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Petrofabric Study of the Lamellar Structures in Quartz

By

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With 1 Table, 13 Text-figures and 1 Plate

ABSTRACT. The lamellar structures of quartz so far described in the literature have been classified into four types, that is, type L1, type L2, type L3 and type L4 (see p. 56). The lamellae of type L1 and of type L2 have been concluded to be relict lamellae which have been evolved from the lamellae of type L3 by annealing. As to the formation of the lamellae of type L3, the basic lamellae, deformation features of quartz grains have been analyzed in detail. The lamellae of type L3 have been regarded as a deformation band inclined at high angles to the glide line parallel or subparallel to the crystallographic c. axis Undulatory extinction bands developed in the grains containing lamellae have been classified into three types: a) undulatory extinction bands with wide width displayed as banding of parts with lamellae and those without lamellae in a grain, b) those with narrow width developed only in parts showing lamellae in a grain, and c) marginal undulatory extinction bands developed parallel or subparallel to the grain boundaries. On the basis of detailed examination of the undulatory extinction bands of the second type, it is pointed out that the boundaries of them in the host crystal coincide with the glide plane, which is responsible for the formation of lamellae, and that the formation of the undulatory extinction bands of the second type may be attributed to inhomogeneous rotation of the secondary glide plane parallel or subparallel to the lattice plane (0001) in each of intervening spaces bounded by the glide plane responsible for the formation of lamellae.

CONTENTS

I INTRODUCTION

Since the lamellar structures in quartz were described by KALKOWSKY in 1878, those in quartz grains in rocks of various types have been investigated by many authors. However, their nature is not always similar in all of examples described in the literature, but several different types of lamellae seem to be distinguishable. The lamellar structures known as "deformation lamellae" and "deformation bands" will be discussed in this paper.

The lamellar structures defined by closely spaced planer structure consisting of solid and fluid inclusions were first described in detail by BÖHM (1883). Such lamellae have been generally known as "BÖHM lamellae" or "BÖHM striae" since. On the other hand, the lamellae consisting of orientation of inclusions described by BECKE (1892) and FAIRBAIRN (1941) etc. showed a refractive index lower than that of the host crystal. This lower index of refraction defining the lamellae may be illustrated by TUTTLE's following terms. TUTTLE (1949) said, "if the fluid escapes from the inclusions (as always happens to those inclusions cut by the surfaces of the thin section), the liquid is replaced by air, which has a much lower index of refraction than has the host crystal. ......" Therefore, it may be noted that above two types of lamellae are synonymous. For reference purposes in this paper those lamellae are collectively designated as type L1.

CHRISTIE and RALEIGH have described the lamellae characterized by orientation of inclusions which were associated with narrow bands of different lattice orientation from the host crystal. The angular distances between the c-axis of the lamellar crystal and that of the host crystal are generally less than 3° (CHRISTIE and RALEIGH, 1959). In this paper these lamellae are designated as type L2.

The other two types of lamellae are characterized by narrow bands of different lattice orientation across the host crystal together. The lamellar stuctures known as deformation bands (RILEY, 1947; WEISS, 1954) correspond to one of those types of lamellae. On the other hand, the lamellae characterized by different lattice orientation described by PRESTON (1958) and HARA (1961) etc. showed a refractive index than higher that of the host crystal. Of those two types of lamellae displayed as narrow bands of different lattice orientation, the lamellae, which do not show different index of refraction from the host crystal, are designated as type L3, and the lamellae, which show higher index of refraction than that of the host crystal, are designated as type L4. The lamellae having refractive indices which are higher than those of the host crystal have been formed in experimental deformation of quartz cylinder at 800°C., 5kb by GRIGGS *et al.* (1960). They said, "these lamellae have an index of refraction considerably higher than that of quartz, which suggests that they may be coesite."

In this paper have been considered mutual relations of the type L1, type L2 and type L3 in genetic sense. The former two types have been concluded to be relict lamellae which have evolved from the type L3 by annealing.

In quartz grains of a quartz vein found in the Sangun metamorphic formation at the Nakase mine, Hyogo Pref., Western Japan, have been recognized the lamellae of type L3. In this specimen deformation behaviours of quartz grains related to the formation of the lamellae of type L3 as basic lamellae seem to be obviously analysed. The deformation behaviours of quartz grains will be described in detail and discussed.

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II Petrofabric Description

A. General Features of the Rock

The host rock of the quartz vein in question is phyllite derived from siliceous shale. The main constituents of the host rock are muscovite, quartz and graphitic matter, accompanied by subordinate chlorite and albite. The host rock shows a single distinct foliation defined by compositional banding as the result of metamorphic differentiation and original sedimentary lamination, and by the preferred orientation of platy minerals. Another conspicuous mesoscopic structure of the host rock is the strong lineations expressed by the parallel arrangement of mineral grains such as muscovite and chlorite within the foliation plane and by the axes of microfolds trending parallel to the former type of lineation. For reference purposes the foliation plane is tentatively selected as the *ab* plane of the fabric and the lineation as the *b*

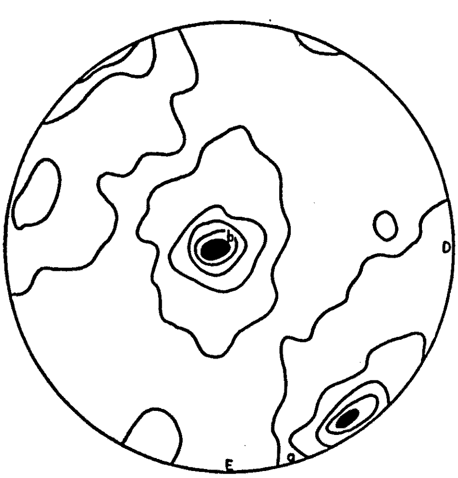

Fig. 1. 200 c-axes of quartz. Contours: 9-7-5-3-1%

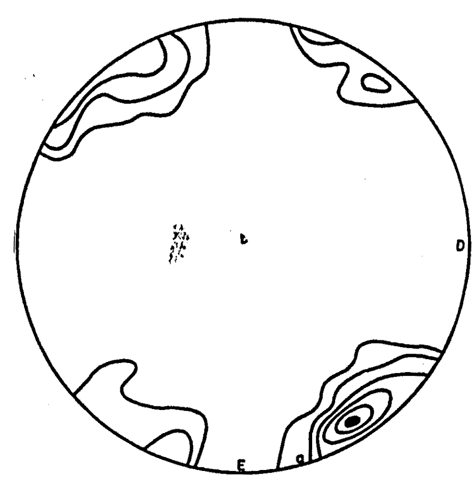

Fig. 2. c-Axes of 51 quartz grains containing lamellae. Contours: 22-18-14-10-6-2%

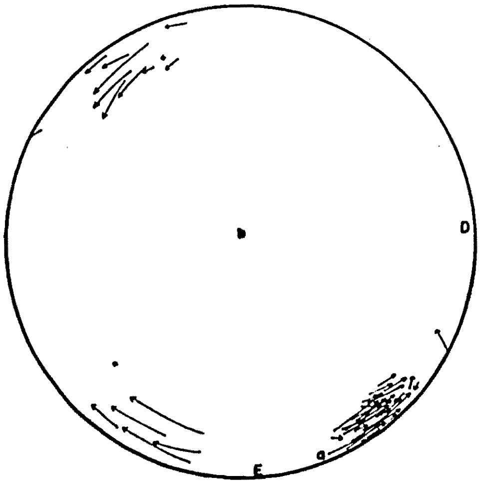

FIG. 3. Poles of lamellae (point of arrow) and c-axes of host crystals (end of arrow).

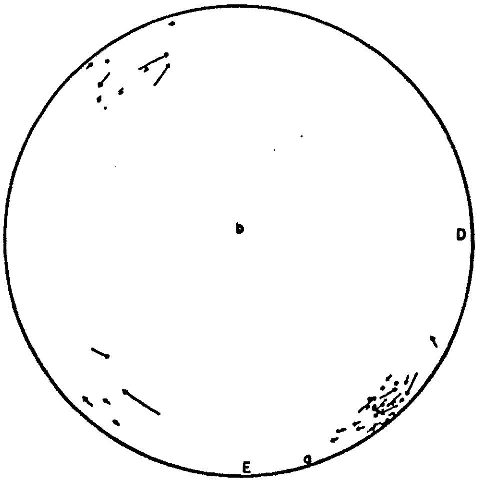

FIG. 4. Poles of lamellae (point of arrow) and c-axes of lamellar crystals (end of arrow).

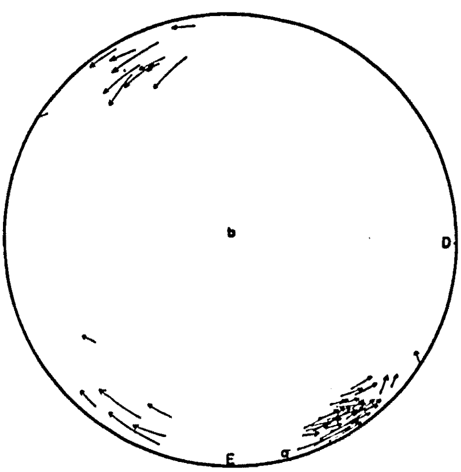

FIG. 5. c-Axes of lamellar crystals (point of arrow) and those of host crystals (end of arrow).

axis.

The quartz vein is running parallel to the foliation plane with width of several dm. The vein is massive without any planer structure, that being different from the host rock. This is a segregation quartz vein formed in the late metamorphic and kinematic stage.

The vein consists only of quartz grains. Most grains of quartz show distinct internal and marginal deformations. The internal deformation is displayed by undulatory extinction bands parallel or subparallel to the crystallographic c axis, the boundaries between neighbouring bands sharpening to the formation of subgrains in many grains. In some grains they are associated with lamellar structure. The marginal deformation is displayed by marginal undulatory extinction bands parallel or subparallel to the grain boundaries, accompanied by the formation of subgrains, and by small grains oriented along the boundaries which have probably sprouted from marginal nuclei.

Microscopic measurements of quartz grains in the vein in the *ac*, *bc* and *ab* thin sections give approximately similar mean grain dimensions parallel to the three fabric axes. The shapes of quartz grains are generally rather equidimensional. The grains, except subgrains formed in the undulatory extinction bands and small grains in grain boundaries, generally vary in size from 0.7 to 7 mm. The preferried orientation of c-axis of the grains is illustrated in fig. 1, based on 200 measurements in the *ac* section. The pattern is characterized by two maxima. The one coincides with the fabric axis *b* and the other approaches closely to the fabric axis *a*. These features of this diagram are quite different from the pattern of the c-axis fabric of quartz grains in the host rock, which is characterized by *ac* girdle. In spite of such remarkably simple pattern of the fabric, at present this cannot be accounted for in termes of "Tektonikgefüge" or of "Wackstumsgefüge" (Sander, 1950).

B. New Data

Development of lamellar structures in quartz grains is insignificant. They are recognized only in 25 per cent of the measured grains. They also cannot be recognized in the small grains oriented along the boundaries of large grains. The lamellae are distinctly displayed as narrow bands of different lattice orientation across the host crystal, terminating within the grain boundaries and being unrecognizable within the marginal undulatory extinction bands. The lamellae have an average width of 0.02 mm and are spaced with an average interval of 0.05 mm. The relative positions between the c-axis of the lamellae crystal and that of the host crystal could be measured accurately in all of the grain containing lamellae. The crystal-

Table I

for the lamellae formed in the earlier stage			for the lamellae formed in the later stage		
$C_L \wedge C_H$	$C_L \wedge L_\perp$	$C_H \wedge L_\perp$	$C_L \wedge C_H$	$C_L \wedge L_\perp$	$C_H \wedge L_\perp$
7	2 (−)	6 (+)	3	1 (−)	2 (+)
17	1 (+)	18 (+)	8	1 (−)	7 (+)
12	2 (+)	14 (+)	4	1 (+)	5 (+)
23	2 (−)	21 (+)	14	2 (−)	13 (+)
8	3 (−)	5 (+)	4	3 (−)	2 (+)
13	3 (+)	15 (+)	5	1 (+)	6 (+)
25	3 (−)	22 (+)	11	2 (−)	10 (+)

lographic location of the lamellae with respect to the lattice direction of quartz could not be directly measured, and only their trends on thin section could be directly measured. From those features of the lamellae in question, these may be correlated with the lamellar structure designated as deformation bands by RILEY (1947) and WEISS (1954). Namely, the lamellae correspond to type L3.

Properties of boundaries between the lamellar and host crystal have been examined in the *ac*, *bc* and *ab* thin sections: some boundaries are displayed as sharp but gradual change of extinction position, and others as discontinuous change of extinction position, weak rupture developing along many of these discontinuous boundaries, which are more or less filled with dark inclusions (Plate 7–3). As mentioned above, the crystallographic location of the lamellae in question cannot be directly measured. Although the lamellae are straightly or with weak arc crossing the host crystal, the boundaries between the lamellar and host crystal are not always even, but are uneven in many parts of them. However, in some parts of the boundaries they are straight

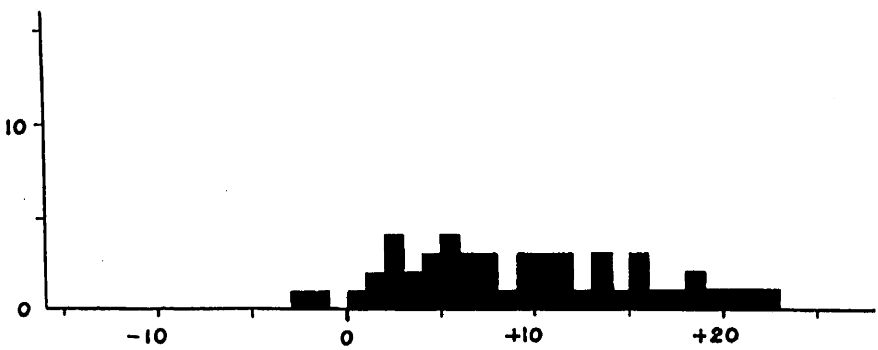

FIG. 6. Histogram showing the variation in the angle between the c-axis of host crystal and the pole of lamellae.

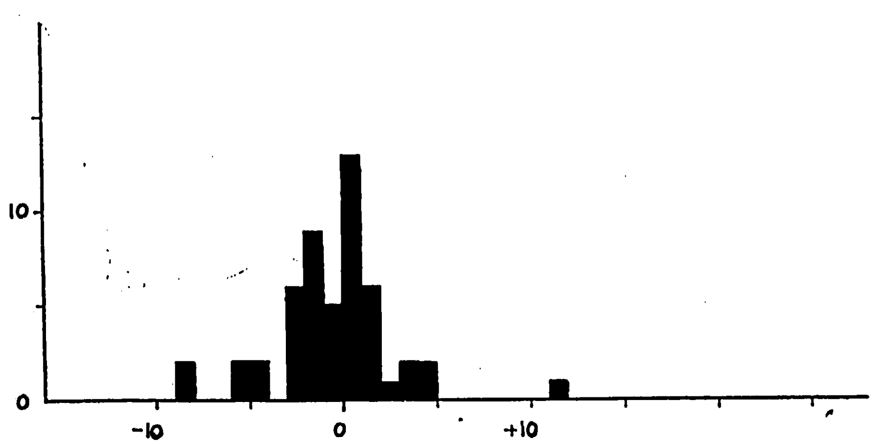

FIG. 7. Histogram showing the variation in the angle between the c-axis of lamellar crystal and the pole of lamellae.

and are trending parallel to the general trend of the lamellae. Therefore, the crystallographic location of the straight boundary ruptures developing in those parts may approximately correspond to that of the lamellae. Thus, tentatively in this paper, the crystallographic location of the lamellae has been indirectly determined by measurement of those straight boundary ruptures. The maximum error of measurement involved is probably $\pm 2°$.

As mentioned above, the relative positions between the c-axis of the lamellar crystal and that of the host crystal could be acculately plotted for all of the grains containing lamellae. The value of shift in the c-axis from the host crystal to the lamellar crystal ($C_L \wedge C_H$)* in measured grains is between 2° and 25°, with a maximum between 6° and 9°, as shown in fig. 8. Between the lamellae within a part of a grain, where the lamellae run straightly through the host crystal, the difference of the shifting value of c-axis from the lamellar crystal to the adjacent host crystal is small in many grains. However, in some grains it is fairly large. In these grains, the lamellae, for each of which the mean value of shift in the c-axis from the lamellar crystal to the adjacent host crystal is smaller, develop in the intervening space between the lamellae, for each of which that value is larger, and the former is trending slightly oblique to the latter, suggesting that the former is younger than the latter (Plate, 7–2). Therefore, it may be noted that the shifting values of the c-axis for the lamellae formed in the earlier stage are larger than those for the lamellae formed in the later stage. The variation between the former and the latter is between 4° and 14°, as shown in Table 1.

From X-ray studies of quartz grains containing undulatory extinction, deformation lamellae, marginal granulation and fracturing in naturally deformed rocks, BAILEY *et al.* (1958) said, "most of the quartz has deformed plastically by bend

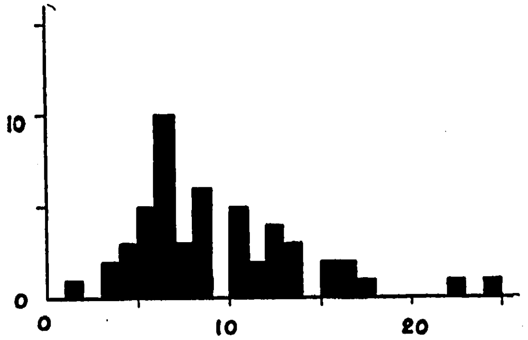

FIG. 8. Histogram showing the variation in the angle between the c-axis of host crystal and that of lamellar crystal.

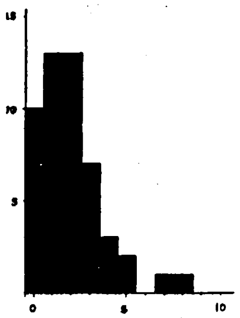

FIG. 9. Histogram showing the variation in the angle of deviation of the pole of lamellae from the great circle, on which the C_H and C_L lie together.

* The C_L and C_H correspond respectively to the mean direction of c-axis in the lamellar crystal and of that in the host crystal within a part of grain, where the lamellae run straightly through the host crystal.

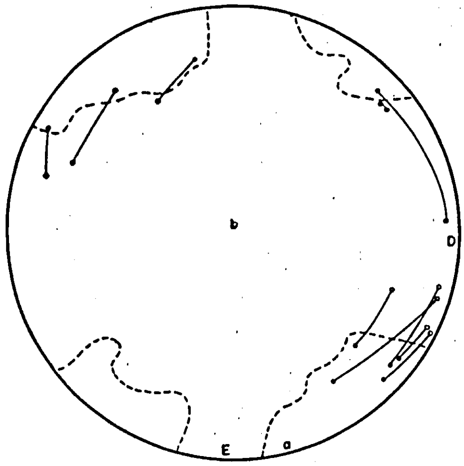

FIG. 10. Relation between the presence or absence of lamellae and the c-axis in different portions of individual grain.

Solid circle——lamellae present, and circle——absent. Brocken lines represent contour line of 2 per cent in the c-axis fabric diagram of quartz grains containing lamellae (fig. 2).

gliding. One of the three crystallographic a axis is always the major axis of bending,......" Therefore, the rotational axis of shift in the c-axis from the host crystal to the lamellar crystal may coincide with the a-axis. From such a point of view, deviation of the pole of lamellae (L⊥) from the great circle, on which CL and CH lie together, has been examined. It is illustrated in the histogram of fig. 9. The angle of deviation is between 0° and 8°, with a strong maximum between 0° and 3°. Therefore, it may be pointed out that the pole of lamellae, CH and CL in any grain seem not always to lie on a single great circle together, though error of measurement on them comes into question. The rotational axis of shift from CL to CH seems not always to coincide with the a-axis.

The preferred orientation of the pole of lamellae in all measured grains containing lamellae is illustrated in fig. 3. They are distributed in two sharply restricted areas, centers of which lie approximately with angular distances of ca. 70° in the fabric plane *ac*, indicating that they are tautozonally oriented and approximately correspond to the (*h0l*) planes with respect to the fabric axes. Similar pattern of preferred orientation is shown in the diagram for CL and CH (fig. 5), and maximum and submaximum in the diagram correspond closely to those in the pattern of lamellae poles.

In figs. 5 and 3 regular positional relationships between CH in any grain and CL in the same grain and between CH and L⊥ are recognized. In figs. 3 and 5, D and E are points which lie midway between maximum and submaximum for the lamellae poles on the *ac* great circle. In all the measured grains containing lamellae, CL in any grain is closer to the point D than CH in the same grain. On the other hand, except two of those grains, the pole of lamellae in any grain is closer to the point D than CH in the same grain. Similar positional relationship between CH and L⊥ has been recognized also for the lamellae of type L1, type L2 and type L4 (INGERSON and TUTTLE, 1945; RILEY, 1947; PRESTON, 1958; CHRISTIE and RALEIGH, 1959; HARA, 1961).

CHRISTIE and RALEIGH (1959) and the present author (1961) pointed out that the positional relationships between CL and CH and between CH and L⊥ in the composite diagrams for those axial data might be used to locate the stress system in the deformation which produced the lamellae. The rule for the establishment of the stress system has been stated as follows by the author: "1) the pole of the lamellae in any grain is closer to the direction of the compressive stress than the c-axis of the host crystal in the same grain; 2) the c-axis of the lamellar crystal in any grain is closer to the direction of the compressive stress than that of the host crystal in the same grain; 3) two groups of the poles of lamellae, distributed separately in angular distances of ca. 90° in the diagram for them, lie together on the plane containing the compression and tension axis; and 4) the compression and tension axis are located to points which lie midway between two groups of the poles of lamellae on the great circle, on which these lie together".

According to the rule, in this specimen the stress system in the deformation related to the formation of lamellae in question may be determined. Then the point D corresponds to the compression axis and the point E to the tension axis.

The crystallographic location of the lamellae with respect to lattice direction of quartz was examined by measurements of angles between L⊥ and CH and between L⊥ and CL respectively (in figs. 6 and 7). The angle between L⊥ and CH (CH∧L⊥) is between 1° and 23°, indicating similar result to that for the lamellae of type L1, type L2 and type L4 obtained by SANDER (1930), FAIRBAIRN (1941), INGERSON and TUTTLE (1945), PRESTON (1958), CHRISTIE and RALEIGH (1959), and HARA (1961). The angle between L⊥ and CL (CL∧L⊥) is between 1° and 12°, with a strong maximum between 1° and 3°. CH∧L⊥ shows larger variation of angle than CL∧L⊥. As mentioned above, in some grains the lamellae formed in different stages coexist. The crystallographic locations of these lamellae are shown in Table 1. CH∧L⊥ for the lamellae formed in the earlier stage is larger than that for those formed in the later stage. The variation between the former and the latter in each grain is between 3° and 12°. On the other hand, seems not to be recognized any available variation between CL∧L⊥ for the lamellae formed in the earlier stage and that for those formed in the later stage.

In figs. 6 and 7 the plus and minus values of CH∧L⊥ and of CL∧L⊥ are defined by following relations: when in any grain the pole of lamellae is closer to the assumed compression axis than CH, CH∧L⊥ is designated as plus value, and, on the contrary when the former is closer to the assumed tension axis than the latter, CH∧L⊥ is designated as minus value. When the pole of lamellae in any grain is closer to the assumed compression axis than CL, CL$\wedge$L$\perp$ is designated as plus value, and, on the contrary when the former is closer to the assumed tension axis than the latter, CL$\wedge$L$\perp$ is designated as minus value. The minus value of CH$\wedge$L$\perp$ has been recognized only in two grains, and maximum minus value was 3°. The plus value of CH$\wedge$L$\perp$ has been recognized in the remaining 49 grains, and maximum plus value was 23°. On the other hand, the plus value of CL$\wedge$L$\perp$ has been recognized in 25 grains, and maximum plus value was 12°. The minus value of CL$\wedge$L$\perp$ has been recognized in the remaining 26 grains, and maximum minus value was 9°. The histogram for CL$\wedge$L$\perp$ in fig. 7 shows a strong maximum between $-3°$ anb $+3°$. Thus, the histogram for CL$\wedge$L$\perp$ shows remarkablly different feature from that for CH$\wedge$L$\perp$ in fig. 6.

Comparison of fig. 2 with fig. 1 shows that CH in all the measured grains containing lamellae is distributed in two sharply restricted areas, that being different from the orientation pattern of the c-axis of all measured grains. In some grains is observed phenomenon that the lamellae develop and do not in different portions of the internal part of grain, apart from marginal undulatory extinction bands, as shown obviouslv in a grain of Plate, and CH of part lacking lamellae in any grain shows distinctly different direction from that of part showing lamellae in the same grain, as shown in fig. 10. Therefore, it can be pointed out that the tendency to form the lamellae depends upon the orientation of quartz crystal relative to the applied stress.

Properties of internal undulatory extinction bands in grains containing lamellae, which are inclining at high angles to these, will now be examined. The undulatory extinction bands are distinguishable to two following types, as observed obviously in a grain of Plate: a) undulatory extinction bands with wide width displayed as banding of parts with lamellae and without these in a grain, and b) those with narrow width developing only in parts showing lamellae in a grain. Generally, the trend of the latter is slightly oblique to that of the former. In the grain of Plate, the trends of both types of undulatory extinction bands are intersecting at angles of ca. 40° each other. The latter type of undulatory extinction bands seems to be very important for the consideration of mechanism of the formation of lamellae. Therefore, the undulatory extinction bands with narrow width developing only in parts showing lamellae in a grain will now be examined in detail.

The shift in the c-axis between the adjacent bands of the undulatory extinction bands in question is gradual or sudden, in some boundaries of bands associating weak rupture. The undulatory extinction bands in the lamellar crystal and those in the host crystal show different value of shift in the c-axis between the adjacent bands and different width of the bands each other: the former has smaller value of shift in the c-axis between the adjacent bands and wider width of the bands than the latter in general, as shown in figs. 12 and 13. Generally, the undulatory extinction bands in the lamellar crystal are insignificant as compared with those in the host crystal. Most of the undulatory extinction bands in the host crystal have widths of between

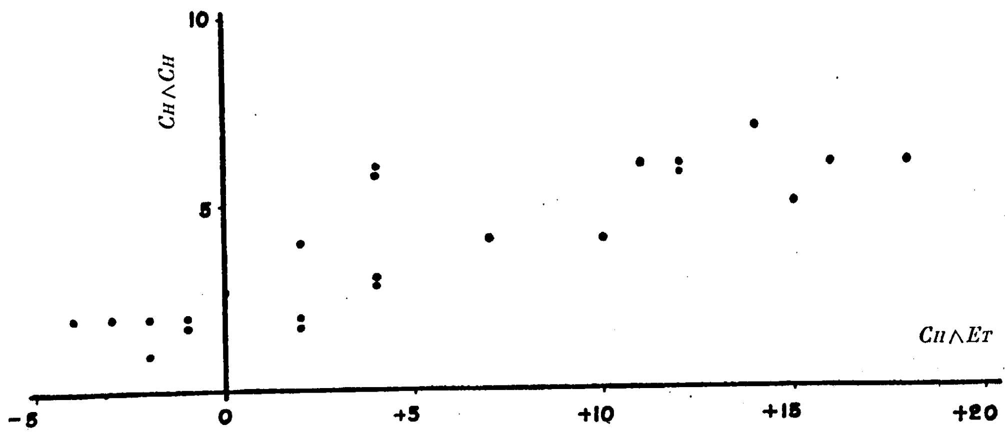

FIG. 11. Relationship of the angle between the c-axis of any undulose extinction band in the host crystal and tren of the same band on the ac thin section to the shifting value in the c-axis between the just adjacent bands.

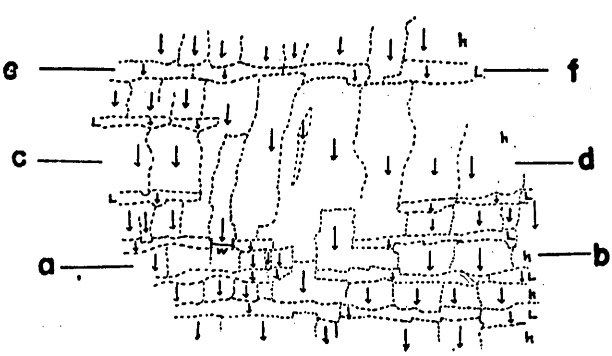

FIG. 12. Distribution of optic axial directions.

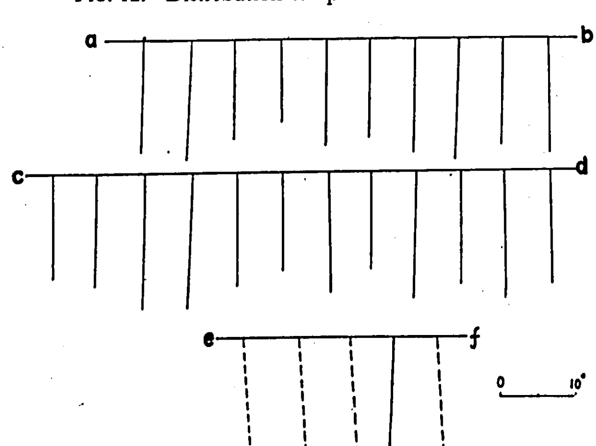

FIG. 13. Diagrammatic representation of the optic axial directions and their inclination in grain of fig. 12.

Solid line represents the optic axial direction of the host crystal. Dotted line represent the optic axial direction of the lamellar crystal.

0.02 and 0.08mm in the *ac* section.

Positional relationship between the c-axis of any undulatory extinction band in the host crystal (CH) and the trend of the same band on the *ac* section (ET) with reference to the stress axes related to the formation of lamellae is very interesting. This relationship has been examined in 22 grains containing lamellae. For angle between the trend of CH of any undulatory extinction band and the trend of the same band on the fabric plane *ac* ($CH \wedge ET$) and value of shift in the c-axis between the just adjacent bands ($CH \wedge CH$) in fig. 11 are used their maximum values in each grain. The plus and minus value of $CH \wedge ET$ in fig. 11 are defined by following relations: when CH is closer to the compression axis related to the formation of lamellae than ET, $CH \wedge ET$ is designated as plus value, and, on the contrary, when ET is closer to the compression axis than CH, $CH \wedge ET$ is designated as minus value. The minus value of $CH \wedge ET$ has been recognized in 6 grains and maximum minus value was 4°. On the other hand, the plus value has been recognized in the remaining 16 grains and maximum plus value was 18°. In grains showing minus value and small plus value of $CH \wedge ET$, $CH \wedge CH$ is small, and boundaries between the undulatory extinction bands concerned are shown rather by gradual change of extinction position, associating boundaries shown by discontinuous change of that. Generally, widths of those undulatory extinction bands are rather wide. On the other hand, in grains showing large value of $CH \wedge CH$, $CH \wedge ET$ is large plus value, and generally boundaries between the undulatory extinction bands concerned are displayed as discontinuous change of extinction position, in some boundaries associating weak rupture. Maximum value of $CH \wedge CH$ is 7°, as shown in fig. 11. Generally, widths of those undulatory extinction bands are narrow, showing an average width of ca. 0.04 mm. for those having larger value than 10° of $CH \wedge ET$.

From different features between the undulatory extinction bands in the host crystal and those in the lamellar crystal described above, it may be concluded that in the later stage of the formation of lamellae the host crystal has independently deformed with different deformation behaviour from the lamellar crystal.

Fig. 12 is a optic axial map of a grain containing lamellae. In this grain, development of internal undulatory extinction bands are insignificant, and boundaries between the bands are gradual in some and discontinuous in others. $CH \wedge ET$ is small plus value. The trends of the c-axes on the fabric plane *ac* and their inclinations to this plane for the grain of fig. 12 are diagrammatically represented in fig. 13. This figure suggests that the shift in the c-axis between the undulatory extinction bands cannot always be regarded as simple plastic bending of a certain lattice plane of quartz about a rotational axis.

III GENETIC INTERPRETATION OF LAMELLAR STRUCTURES

From the regular positional relationships between CH and CL and between L⊥ and CH in the diagrams for those axial data, according to the author's method

(1961), has been tentatively established the stress system in the deformation which produced the lamellae in question. Under the stress system the lamellae must be illustrated as deformation bands or kink bands, as pointed out already by the author. In order to examine whether such the inference is true for the lamellae in question or not, data deduced from histograms for CH$\wedge$CL, CH$\wedge$L$\perp$ and CL$\wedge$L$\perp$ will be now examined with reference to the assumed stress system.

CH$\wedge$L$\perp$ for the lamellae formed in the earlier stage in any grain shows larger value than that for those formed in the later stage, as shown in Table 1, suggesting progressive increase of CH$\wedge$L$\perp$ with progress of deformation. On the other hand, CL$\wedge$L$\perp$ for the former ones shows similar value to that for the latter ones. CL$\wedge$L$\perp$ seems not to change its value with progress of deformation. Thus, from the plus value of CH$\wedge$L$\perp$ in all grains except two grains in comparison of the histogram for CH$\wedge$L$\perp$ with that for CL$\wedge$L$\perp$, it may be judged that CH shifts progressively to the assumed tension axis (with reference to L$\perp$) with progress of deformation, because at the initiation of the formation of lamellae CH$\wedge$L$\perp$ and CL$\wedge$L$\perp$ have the same value. On the other hand, the sense of rotation in the lamellar crystal must be opposite to that of CH and consequently CL could scarecely shift to the assumed tension axis (with reference to L$\perp$), indicating similar value of CL$\wedge$L$\perp$ for the lamellae formed in different stages in any grain. Thus, the lamellae and the boundary between the lamellar and host crystal cannot be regarded as active glide planes. However, the shifting attitudes of CL and CH mentioned above can be clearly illustrated in accordance with the assumed stress system by regarding the lamellae in question as deformation bands, though the active glide plane related to the formation of the lamellae as deformation bands comes into question.

As mentioned above, CL$\wedge$L$\perp$ seems scarecely to change its value with progress of deformation. Therefore, initial crystallographic location of the lamellae may be approximately inferred from CL$\wedge$L$\perp$. According to fig. 7, it may be concluded that initial crystallographic locations of the lamellae in question correspond approximately to lattice planes inclining to (0001) at angles varying from 1° to 12°. Also the minus value of CH$\wedge$L$\perp$ in two grains suggests that the lamellae in these grains initially were formed obliquely to (0001). Thus, it is safely pointed out that the lamellae initially do not always develop normal to the c-axis, but that their initial crystallographic locations are fairly variable.

Glide plane and glide direction in quartz lattice in the deformation related to the formation of lamellae must be inclining at high angles to them, just as well as in the formation of deformation bands in minerals and metals reported so far. Possibility of translation gliding parallel or subparallel to the c-axis, which is inclined at high angles to the lamellae, so far has been discussed by many authors (HIETANEN, 1938; GRIGGS and BELL, 1938; FAIRBAIRN, 1939; WEISS, 1954; CHRISTIE and RALEIGH, 1959). This problem will be analyzed in connection with the undulatory extinction bands with narrow width developing only in parts with lamellae of grain in following pages.

As mentioned in preceding page, in the later stage of the formation of lamellae the host crystal has deformed with the formation of undulatory extinction bands with narrow width independently from the lamellar crystal. Between $CH \wedge CH$ and $CH \wedge ET$ have been recognized following relations: the larger becomes the $CH \wedge CH$, the larger with plus value becomes $CH \wedge ET$. When $CH \wedge CH$ shows small value, the undulatory extinction bands are trending subparallel to the c-axis, that is approximately parallel to the assumed glide line for the formation of the lamellae as deformation bands. The progressive increasing of plus value of $CH \wedge ET$ corresponds to progressive rotation of CH to the compression axis with reference to ET, and also corresponds to progressive rotation of (0001) to the tension axis with reference to ET. The progressive increase of value of $CH \wedge CH$ corresponds to inhomogeneity of progressive rotation of (0001) in each of the undulatory extinction bands to the tension axis. Thus, the formation of the undulatory extinction bands in the host crystal in question seems to be well illustrated by the following hypothesis: in the grains containing lamellae, the plane (0001) approaches closely to zone of maximum shear stress in the stress system related to the formation of lamellae. In the later stage of the formation of lamellae, intervening space bounded by the glide planes parallel or subparallel to the c-axis, which are responsible for the formation of lamellae, has been deformed by secondary translation gliding parallel or subparallel to the plane (0001). In this stage of deformation, gliding along the first glide plane responsible for the formation of lamellae has only subordinate significance for the deformation of quartz grain. In further progress of deformation the secondary glide planes rotate progressively to the tension axis. Inhomogeneity of shifting magnitude of the secondary glide plane in each of the intervening spaces bounded by the first glide planes will give progressive increasing of $CH \wedge CH$ with progress of deformation. Thus, the first glide planes coincide with the boundaries of the undulatory extinction bands in the host crystal. Rotation of the secondary glide plane to the tension axis, accompanied by subordinate rotation of the first glide plane to it, will give large plus value of $CH \wedge ET$ in progressive increase of the value of $CH \wedge CH$. Inference that the first glide planes may coincide with the boundaries of the undulatory extinction bands seems to be strongly confirmed on the basis of following facts: in fig. 12, width w of the host crystal, which cut across the lamellae, is approximately equal to that of undulatory extinction band in the host crystal and edges of the lamellae approximately coincide with boundaries of the undulatory extinction band in the host crystal. And also widths of the undulatory extinction bands with narrow width in the host crystal correspond approximately to the length of angular convex and concave part of boundary lines between the lamellar and host crystal in the *ac* thin section, as shown in fig. 12. From preceding discussions, translation gliding parallel or subparallel to the c-axis, which must be responsible for the formation of lamellae, seems to have been confirmed. Lines of weakness in the quartz lattice known as lineage structure tend to develop in a direction parallel to the c-axis (BUERGER, 1934; FAIRBAIRN, 1939). The lines of weakness seem to be very important for the translation gliding parallel or subparallel to the c-axis in question, as many authors have pointed out.

As described in preceding page, most grains of quartz in the vein show marginal undulatory extinction bands parallel or subparallel to the grain boundaries and small grains oriented along them. These features are attributable to grain boundary shear in deformation related to the formation of lamellae in the internal part of grain, though this problem will be discussed in other paper. Deformation behaviours of quartz grains in the vein, such as the formation of the lamellae as deformation bands and the grain boundary shear, correspond with those of metal aggregate in experimetal creep deformation.

About the formation of deformation bands or kink bands in creep deformation of polycrystalline aggregate, A. H. SULLY (1956) said, "as slip proceeds, local stress concentrations are set up inside individual crystals, due to the interaction of slip with grain boundaries and the constraining effect of neighbouring grains. These stress concentrations may be relieved by local distortions of the crystals which take the form of kink or deformation bands." About the formation of the lamellae in quartz grains in question, similar inference may be probable.

As described in preceding pages, some boundaries between the lamellar and host crystal are displayed as sharp but gradual change of extinction position, and others as discontinuous change of it, weak rupture developing along many of these discontinuous boundaries, which are more or less filled with dark inclusions. The latter type of boundary is regarded as the result of the polygonization of the former type. The lattice structure of quartz in the polygonized boundary exists in a disordered condition. Therefore, silica in those discontionuous boundaries may be remarkablly soluble with respect to water in certain condition. Under such a condition as annealing of deformed quartz grains takes place more or less, into those discontinuous boundaries may diffuse and intrude molecules and fluid materials, which existed in crystal and crystal boundaries. Then, fluid and solid inclusions are formed along those boundaries with differential solution and deposition of silica (Plate. 7–3). After the process has continued for some time, those inclusions become large and the boundaries between the lamellar and host crystal may be displayed as planes of inclusions with respectable thickness. In this stage, the lamellae, which had been formed as narrow bands of different lattice orentation across the host crystal, would change to narrow bands of different lattice orientation bounded by planes of inclusions, those corresponding to the lamellae of type L2. In other case the lamellar crystals may disappear because of considerable growth of inclusions, and consequently the lamellae defined only by orientation of inclusions may be formed in quartz grains. These lamellae correspond to the lamellae of type L1, that is, "BÖHM lamellae."

On the basis of preceding discussions, it may be concuded that the lamellae of type L1 and type L2 are relict lamellae which have evolved from the lamellae of type

L3 by annealing. Therefore, it is natural that for those three types of lamellae have been recognized similar results about the crystallographic location of them, the orientation pattern of the poles of lamellae in the diagram for them and regular positional relationship between L⊥ and CH in the composite diagram for these axial data.

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Explanation of Plate

Fig. 1. The lamellae showing small value of the $C_H \wedge C_L$. Many boundaries between the lamellar and host crystals are displayed as sharp but gradual change of extinction position. Undulatory extinction bands in the lamellar and host crystals are negligible. Crossed nicols. ×500

Fig. 2. Relation between the lamellae probably formed in the earlier stage (L_E) and those formed in the later stage (L_L). Crossed nicols. ×200

Fig. 3. Row of inclusions filling boundaries between the lamellar and host crystals. Crossed nicols. ×300

Fig. 4. Undulatory extinction bands in the host crystal showing large values of the $C_H \wedge C_H$ and of the $E_T \wedge C_H$. Crossed nicols. ×300

Fig. 5. A example of relation between parts with the lamellae and parts without lamellae in a grain. Undulatory extinction bands in the host crystal of the patrs with the lamellae are distinctly displayed with narrow width, and their trends are oblique with angles of ca. 40° to the boundaries between parts with the lamellae and parts without lamellae. Crossed nicols. ×100

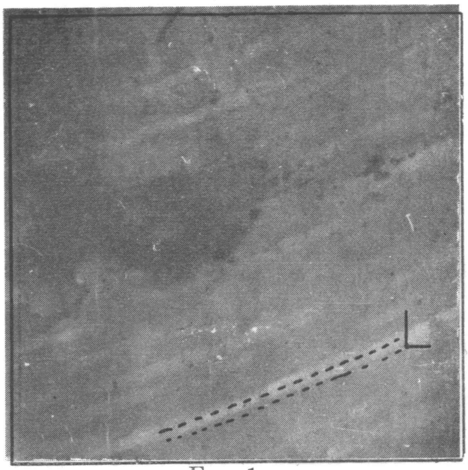


FIG. 1

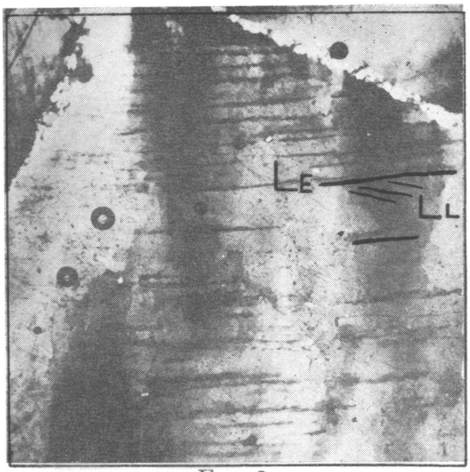


FIG. 2

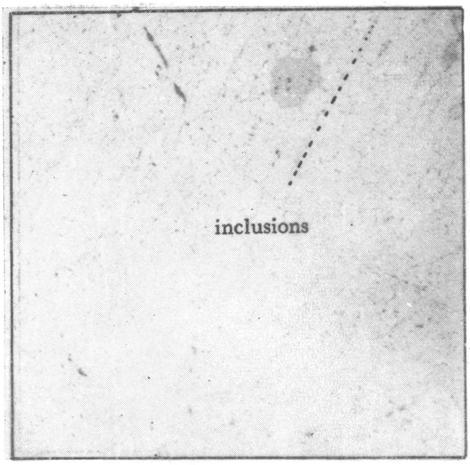


FIG. 3

FIG. 4

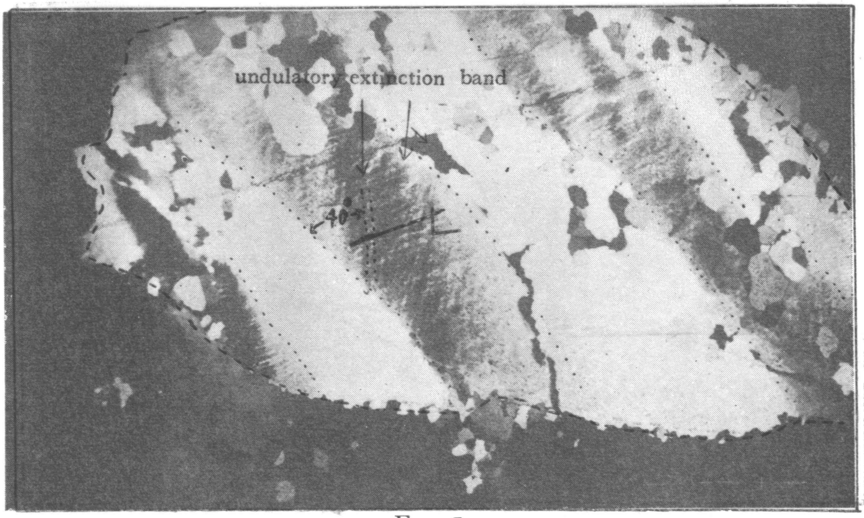


FIG. 5

FIG. 1

FIG. 2

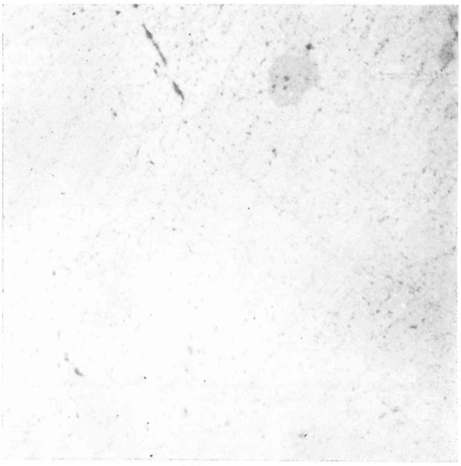


FIG. 3

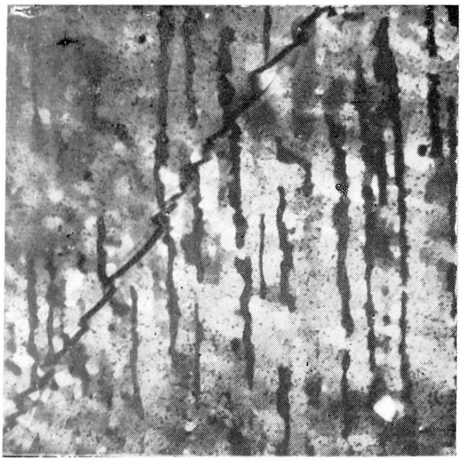
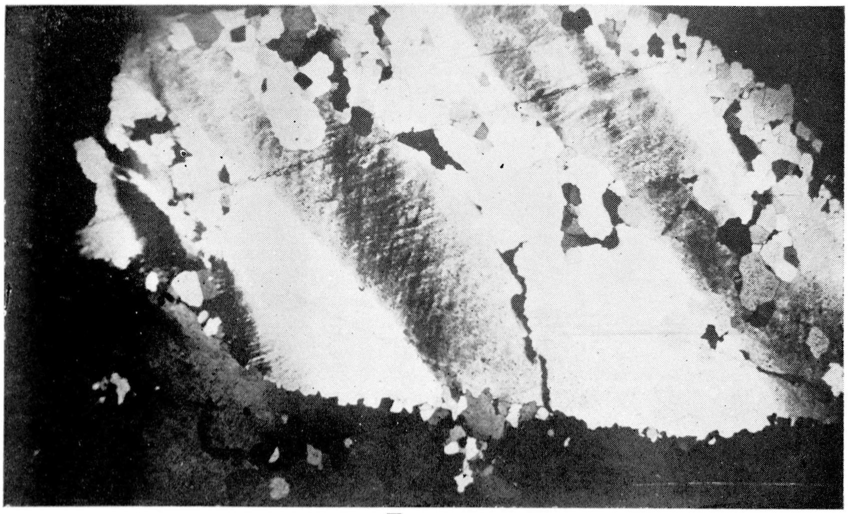


FIG. 4



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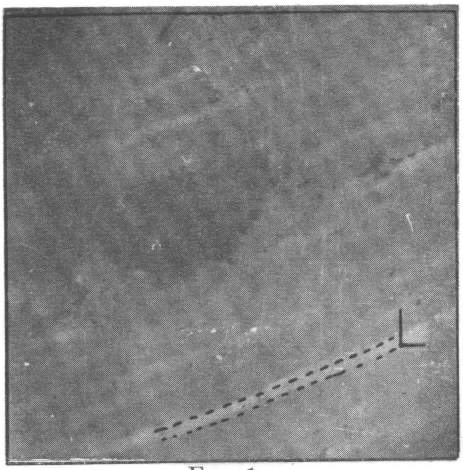

FIG. 1

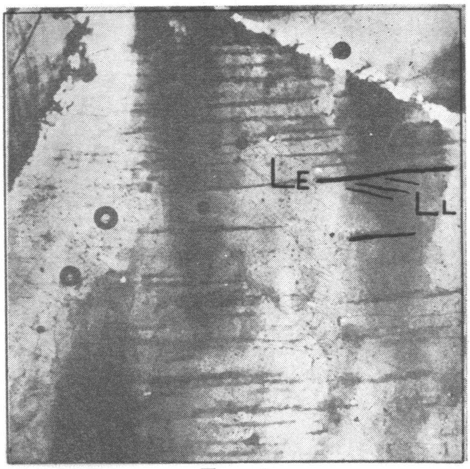

FIG. 2

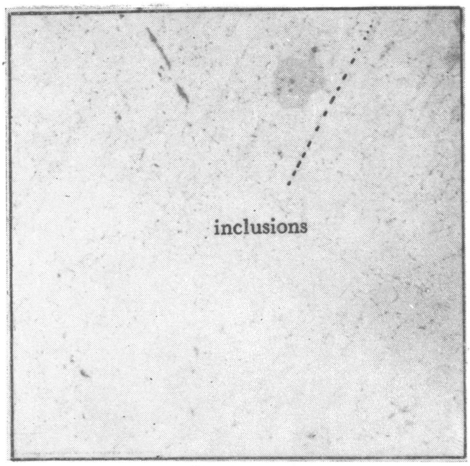

FIG. 3

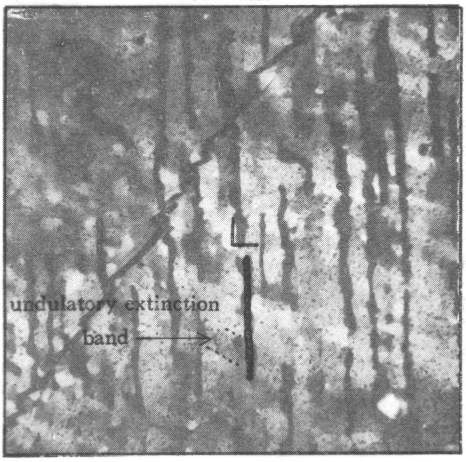

FIG. 4

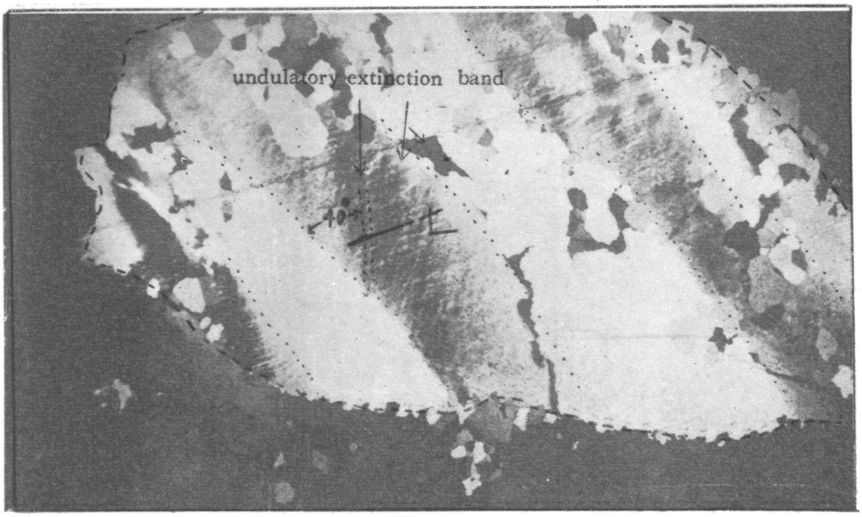

FIG. 5

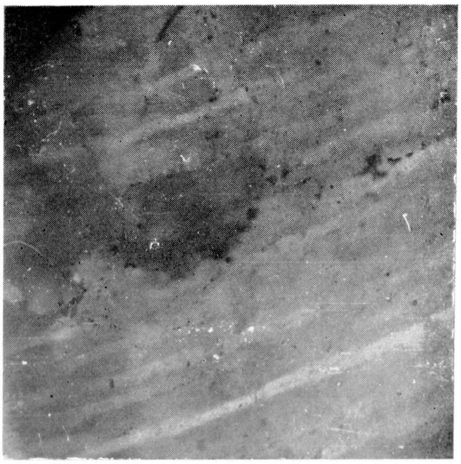

FIG. 1

FIG. 2

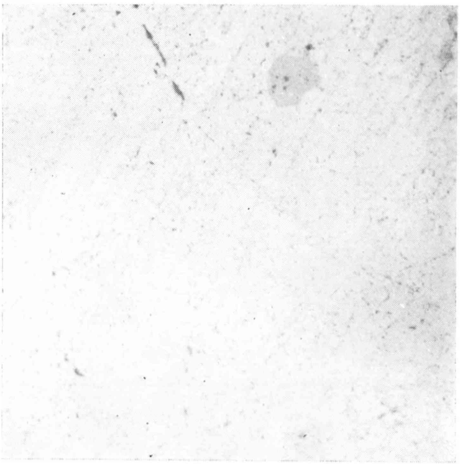

FIG. 3

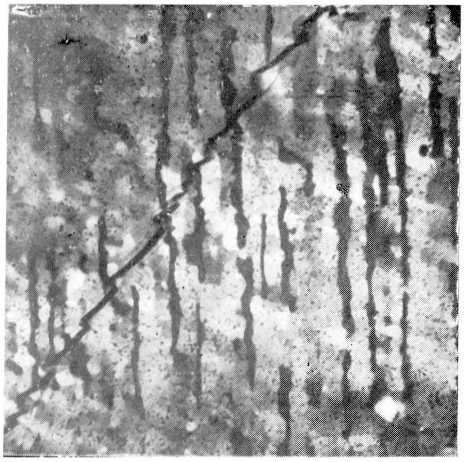

FIG. 4

FIG. 5