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THE DEFORMATION OF A BASEMENT GRANITE AND THE DEVELOPMENT OF MAJOR SILICIFIED SHEAR ZONES IN UGANDA

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ABSTRACT. The structures occurring in a foliate porphyritic granite and in a silicified shear zone are described, and the sequence of their formation is established. The Kateti shear zone is of exceptional interest because almost continuous exposures show a complete gradation over several hundred feet, from foliate granite through granulated and partly silicified rocks into banded quartz tectonites. The structures of the rocks occurring at Kateti suggest that this shear zone represents an intermediate stage in the development of more massive and continuous bodies of quartz rocks which are completely detached from the adjacent granite.

Petrofabric analyses have been made of the limbs of minor concentric and kink folds formed by flexure of parts of the banded quartz rock in a shear zone. The marked preferred orientation of the quartz crystals in the quartz tectonites was retained in the rotated limbs of the minor folds until the banding was almost parallel to the axial planes of the folds. In this position the orientation pattern was considerably modified. It is concluded that an earlier formed orientation pattern of quartz optic axes may be retained during the formation of certain types of flexure folds.

INTRODUCTION

A perfectly fresh porphyritic granite forming part of the basement complex, outcrops over a wide area in the eastern part of Ankole district in Uganda (Phillips, 1959). The granite is crossed by several prominent ridges of quartz rocks which trend 120° E. and less commonly N. 60° E. and rise sometimes 400 feet above the surrounding exposures of granite. The ridges are 1 to 2½ miles in length and are arranged en echelon. The ridge which extends west-northwest of Kateti triangulation point (0° 31′ S.; 31° 03′ E.) is of particular interest because excellent exposures occur on the sides of the ridge (fig. 1a).

THE PETROGRAPHY OF THE GRANITE

The granite consists of numerous pinkish crystals of microcline-microperthite, generally 2 to 5 centimeters in length, and lenticular masses of blue opalescent quartz, with small biotite flakes and small partly altered crystals of plagioclase. The rock has a pronounced foliation structure due to the parallel alignment of the microperthite crystals. In thin section, zones of small biotite flakes and small intergrown, elongated quartz crystals lie sub-parallel to the microperthite crystals.

In the outcrops near Kateti ridge the granite shows increasing signs of deformation. The large crystals of microperthite and lenticular shaped crystals of quartz remain as porphyroclasts which are generally completely surrounded by a very fine grained micaceous matrix (pl. 1-A; fig. 1b). The microperthite porphyroclasts are broken by fractures which are steeply inclined to the foliation, and most of the crystals show the separation of fragments and some modification of the shape.

The foliation in the porphyritic granite commonly strikes due north, and the dip varies from vertical to 65° W., though locally the foliation dips to the east. Near Kateti ridge the strike of the foliation in the deformed granite tends to swing from north-south to N. 165° E.

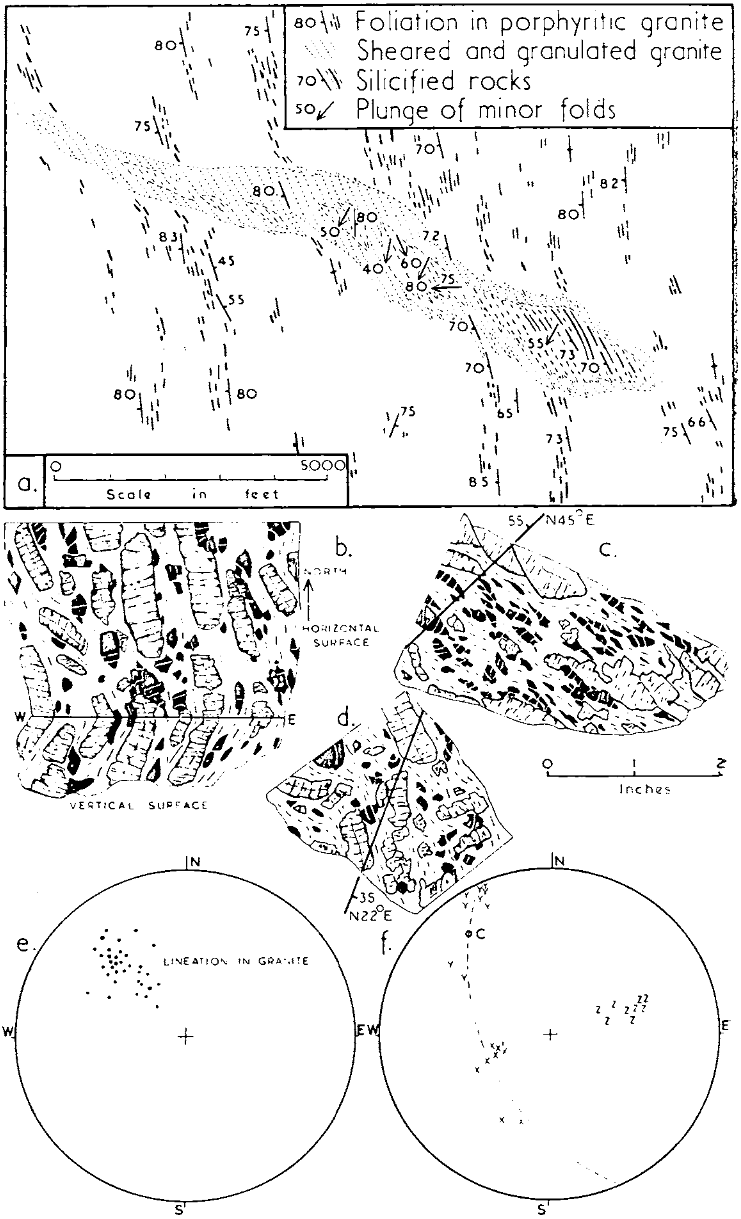


Fig. 1. a. Map of Kateti ridge; b. surfaces of granite showing the foliation structure; c. surface cut parallel to a lineation; d. surface cut perpendicular to the lineation; e. plot of the lineation on a stereographic projection; f. plot of the principal vibration directions of microperthite crystals on a stereographic projection.

A.

B.

C.

PLATE 1

A. Porphyritic granite with strong foliation near the southeast end of Kateti ridge.
B. Granulated granite on the south side of Kateti ridge.
C. Banded quartz rocks on Kateti ridge.

In the more deformed granite the microperthite porphyroclasts do not always occur in parallel alignment. Some crystals lie in planes oblique to the main foliation and usually strike northwest to southeast (fig. 1b). In many places adjacent to the ridge the foliation is replaced by a very strong lineation formed by the parallel alignment of the longest dimensions of the microperthite crystals and elongated. spindle-like porphyroclasts of quartz (fig. 1c). The surface cut perpendicular to this lineation shows the relatively small and generally equidimensional cross sections of the quartz spindles and the otherwise random orientation of the microperthite crystals (fig. 1d). The lineation can usually be seen in the micaceous matrix where it is produced by the intersection of layers of micas which curve around the larger crystals. The orientations of the linear structure in the deformed granite adjacent to Kateti ridges are shown in figure 1e. The plots of the principal vibration directions in a small number of microperthite porphyroclasts are shown in figure 1f.

The surface cut parallel to the lineation (fig. 1c) illustrates that the quartz porphyroclasts have been drawn out in the direction of the lineation and that the spindle shapes are frequently separated by open fractures. The microperthite crystal at the top edge of the specimen is broken by two prominent fractures which lie oblique to the length of the crystal. The displacement of the fragments of the crystal on these oblique fractures indicates that the crystal has been extended in the direction of the lineation. These textural features establish that the lineation in the deformed granite was a direction of extension.

THE KATETI SHEAR ZONE

On the Kateti ridge the strongly deformed porphyritic granite can be traced into granulated rocks in which small scattered fragments of microperthite and quartz are the only remnants of the original granite (pl. 1-B). The granulated rocks usually show a planar structure equivalent to the foliation in the porphyritic granite. This structure strikes approximately N. 150° E. and is oblique to the trend of the ridge so that there is a flexure in the strike of the foliation planes of the deformed granite across the ridge.

At one point on the south side of Kateti ridge the deformed granite is crossed by a band of granulated material. one foot wide, which strikes between N. 60° E. and N. 70° E. Crinkles occurring in the granulated rock have the shorter limbs on the northeast side. To the north of Kateti ridge there are several major quartz ridges which trend N. 60° E.

In places on Kateti ridge quartz has recrystallized in bands parallel to the foliation in the granulated rocks. and conspicuously banded rocks have been produced. Silicification also produced some transgressive veins. and in several places fractured and folded veins have been observed. The partly silicified micaceous rocks grade into white rocks which are composed almost entirely of quartz. though the original foliation is marked by a banding due to variations in the grain size and in the amount of mica remaining in the rock (pl. 1-C). The most silicified rock consists almost entirely of intergrown quartz crystals which range in size from 0.01 to 0.5 of a millimeter in length.

The quartz rock forms several large elongate masses along the ridge. The banding or foliation structure strikes about N. 150° E. and is everywhere

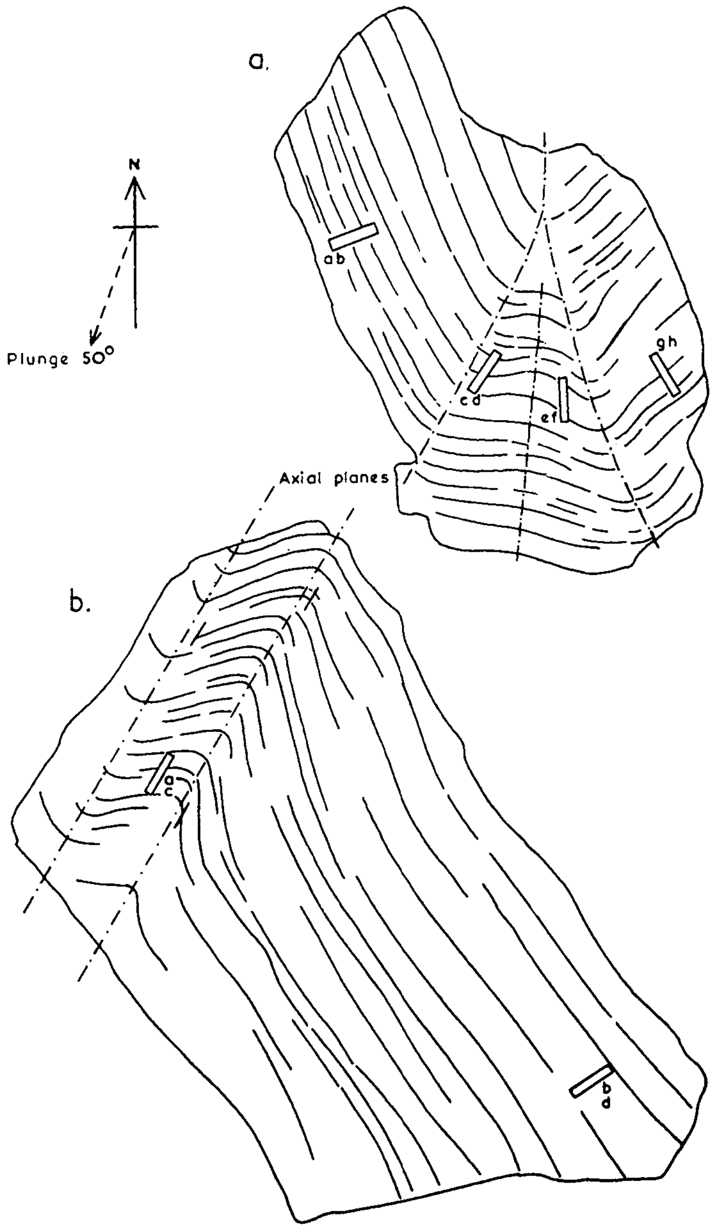


Fig. 2. a. Cross section perpendicular to the axis of a concentric fold, showing the areas selected for petrofabric analysis (see fig. 3); b. cross section perpendicular to the axis of the kink fold showing the areas selected for petrofabric analysis (see fig. 4).

oblique to the direction of the ridge. The banding dips to the west-southwest at 70° to 80°. The orientation patterns shown by the optic axes of the quartz crystals in the granulated granite and partly silicified rocks are variable, but the almost pure quartz rocks show simple, well marked patterns.

THE LATE MINOR FOLDS IN THE QUARTZ ROCKS

Some of the most compact quartz layers contain asymmetrical cylindrical minor folds. Two main types of minor fold have been distinguished, and a representative of each has been studied in some detail.

The profile of one fold is shown in figure 2a, and it can be seen that the sharpest curvatures occur across two axial planes that converge to form a single axial plane in the core of the fold. A slight reversed curvature occurs between the two main axial planes. There is no apparent increase in the thickness of the individual bands in the rock along the axial zones, and the amount of curvature of the fold decreases as the two axial planes converge. The fold can be described as concentric.

A section of a fold of a different kind is shown in figure 2b. This consists of a short limb bounded by two parallel axial planes which intersect the banding at 65°. It retains a similar appearance parallel to the axial planes as in kink-bands and can be described as a kink fold, which was formed by the rotation of the banding of the short limb between the axial planes. It can also be regarded as a flexure fold.

Folds of the concentric type occur where the kink planes pass into areas of bend gliding. The sharpest curvatures usually occur on planes that are approximately parallel to the axial planes of the kink folds or to the banding in the quartz rock.

THE PETROFABRIC ANALYSIS OF THE BANDED QUARTZ ROCK

The most silicified rock consists almost entirely of intergrown quartz crystals which range in size from 0.01 to 0.5 of a millimeter in length. Flakes of muscovite ranging in size from 0.01 to 0.06 of a millimeter in length are scattered throughout the rock but are also concentrated in some planes, generally 0.5 to 1 millimeter apart, where they form continuous trains up to 3 millimeters in length. Bands characterized by quartz crystals of similar size lie parallel to the planes of mica flakes which sometimes form relatively sharp boundaries between bands consisting of quartz crystals of very different size (pl. 2-A).

The smaller quartz crystals tend to be equidimensional, but the larger crystals show an elongation up to 2.5 to 3 times their width in a plane that is oblique to the banding. The larger grains have intimately sutured margins with bays and lobes approximately the same dimensions as the smaller equidimensional quartz crystals. Undulose extinction is present in almost all the larger crystals and is everywhere parallel to the banding.

The fabric of the most pure quartz rocks is represented by figure 3.a and b, and is composed of the following elements:

S_1 The prominent planar structure formed by the bands of quartz crystals of different sizes and by the discontinuous sheets of mica flakes.

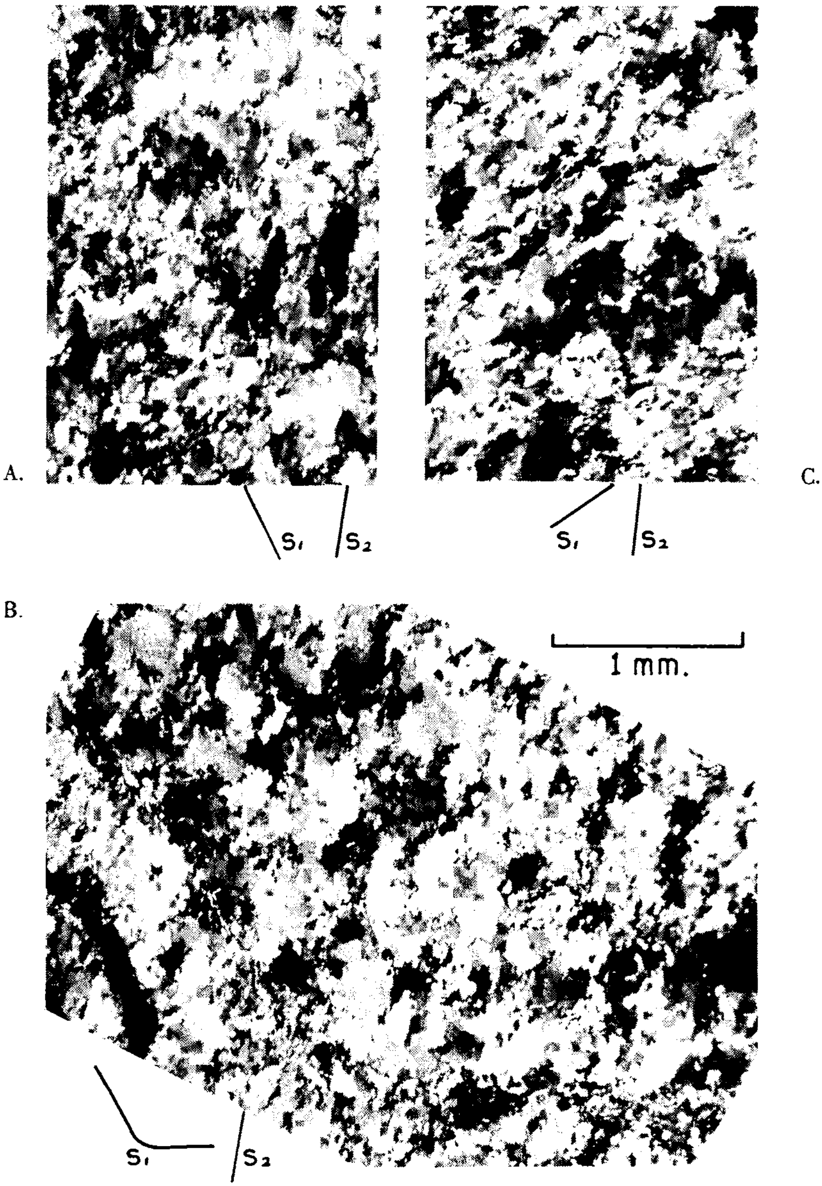


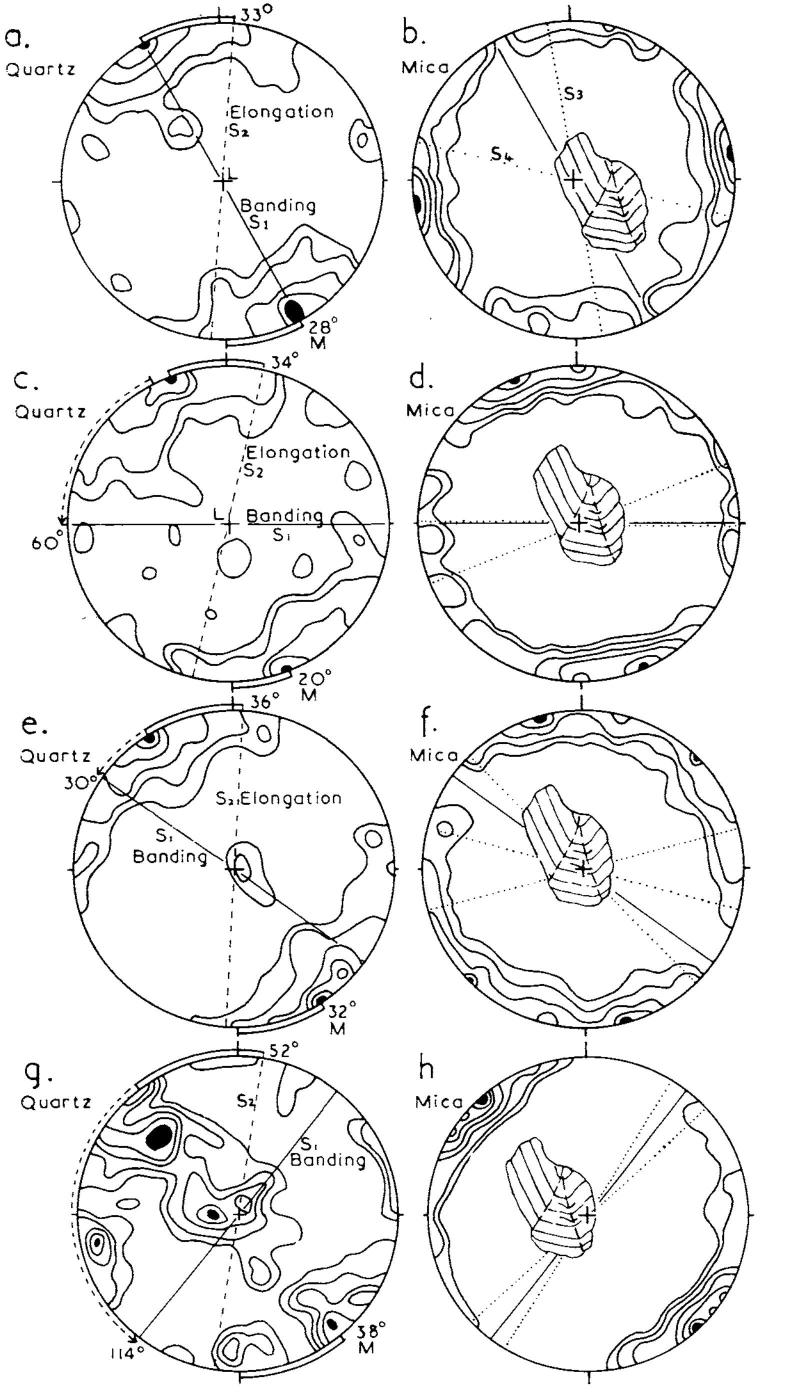
PLATE 2

A. Part of the unrotated limb of the concentric fold showing the banding S_1 and crystal elongation S_2 (see fig. 3a).

B. The axial zone of the concentric fold near the area of figure 3c.

C. The overturned limb of the concentric fold showing the elongation of some crystals parallel to the banding (see fig. 3g).

Fig. 3. Petrofabric diagrams of quartz optic axes and poles to the (001) planes of mica from the four areas on the concentric fold (fig. 2a). a. 300 quartz axes; contours at 1, 2, 5, and 10 percent per 1 percent area; maximum 13 percent. b. 200 mica flakes; contours at 1, 2, 5, 10, and 15 percent per 1 percent area; maximum 26 percent. c. 300 quartz axes; contours at 1, 2, 5, and 7 percent per 1 percent area; maximum 10 percent. d. 200 mica flakes; contours at 1, 2, 5, 10, and 15 percent per 1 percent area; maximum 19 percent. e. 300 quartz axes; contours at 1, 2, 5, and 10 percent per 1 percent area; maximum



14 percent. f. 200 mica flakes; contours at 1, 2, 5, and 10 percent per 1 percent area; maximum 12 percent. g. 300 quartz axes; contours at 1, 2, 3, and 4 percent per 1 percent area; maximum 6 percent. h. 200 mica flakes; contours at 1, 2, 5, 10, 20, and 27 percent per 1 percent area; maximum 34 percent.

S_2 The plane in which the quartz crystals are elongated.
S_3 The plane of preferred orientation of the mica flakes.
S_4 The plane indicated by the weaker concentration of mica flakes. (Actually the poles to the mica flakes form a girdle which has two distinct breaks.)
L A lineation formed by the intersection of the planes of mica flakes with S_1 (L is the axis of the mica girdle).
M The quartz optic axis maximum.

The diagrams representing the orientation of mica flakes were drawn from measurements made in only one plane so that each contains a central blind area. Sections cut perpendicular to the areas represented by figure 3,a and b, and figure 4,b and d, were measured, and the diagrams showed the same features except that part of the mica girdle was unobserved and the quartz crystals tended to be elongated parallel to the banding.

The plane of elongation of the quartz crystals (S_2) lies at an angle of 33° to the banding in the rock (S_1), which it intersects along the lineation L. The fabric has monoclinic symmetry with the visible lineation L parallel to the axis of symmetry. The axes of the minor folds are parallel to the lineation.

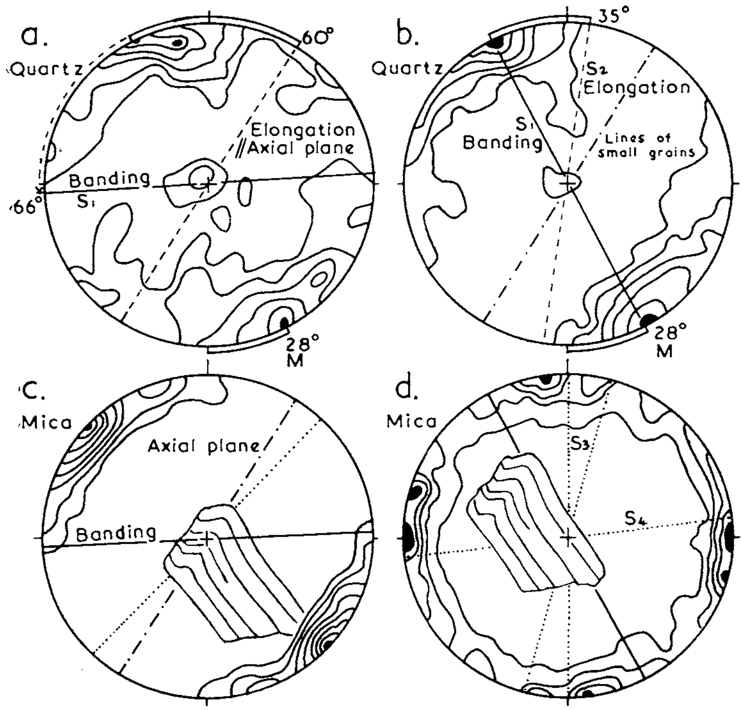


Fig. 4. Petrofabric diagrams of quartz optic axes and poles to mica cleavage from two areas on the kink fold (fig. 2b). a. 300 quartz axes; contours at 1, 2, 4, 6, and 8 percent per 1 percent area; maximum 9 percent. b. 400 quartz axes; contours at 1, 2, 5, 10, and 15 percent per 1 percent area; maximum 18 percent. c. 200 mica flakes; contours at 1, 3, 5, 10, 15, 20, and 25 percent per 1 percent area; maximum 30 percent. d. 200 mica flakes; contours at 1, 2, 5, and 10 percent per 1 percent area; maximum 12 percent.

THE PETROFABRIC ANALYSIS OF THE CONCENTRIC FOLD

In the area represented by figure 3.c and d, the banding has been rotated through 60° from the long limb (pl. 2-B). The pattern of the preferred orientation of the quartz optic axes and the plane of elongation of the quartz crystals remain unchanged and are only 7° from their original position (fig. 3c). In contrast the planes of preferred orientation of the mica flakes (fig. 3d) have been rotated with the banding but have not retained their original orientation in relation to the banding.

In the area represented by figure 3.e and f, the banding has been rotated 30° from its original position, and this might be regarded as intermediate between the a and c positions of figure 3. The quartz optic axis maximum and the plane of elongation of the quartz crystals have retained their original position to within 3°. The planes of preferred orientation of the mica flakes have rotated with the banding and retain to some extent their angular relation with the banding, although the plane of maximum concentration of the mica flakes has changed.

The banding in the area represented by figure 3.g and h, has been rotated through 114° and forms part of the overturned section of the fold. The pattern of orientation of the quartz optic axes in this area (fig. 2g. h) is very different from the diagrams obtained on the less rotated parts of the fold. The pattern shows an almost complete girdle parallel to the fold axis but perpendicular to the banding. The girdle contains a maximum almost perpendicular to the fold axis and only 7° from the position of the original single maximum (M) together with two new maxima parallel to and 70° from the fold axis. Symmetrically arranged minor maxima occur about 40° on either side of the banding and perpendicular to the fold axis.

Despite the change in the pattern of the orientation of the optic axes in this overturned section, the elongation of the crystals in the almost north-south plane is still prominent although it has been partially modified by an elongation parallel to the banding (pl. 1-C). The mica flakes have been rotated with the banding and are concentrated in the plane of the banding or in two symmetrically arranged, intersecting planes which are slightly oblique to the banding.

THE PETROFABRIC ANALYSIS OF THE KINK FOLD

The fabric of the long limb of the fold is illustrated by the diagrams of the orientation of the quartz optic axes (fig. 4b) and the mica flakes (fig. 4d). These diagrams are almost identical to those obtained on the unrotated limb of the concentric fold (fig. 3a. b). but irregularly spaced shear planes, sometimes marked by smaller crystals of quartz, intersect the banding at 60°. These planes are parallel to the axial planes of the adjacent fold, but they clearly have had little effect on the existing preferred mineral orientation.

The banding on the short limb of this kink fold has been rotated through 66°, and the orientation patterns of this area (fig. 4a, c) can be compared with those obtained in the area of the concentric fold represented by figure 3.c and d. The orientation pattern of the quartz axes (fig. 4a) has been modified only slightly during the rotation even though the elongation of the crystals tends to be parallel to the axial planes of the folds. The orientation diagram for the

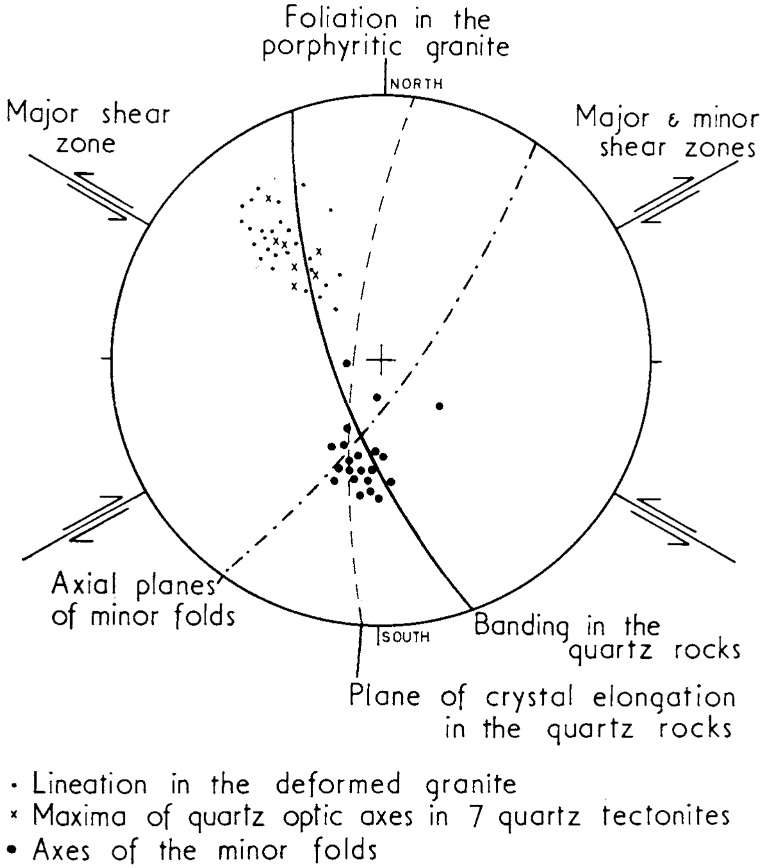


Fig. 5. The spatial relationships of the structures.

mica flakes (fig. 4c) shows that most of the mica flakes lie in a plane that is parallel to the fold axis and intersects the axial plane at 12°.

THE SEQUENCE OF FORMATION OF THE STRUCTURES

The spatial relationships of the different structural elements are shown in figure 5. The sequence of formation of the main structural elements is shown diagrammatically in figure 6, a to e, and is summarized below:

Stage 1. The parallel alignment of the microperthite crystals in the porphyritic granite appears to have been produced before the consolidation and subsequent deformation of the rock, because the phenocrysts have suffered only a slight degree of deformation (fig. 6a). This mineral orientation is present in the porphyritic granite over an area at least 20 miles wide, and it can be regarded as a primary foliation.

Stage 2. Deformation after consolidation resulted in the recrystallization of zones of small intergrown quartz crystals and small mica flakes with sub-

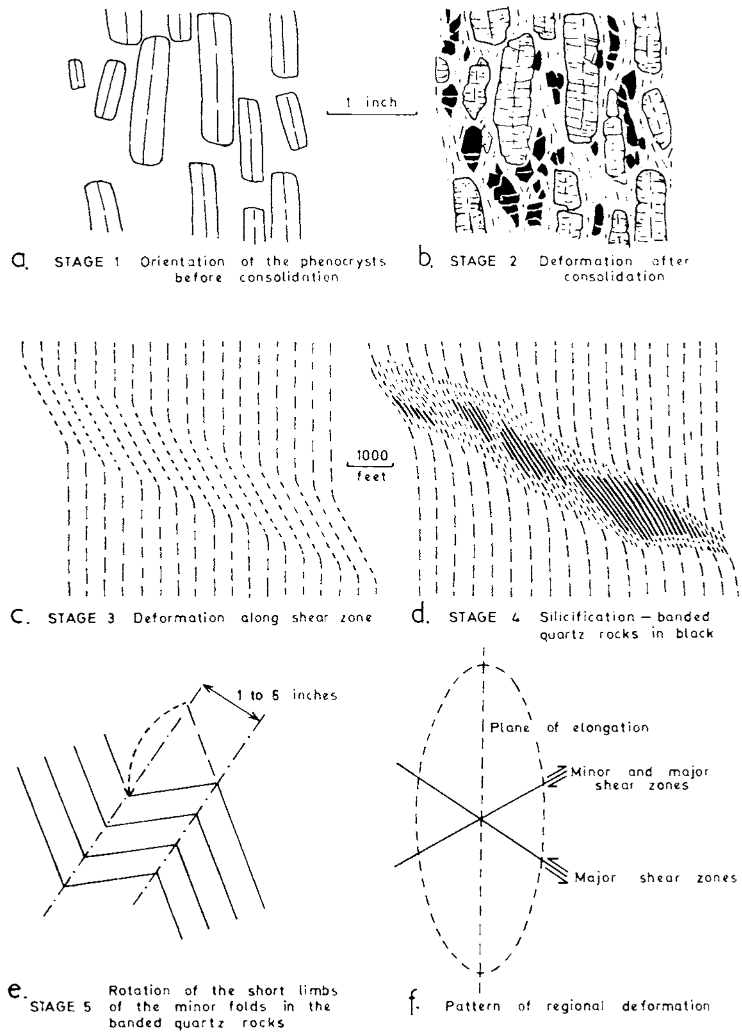


Fig. 6. Diagrammatic representation of the sequence of formation of the structures. a. The primary foliation, orientation of the microperthite phenocrysts; b. the secondary foliation; c. the shear zone; d. silicification within the shear zone; e. the minor folds in the quartz rocks; f. the relationship between the foliation and the major shear zones in the granite.

parallel alignment. The margins of some of the phenocrysts have been slightly modified by recrystallization, and groups of intergrown quartz crystals sometimes occur at the ends of the quartz and microperthite phenocrysts forming features similar in appearance to pressure shadows. The mica flakes generally form discontinuous, undulating surfaces which curve around the slightly deformed phenocrysts, and the resulting lenticular structure is here referred to as the secondary foliation (fig. 6b).

Stage 3. The foliated porphyritic granite was greatly deformed along laminar zones which strike N. 60° E. or N. 120° E. Along the Kateti shear zone the foliation present in the porphyritic granite can be traced into completely granulated rocks which strike N. 160° (fig. 6c).

Stage 4. Silicification occurred parallel to the planes of foliation in the granulated rocks, and the deformation of partly silicified rocks indicates that the silicification commenced before the movements ceased (fig. 6d). The texture of the quartz rocks and the strong preferred orientation of the quartz optic axes also indicate that silicification proceeded during deformation. The quartz rocks are secondary tectonites (Knopf and Ingerson, 1938, p. 40).

Stage 5. Minor flexure folds developed in some of the bands of the quartz rocks within the shear zone. These folds are associated with axial planes which strike N. 35° E. and dip at about 80° SE. The direction of rotation of the short limbs of the minor folds relative to the banding was the same as the direction of rotation of the foliation planes within the shear zone (fig. 6e).

Since the spatial relationships and relative time of formation of the different structures have been established, it is possible to speculate on the genetic relationships.

SPECULATIONS CONCERNING THE DEFORMATION OF THE GRANITE

It is possible that the parallel alignment of the microperthite crystals may have been produced by the preferential growth of these crystals in a particular plane due to the influences of regional stresses. However, there is very good evidence of the development of a strong preferred orientation of microperthite crystals due to growth parallel to the banding in granulites and granodioritic rocks which strike N. 80° E. just 7 miles south of Kateti ridge. The granodiorite rocks are characterized by replacement textures and appear to have been formed by the transformation of granulites. The more feldspathic bands contain numerous large, aligned porphyroblasts of microperthite. The narrow area between the porphyritic granite and the granodioritic rocks is not exposed, but it is possible that the porphyritic granite represents the mobilized end product of the granitization processes that produced the granodioritic rocks from the granulites. The marked preferred orientation of the slightly deformed microperthite phenocrysts in the granite suggests that the initial orientation of these large tabular crystals was produced by the non-turbulent, laminar shear flow of a mixture of crystals and intergranular liquid.

The lenticular structure formed by the curved surfaces of small aligned mica flakes and recrystallized quartz crystals is present throughout the granite and can be regarded as a post-consolidation, penetrative deformation structure. The plane bisecting the oblique mica surfaces is approximately parallel to the plane of preferred orientation of the tabular feldspar phenocrysts. This penetrative secondary foliation in the granite is not a purely cataclastic structure but was produced by the fracturing of some minerals, mainly the feldspars, and the recrystallization of other minerals, particularly quartz and mica, sometimes with the development of a marked preferred orientation. The penetrative nature of the secondary foliation suggests that the rock had just begun to consolidate due to the mutual interference of the crystals and was probably still at a high temperature.

Later deformation was confined in well defined laminar shear zones, and this suggests that at this stage the granite was in a more consolidated state and probably at a lower temperature. Along the Kateti ridge the deflection in the strike of foliation planes from N. 180° E. to N. 50° E. indicates that displacements in a sinistral sense occurred along the shear zone that strikes N. 60° W. Displacements in a dextral sense occurred on the large, silicified zones to the north and also on a minor shear zone on the south side of Kateti ridge, all of which strike approximately N. 60° E. The two sets of major shear zones are symmetrically disposed in relation to the foliation in the granite, and the regional deformation pattern appears to have orthorhombic symmetry. It seems likely that the two sets of shear zones represent complementary shear planes (fig. 6f). It is possible that the secondary foliation which formed before the shear zones was produced by elongation approximately parallel to the foliation planes and flattening perpendicular to the foliation.

Within the main Kateti shear zone the foliation planes were rotated up to 30° in an anticlockwise direction relative to their orientation in the granite (fig. 5d). There is clear evidence that the foliation planes in the granulated rocks of the Kateti shear zone were planes of movement and that the lineation which plunges to the northwest in the planes of foliation was a direction of relative extension of the deformed phenocrysts. It seems likely therefore that the foliation planes continued to act as planes of elongation during their rotation within the shear zone.

The transitional state of deformation is the most interesting because it was during this state that deformation combined with recrystallization produced the greatest modification on the rock as a whole. A detailed study of the deformation structures of large quartz porphyroclasts in the granite near Kateti ridge (Phillips, 1965) suggests that the sequence of development of the microscopic structures was related to a change in the physical state of the crystals during deformation, and that the most pronounced reorientation of the crystal structures occurred during an intermediate stage of deformation.

SPECULATIONS CONCERNING THE SILICIFICATION AND THE DEVELOPMENT OF THE QUARTZ TECTONITES

Sets of large ridges consisting almost entirely of quartz and commonly showing signs of deformation occur within many areas of the basement gneisses and granites of Uganda (Combe, 1932; Bisset, 1939). Although sedimentary structures are absent in these quartz rocks, they were at first thought to be remnants of sedimentary quartzites. After studying similar quartzose bodies in the central area of Uganda, Hepworth concluded that they were crush breccias which had grown by accretion during continued movement (Hepworth, 1954). The Kateti ridge described here is exceptional in that good exposures occur along its flanks so that a gradation from granite through granulated rocks to quartzite can be traced and related directly to deformation.

The silicified bands at Kateti ridge strike oblique to the shear zone. In most other ridges the banding is nearly parallel to the trend of the ridge so that it would appear that the Kateti ridge is not only unique in that the gradational rocks are exposed but also in that it represents a halfway stage in the development of the silicified shear zones. Presumably in some cases, continued rotation of the foliated granulated rocks within the shear zone would have brought the foliation parallel to the shear zone so that the two sides of the shear zone might be regarded as being detached from each other. Silicification along such detached shear zones would produce more continuous quartz rocks extending along the zone and showing no structural connection with the adjacent granite.

The segregation of silica in the center of the shear zone was probably largely balanced by the increase in the amount of micaceous minerals in the adjacent granulated rocks. However, upward migration of silica along the shear zone may have produced more dike like masses at higher levels in the crust. In many of the ridges further east, vein like masses of quartz are more common and are associated with breccia veins and with small, scattered crystals of hematite. Hematite is more abundant in the quartz rocks that appear to have undergone the greatest degree of brecciation, and in places hematite masses have been formed.

The pronounced preferred orientation of the quartz optic axes and the elongation of the quartz crystals in the most silicified bands developed while the movements were taking place along the shear zone. Because the banding (S_1) of the quartz rocks is parallel to the foliation in the granulated rocks which shows clear evidence of the extension of deformed quartz porphyroclasts and the separation of fractured feldspar crystals, the banding (S_1) can be regarded as a plane of movement. The quartz maximum (M) lies in the plane of movement and is approximately parallel to the direction of greatest extension of the deformed minerals in the granulated rocks, so it can be interpreted as the direction of greatest extension. The maximum (M) might be regarded as maximum (I) of Sander's synoptic diagram. The lineation (L) lies in the plane of movement and is perpendicular to the direction of movement, so it can be regarded as the axis of rotation of the monoclinic symmetry pattern.

The most important feature of the fabric diagrams of the rotated limbs of the flexure folds is that the pronounced quartz maximum (M) and the plane of elongation of the quartz crystals (S_2) retain their approximate original orientations even where the banding (S_1) has been rotated through 60°. Only in the overturned section of the concentric fold has the fabric been greatly modified.

Ladurner (1954), Jones (1959), and Ball (1960) have described folds with heterogeneous fabrics and have claimed that the fabric patterns have similar orientations when the folds are only partially "unrolled". They assume that this constant orientation indicates that the initial stage of folding was produced by shearing and that the pattern was subsequently modified by flexuring. The observations presented here indicate that a previously formed preferred orientation pattern of quartz axes may be retained during the formation of a flexure fold, and it follows therefore that a similar orientation after partial unrolling does not necessarily imply shearing on axial planes at an early stage of folding.

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