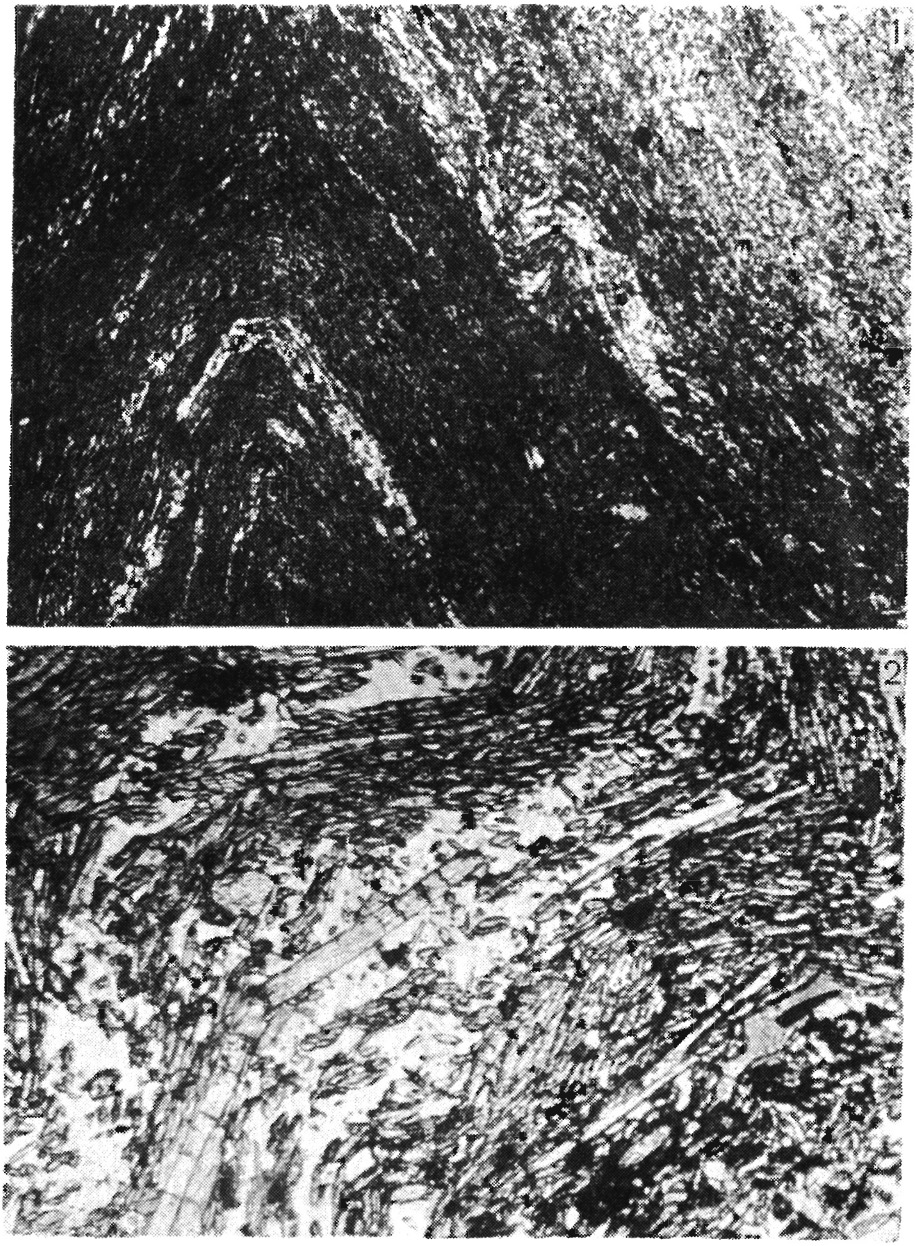
1 — Foliae broken at the hinge. Small amount of cataclasis along kink band margin must have occurred and therefore micas not seldom do fail a perfectly oriented foliation. Strain is discontinuous across this portion of kink surface. Across other parts of the same surface strain may be continuous. Note non-planar trace of "long" limbs immediately to hinge zone. Without analyser. Field of view 0.45 mm wide.

2 — Distinct strain continuity across kink surface. Without analyser. Field of view 0.45 mm wide.



1 — Inception of kink band. Without analyser. Field of view 1.25 mm wide.

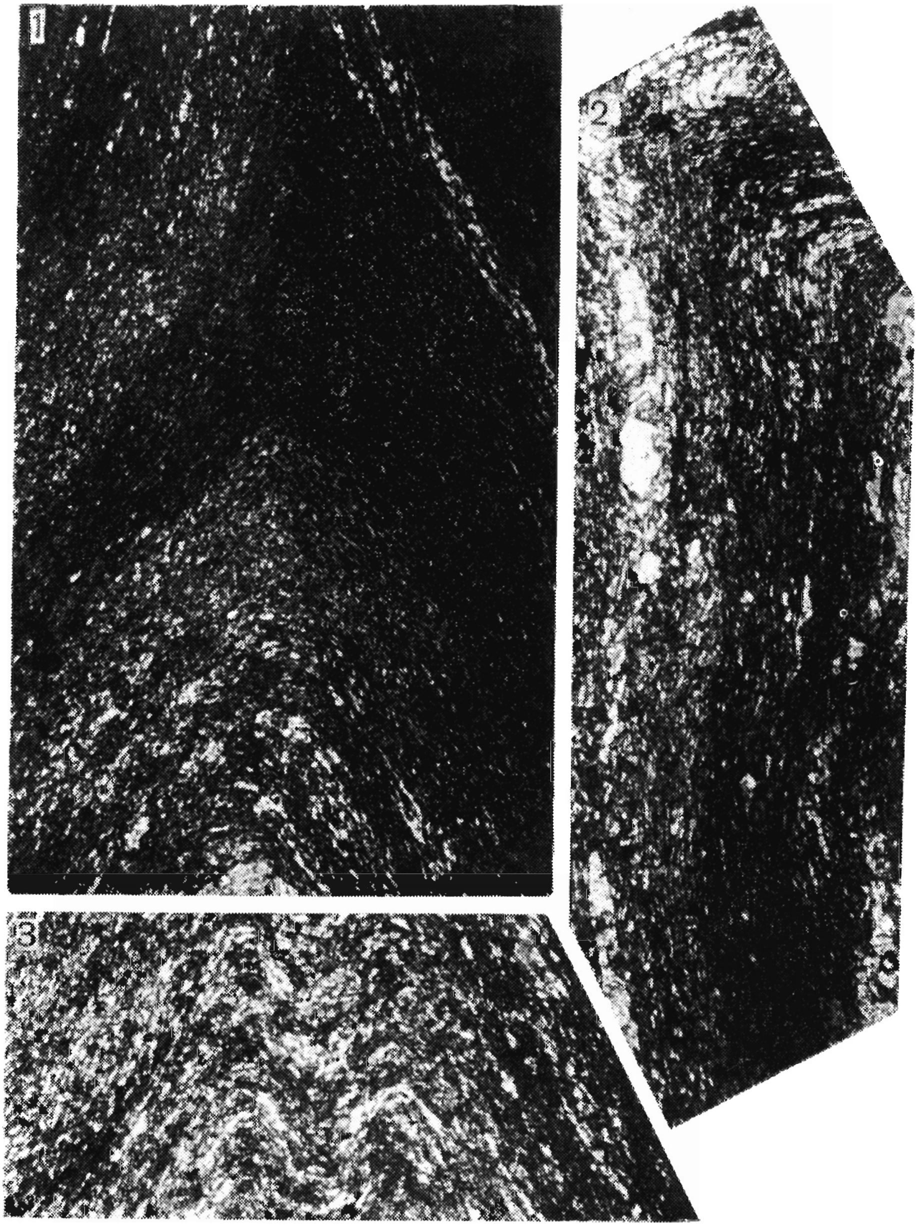
2 — Late distinct shear along axial surface to kink fold. Note a little earlier plate minerals growth strictly parallel with kink surface. Chlorite felt may occur here occasionally. Without analyser. Field of view 2.6 mm wide.



Development of kink fold due to flexural slip mechanism

1 — Small drag fold in a more competent layer in the "long" limb of kink fold. Without analyser. Field of view 1.08 mm wide.

2 — Tension fissures affecting larger mica flakes while tiny ones are displaced to each other by slip in the kink fold limbs. Without analyser. Field of view 0.45 mm wide.

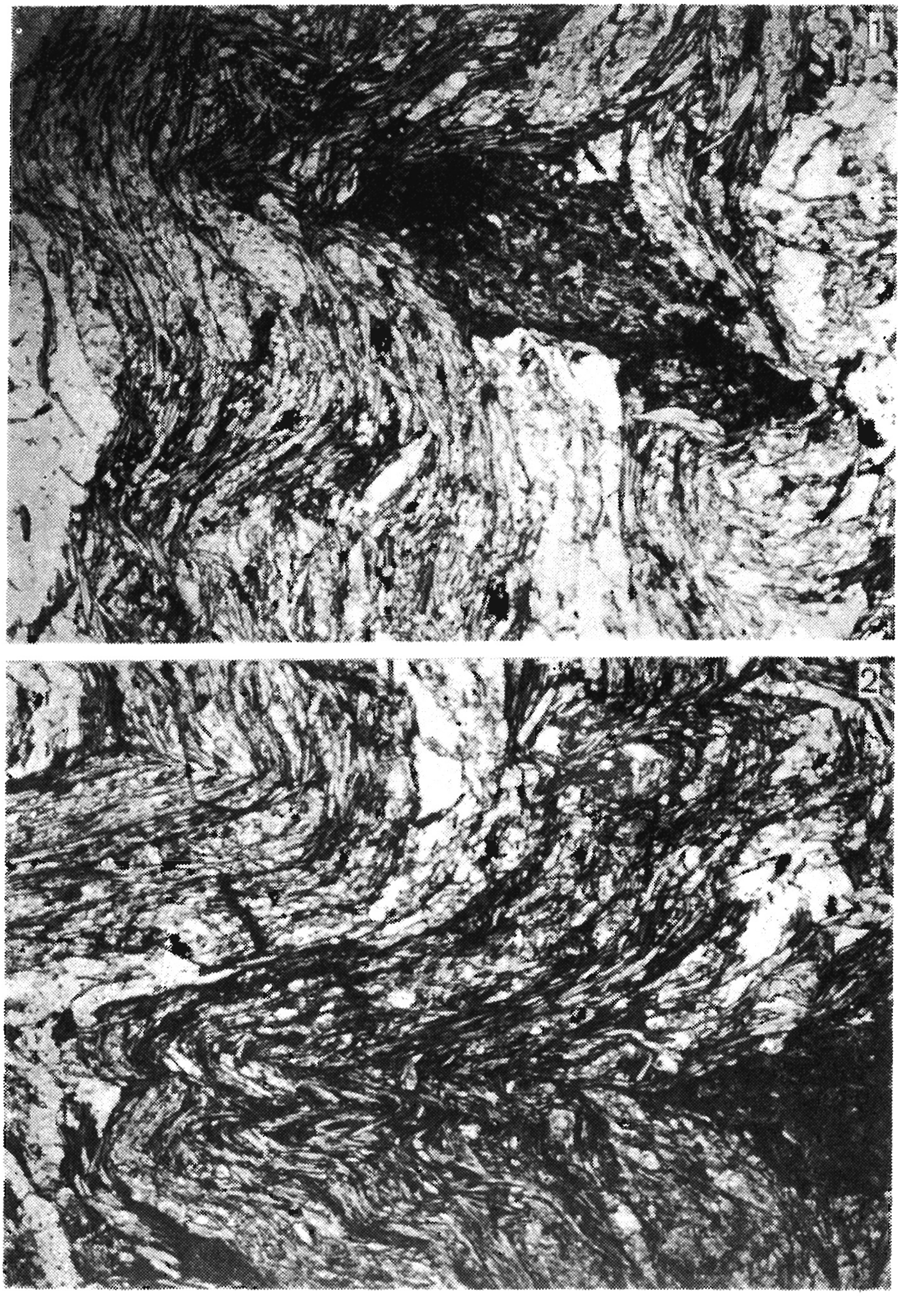


Simple shear on kink surfaces

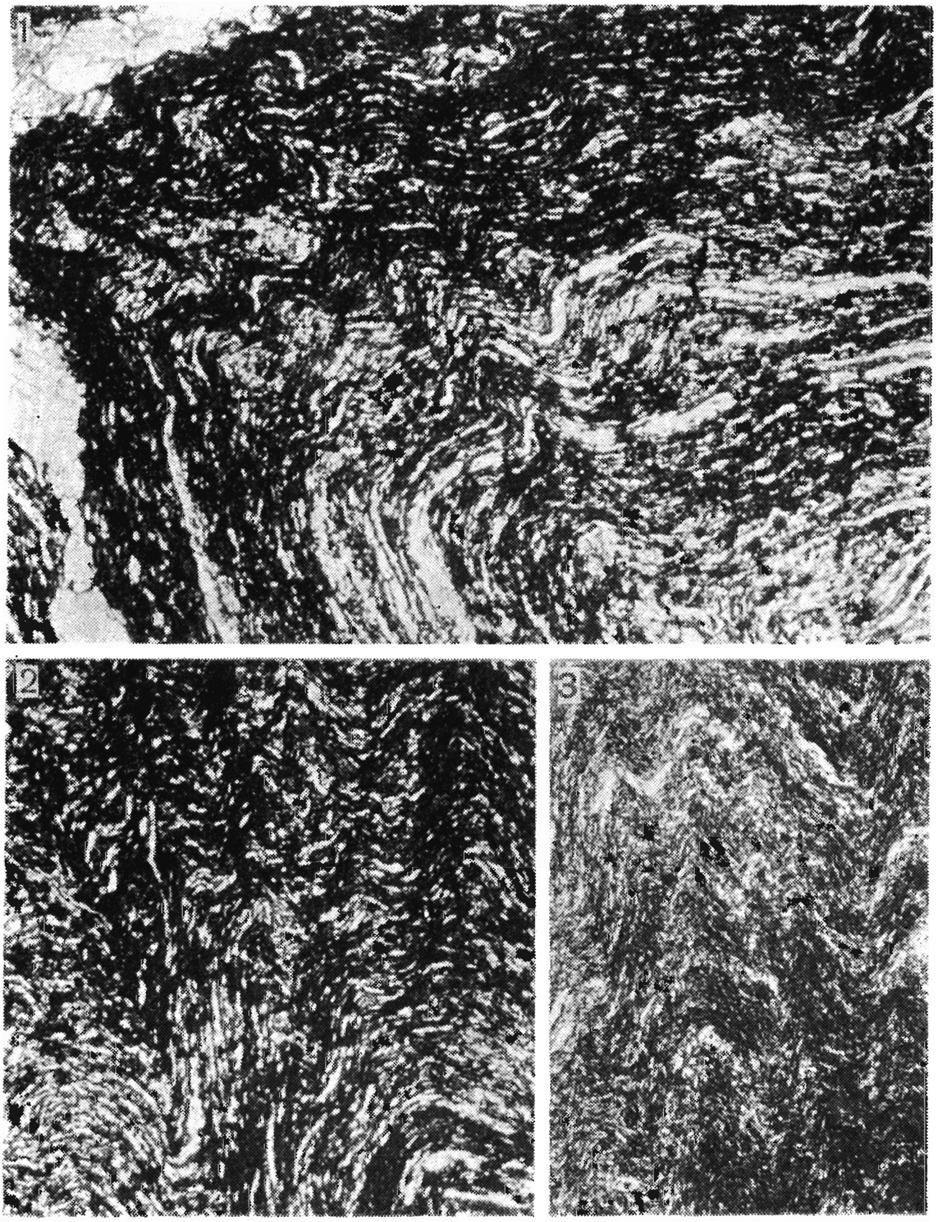
1 — Change in the orthogonal layer thickness throughout the kink fold. Thickness increases due to simple shear on kink surface ("short" limb on the left hand side of the photo). Without analyser. Field of view 1.09 mm wide.

2 — Slight external rotation of the ends of layer within "long" limb immediately to kink surface. Sense of rotation the same as that shown by "short" limb. Without analyser. Field of view 0.54 mm wide.

3 — Development of small double fold in the axial zone due to acceleration of movement on the axial surface to kink fold. Without analyser. Field of view 1.02 mm wide.



1 and 2 — Small zones of brecciation developed along the axial surfaces of kink folds due to rapid but very local stress relaxation resulting in severe shears. Without analyser. Field of view in both photograps 2.5 mm wide



Mode of the kink surfaces arrangement throughout the rock

1 — Replacement of larger kink fold by several smaller ones near the buckled intervening much thicker and competent layer. Without analyser. Field of view 1.01 mm wide.

2 — Resolution of shear along one kink surface into a few weaker ones operating on new slightly fanned surfaces which are poorly developed. Without analyser. Field of view 0.57 mm wide.

3 — Passage of one kink structure into the other. Without analyser. Field of view about 1.3 mm wide.