STRUCTURAL PETROLOGY
OF
PLANES OF LIQUID INCLUSIONS

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by

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ABSTRACT

Planes of liquid inclusions are common in the quartz of igneous and metamorphic rocks. The planes have a high degree of preferred orientation, and it is believed that they represent fractures in the quartz grains that have been filled with intergranular liquid which subsequently changed to individual inclusions by differential solution and deposition of silica. The planes of inclusions commonly extend through several quartz grains of different orientation with no deflection at the grain boundaries, indicating that there is little or no crystallographic control of their orientation.

The planes of inclusions have been found to have a remarkably uniform orientation over an area of 15 by 20 miles. They strike northwest and dip steeply to the northeast through the area, whereasthe primary structures, contacts and foliations strike north-south and dip westward, indicating that the planes of liquid inclusions have been superimposed on the primary structure.

Detailed work on drag-folds indicates that the planes of inclusions may develop in the shear-directions of the deforming stress-pattern and that one set tends to predominate. The poles to the planes tend to lie in a partial girdle about the fold-axis. Some evidence was found indicating that the planes may develop in the tensional direction.

Quartz, then, may fail by shear or tensional rupture and in certain cases by deformation which produces lamellae that may be a type of translation-gliding. Failure by rupture

along crystallographic directions has been described by one investigator, and has been produced experimentally in the laboratory. These different phenomena are believed to represent failure under varying environmental conditions and the optimum development of any one type of failure depends on such factors as confining pressure, temperature, composition, and the presence (and character) of solutions.

If several sets of planes of liquid inclusions develop at different times, the relative ages of the planes can be discerned from the character of the planes. Planes of inclusions that are very "young" appear as extremely thin sheets of liquid, whereas "old" planes are made up of inclusions that are nearly equant, with some of the inclusions having crystal planes as boundaries (negative crystals).

INTRODUCTION

General

Liquid inclusions have been recognized in the quartz grains of rocks since the advent of the microscope, and many observers have noted that they are commonly aligned in planes. The writer recently became interested in these structures when studying liquid inclusions in granitic rocks and associated quartz veins. Examination of oriented sections of a granitic rock from the Washington, D. C. area revealed a remarkable parallelism of the planes. Further observations on crystalline rocks in general showed that planes of liquid inclusions are very common; indeed, it is unusual to find quartz-bearing rocks that do not contain planes of liquid inclusions. Using the universal stage, a statistical study of the orientation of the planes of liquid inclusions disclosed a remarkably high degree of orientation.

A cursory examination of the literature left much to be desired in the way of explanation of the origin and significance of the planes of inclusions. Several conflicting theories had been advanced for their origin and no mention was made of the high degree of orientation. It was at this stage that the writer decided to make an extensive study of the inclusions. The following report deals with those studies, which began in 1941 and continued until the summer of 1942 when full time work was temporarily discontinued. However, laboratory work was continued intermittently, much of it at the Geophysical Laboratory, until 1946, when the present work was completed. Field studies were commenced, and continued along with the laboratory studies during parts of 1943, 1944, and 1945.

Character of Liquid Inclusions

Liquid inclusions may be divided into two genetic groups, 1) primary and 2) secondary. Primary inclusions are emplaced during the growth of the host crystal whereas secondary inclusions are introduced at some subsequent time. Only the latter will be considered here, as primary inclusions are usually randomly distributed throughout a crystal or, if aligned in planes, the planes represent growth directions (zoning or lineage (Buerger 1*)) in the crystal.

Liquid inclusions in quartz crystals vary in size from submicroscopic to cavities containing more than 50 cc. of solution. The large inclusions are in all probability primary inclusions emplaced during growth. The secondary inclusions which are considered in detail here rarely contain as much as 0.001 cc. of solution. They vary in size from submicroscopic up to a few hundredths of a mm. in largest dimensions.

The shape of liquid inclusions is extremely variable. There are all gradations in shape from a thin sheet-like inclusion with extremely irregular outlines to nearly equant inclusions bounded by crystal planes characteristic of the host crystal. Between these two extremes round, elliptical,

*Numbers in parenthesis refer to references page 46.

cylindrical, cigar-shaped, pear-shaped, or irregular branching forms are found. Secondary inclusions usually have two dimensions considerably greater than the third. The inclusions usually lie in a plane with the planar dimension of the inclusions parallel to the plane.

Liquid inclusions are characterized by a vapor bubble which formed on cooling as a result of the much higher coefficient of expansion of the liquid than the host crystal. In comparison with the liquid the bubble is usually small and it is not unusual to find it in constant motion (Brownian movement). This mobility of the bubble serves to distinguish liquid inclusions from glass inclusions found in some extrusive rocks.

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 the host crystal. In many cases this index difference causes the cavities to appear opaque; in others it is obvious that the inclusion is filled with air. This apparently explains the common description in the literature of "rows of vapor, fluid, and opaque inclusions."

Liquid inclusions commonly consist of two immiscible liquids and a vapor bubble. Gentle heating of this type of inclusion above 31° C. causes one liquid to disappear, indicating that it is carbon dioxide. Cubes of sodium chloride and potassium chloride are occasionally seen in liquid inclusions.

Figure 1 is a photomicrograph of a plane of secondary liquid inclusions. The plane is perpendicular to the

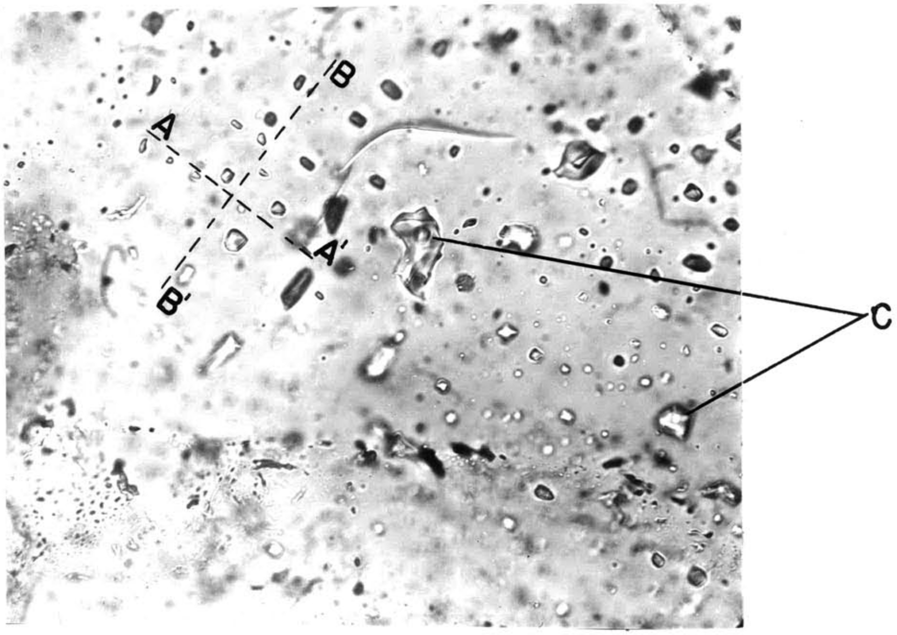


Figure 1. Plane of liquid inclusions in quartz grain. The plane is nearly perpendicular to the microscope axis. The inclusions in the upper left hand part of the photograph have boundaries that suggest imperfect negative crystal faces. The trace of two crystallographic directions is believed to be along AA' and BB'. Two of the inclusions have vapor bubbles (c) that are nearly in focus. The bubbles are in constant motion (Brownian movement). x 500.

microscope axis. The inclusions in the upper left hand part of the photograph have boundaries that suggest imperfect negative crystal faces. The trace of two crystallographic directions is believed to be along AA' and BB'. The large irregular inclusion near the center has a vapor bubble (c) which is in constant motion.

Previous Observations

One of the first descriptions of planes of liquid inclusions was made by Kalkowsky (2) in 1878. He described and sketched planes of inclusions in the quartz of a gneiss. The planar character was noted but the orientation was not mentioned. Apparently considerable thought had been given to the origin of the planes, for he wrote, "Man mochte vermuthen, dass auch dieze Spalten nicht einer rein mechanischen Ursache ihren Ursprung verdanken." It could be interpreted from this that he believed that a chemical origin was most likely.

Böhm (3) described planes of liquid inclusions in the quartz of schists and gneisses of the central Alps. He observed that planes of liquid inclusions commonly cut through several quartz grains without deflection. He noted the parallel arrangement of the planes and part of his description suggests deformation lamellae rather than planes of inclusions. The orientation of the structures was not discussed.

In 1884 Hicks (4) described planes of inclusions in quartz pebbles in a conglomerate and believed them to be of secondary origin. The planes of liquid inclusions, he writes on page 194, ".... may have been closed up by a secondary deposition of quartz."

J. W. Judd (5) was apparently the first investigator to relate planes of inclusions to structural features. His observations can best be described in his own words (page 81): "Near the gigantic fault which bounds the southern edge of the Scottish Highlands, the quartzite-pebbles of the Old-Red-Sandstone Conglomerate are found exhibiting striking evidence of the tremendous mechanical forces to which they have been subjected; sometimes one pebble is found deeply impressing another, and not unfrequently the whole of the pebbles are found to be crushed to fragments, which have been re-cemented by the deposition of secondary quartz or of calcite. In the case of a quartzite pebble which has been faulted — the mass yielding at last to the tremendous stress upon it — it occurred to me that before the pebble gave way to the force operating upon it, it must have been in a state of prolonged and violent strain along planes parallel to that in which it eventually yielded.

"On making thin sections across such faulted pebbles, I found my anticipations to be fully realized. The quartzite is seen under the microscope to be made up of sand-grains which are portions of quartz crystals, these being cemented by secondary quartz deposited in crystallographic continuity with them .... These crystalline fragments lie in every possible position, as is shown when they are viewed by polarized light, and they contain the acicular crystals of rutile and other minerals with the original liquid-cavities which distinguished the quartz of the rock from which they were derived. But running through all the grains, quite irrespectively of their orientation, we see under the microscope a series of dark lines, straight as if ruled, and showing an unmistakeable parallelism with the plane along which faulting has taken place .... By the use of higher powers of the microscope these dark lines are resolved into bands of cavities containing liquids or with secondary infillings of solid matter. It is impossible to doubt that these bands of cavities with their fluid and solid inclusions have been produced by solvent action along the bands of strain."

Judd's theory for the origin of planes of liquid inclusions is essentially chemical, and possibly is the same mechanism that Kalkowsky (2) had in mind (page 4).

Van Hise (6) described planes of liquid inclusions in quartz and believed their origin to be mechanical. He writes, "Mechanical action has cracked the grains in parallel planes. These cracks have become filled with liquid. Later, by the deposition of quartz, they have again become cemented and retained at times numerous liquid inclusions."

Bastin (7) noted that bands of liquid inclusions are common in the quartz of pegmatites and quartz veins. He wrote, "Some of these bands terminate abruptly at the border of a quartz grain, but others pass without change or deflection from one quartz grain to another. The bands sometimes terminate at the border of a shear zone although they were also observed to continue through the fractured ares." It was also reported that the bands in pegmatite quartz were commonly aligned in two sets which were at right angles to each other.

A most extensive study of planes of liquid inclusions, with qualitative data on their orientation, was made by Dale (8) on crystalline rocks in New England. He described over forty granites, gneiss, quartz veins, and pegmatites containing planes of liquid inclusions. Some contained two sets of planes parallel to the rift and grain of the rock, whereas others contained only one set which was parallel, perpendicular, or diagonal to the foliation. In other cases the "strike" of the two sheets of liquid inclusions corresponded to the rift and grain of the granite.

Dale recognized that some planes of inclusions were of secondary origin; however, he apparently believed that most of the planes of liquid inclusions were primary. For example, he writes (page 24), "..... nor is the passage of sheets of cavities without deflection from one crystal to another evidence that the cavities were formed or arranged after the crystallization of the quartz. The arrangement of the cavities and the crystallization of the quartz, the first governed by crustal strains and the second by crystalline coehesion, may have been synchronous processes."

Again he writes (page 25), "During the consolidation of granite, when the quartz, the last constituent to consolidate, was crystallizing, the fluidal cavities were formed and, in obedience to crustal strain, were largely alined, some in approximately horizontal sheets and others in vertical sheets."

The most recent work on planes of liquid inclusions is by Anderson (9). Fractures, planes of liquid inclusions, and partings were studied in eight quartz grains from a quartz vein. The structures were related to crystallographic directions and preferred rupture directions were deduced. Statistical studies were not carried out and it is impossible to relate the orientation of the planes of inclusions to structures in the enclosing rocks. Anderson apparently believes that the planes of inclusions represent crystallographically controlled fractures.

Acknowledgments

Thanks are especially due Professor W. H. Newhouse for encouraging a study of liquid inclusions, and for frequent discussion of the many problems encountered during this work, begun under his supervision.

Professor H. W. Fairbairn has had a continuing interest in this work, and has made numerous helpful suggestions for which I am grateful. The thin sections studied from areas other than Washington, D. C. were kindly made available by Professor Fairbairn.

To Dr. Earl Ingerson go my thanks for independently checking the personal element in preparing fabric diagrams of planes of liquid inclusions. He kindly spent considerable time preparing diagrams of different thin sections, which, I am pleased to report, gave results identical with mine.

I am indebted to my wife for contouring many of the fabric diagrams and for typing and assembling this report.

ORIGIN OF SECONDARY PLANES OF LIQUID INCLUSIONS

Three different hypotheses have been proposed by various writers for the origin of planes of liquid inclusions. Two of the hypotheses require a secondary origin for the planes whereas the third requires that the planes be primary. They may be termed, 1) fracture, 2) solution, and 3) growth.

The fracture hypothesis was apparently first proposed by Hicks (4) in 1884. In describing planes of liquid inclusions in quartz grains of a conglomerate he noted that they passed from one grain to another of different orientation without deflection. This let him to believe that they were secondary, that is, fractures which were "closed up by a secondary deposition of quartz."

The solution hypothesis is essentially chemical and was first proposed by Judd (5). He believed that the planes of inclusions were formed by solution entering along "planes of easy solubility." These solution planes, writes Judd (page 82), "..... like the cleavage planes and glide planes, have definite relations with the symmetry of the particular system to which the crystal belongs." It follows then that planes formed in this manner should have definite crystallographic relations to the host crystal. This of course is not the case, as even Judd recognized, for later (page 90), in describing planes of liquid inclusions in a quartz pebble he writes, ".... streams of bubbles are seen running through all the grains of quartz, quite irrespective of their orientation."

The third hypothesis for the origin of the planes of inclusions was first advanced by Dale (8). The exact mechanism is not clear, but it is apparently a growth phenomenon, as he writes (page 25) ".... during the consolidation of granite, when the quartz, ... was crystallizing, the fluidal cavities were formed....." Dale also recognized that some planes of inclusions were secondary but believed that those in granites were largely primary.

The investigation described in the following pages shows that planes of liquid inclusions in quartz grains of crystalline rocks have a high degree of orientation. The orientation in general is as pronounced as, say, the orientation of mica crystals in a well-foliated rock. This immediately suggests that any theory explaining their origin must include a process for aligning the planes into subparallel orientation over wide areas. The author's field work in the D. C. area shows an orientation persistant over an area of 200 square miles and requires therefore a regional deformation. It appears, then, that planes of liquid inclusions are a deformational structure of the same general type as cleavage, jointing or faulting.

The author's theoretical mechanism for producing a single plane of liquid inclusions is illustrated in figure 2. The first step is fracturing of the quartz grains and filling of the fracture with liquid. Individual inclusions are then formed along the fracture by differential solution and deposition of silica.

The first stage in this final process of solution and

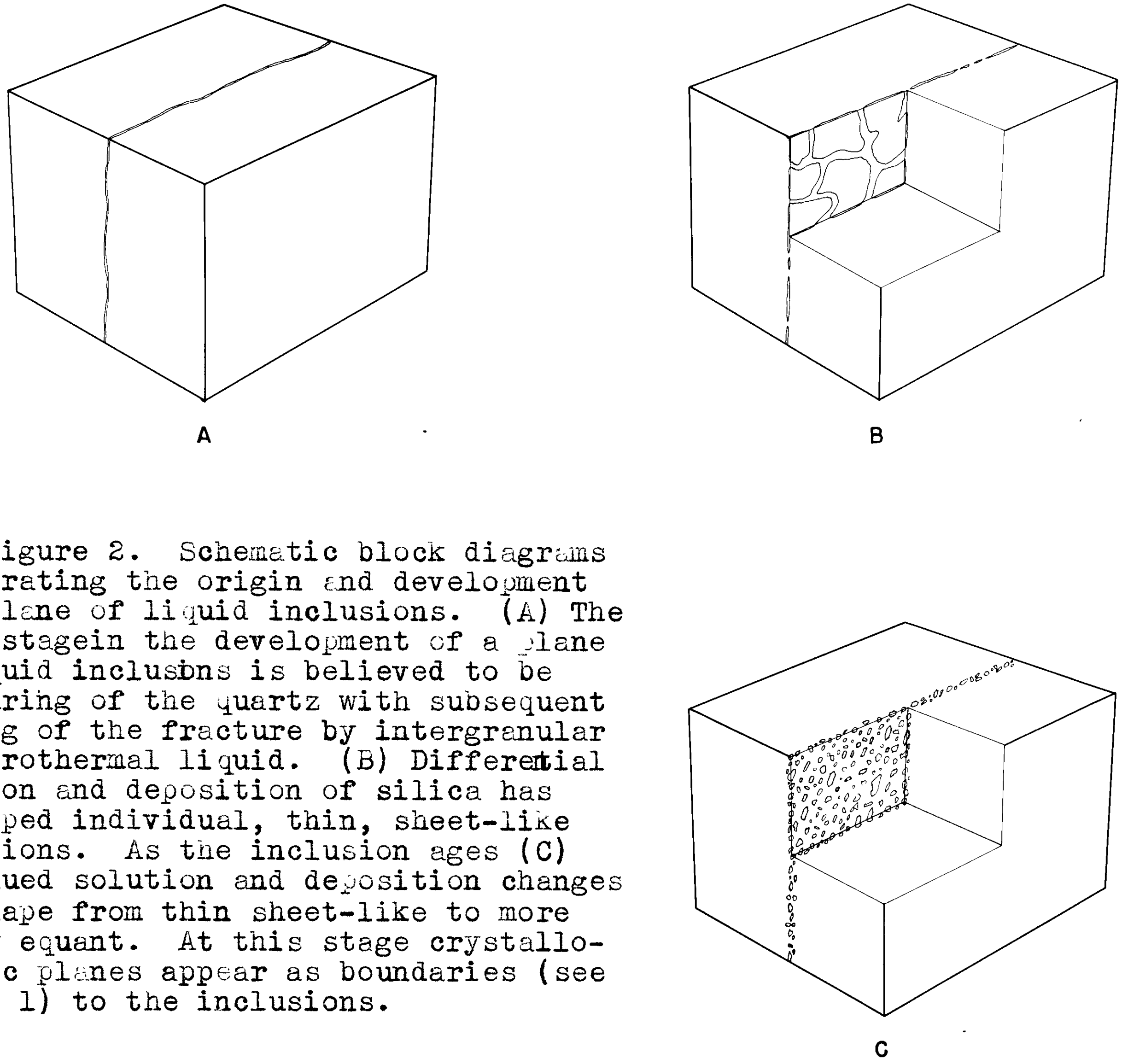


Figure 2. Schematic block diagrams illustrating the origin and development of a plane of liquid inclusions. (A) The first stagein the development of a plane of liquid inclusions is believed to be fracturing of the quartz with subsequent filling of the fracture by intergranular or hydrothermal liquid. (B) Differential solution and deposition of silica has developed individual, thin, sheet-like inclusions. As the inclusion ages (C) continued solution and deposition changes the shape from thin sheet-like to more nearly equant. At this stage crystallographic planes appear as boundaries (see figure 1) to the inclusions.

deposition is the formation of large thin sheet-like inclusions having an extremely irregular outline. This type, when viewed in thin section on the universal stage almost disappear when turned parallel to the microscope axis. Continued differential solution and deposition of silica gradually change the shape of the individual inclusions from thin sheets to more nearly equant bodies. The influence of crystallographic directions becomes apparent after the process has continued for some time so that crystal planes appear as boundaries to the inclusions. At this stage the individual inclusions no longer lie in a sharp plane, but have grown laterally to some extent so that the plane has considerable thickness (C figure 2). Planes of liquid inclusions have been observed in all stages of development from a thin fracture filled with liquid to a broad band of nearly equant inclusions, many of which are bounded by crystal planes.

This suggests a method of estimating the relative ages of two or more sets of planes of liquid inclusions. The method can be illustrated in a mica schist in the Washington, D. C. area, where an independent check is afforded by the relation of the two sets of liquid inclusions to small drag folds. The older set of planes is made up of nearly equant inclusions, whereas the younger set consists of thin sheet-like inclusions. The older set of planes is not symmetrically related to the drag folds and it has been established that these planes were rotated during the drag folding (figure 86). On the other hand the younger sheet-like planes are symmetrically related to the drag folds and are believed to be genetically related. The set of sheet-like planes would certainly have been considered younger without the independent evidence introduced by the drag folds.

A method of establishing the difference in age of the two sets of planes is by the character of the inclusions. This is illustrated by a thin section of a granite (locality unknown) containing two sets of planes, one of which has inclusions consisting of three phases, water, liquid carbon dioxide and vapor bubble, whereas the other set consists of inclusions containing only water.

Solution and deposition along a fracture in a crystal can be impelled by mechanical or thermal energy. As differential pressures are certainly present the so-called "Riecke principle" (10) may be operative and mechanical energy may motivate solution and deposition. This principle requires that in the presence of saturated solution and differential pressure solution will occur at points on a crystal under greatest stress, and precipitation will take place at points of least stress. Immediately after fracture the two sides of the fracture would be in contact over a small proportion of the total area and these portions of the crystal would be subjected to a greater stress than neighboring areas which are not in contact. Consequently solution will take place in these highly stressed areas and deposition will occur in the regions that are not in contact. The net effect of this process will be to increase the area under stress, thereby decreasing the stress per unit area. The area under stress would increase only by decreasing the area not stressed, and the end result would be nearly equant liquid inclusions.

A second mechanism for differential solution and deposition would be important if the temperature of the crystal oscillated frequently. Increased temperature would cause silica to be taken into solution in the liquid of the inclusion (if the solubility is normal) and subsequent cooling would cause precipitation on the walls of the inclusion. It seems reasonable to assume that crystal faces would develop with continued solution and deposition just as a growing crystal assumes euhedral faces.

Theoretically it also appears reasonable that an irregular inclusion is not at its lowest possible energy level, and given sufficient time, even without temperature oscillation, solution and deposition may take place until the inclusion has reached this lowest level which would in all probability be expressed by a liquid inclusion bounded by crystal planes.

The Riecke principle would certainly be operative immediately after fracturing of the quartz and would be responsible for initiating solution and deposition of silica. Later in the process the other two methods would in all probability be more important in continuing the solution and deposition.

METHOD OF STUDY

The orientation of the planes of liquid inclusions is measured in oriented thin sections in the conventional manner. Each plane of inclusions to be measured is rotated on the inner vertical axis of the universal stage until the trace of the plane is parallel to one of the cross hairs. By rotation on the horizontal axis parallel to this trace the position at which the plane of inclusions appears as a very fine line, and hence parallel to the microscope axis, can be determined with considerable accuracy.

Identification and measurement of planes of liquid inclusions can be greatly expedited by preparing thin sections four or five times the normal thickness. Planes of large, equant liquid inclusions cannot be measured at all in a section of normal thickness. They appear as a row of inclusions which do not show a planar direction when rotated about a horizontal axis on the universal stage, thus accounting for the common description in the literature of "rows of liquid, gaseous and opaque inclusions."

Planes of liquid inclusions are seldom uniform in the geometrical sense. The word plane is used here in the same sense as the geologist uses "fault plane" or "joint plane." The planes undulate considerably and when aligning the "strike" of a plane parallel to a cross hair of the microscope it is sometimes necessary to merely approximate the average "strike." When this question came up early in the investigation several fabric diagrams of the planes of liquid inclusions were prepared from the same thin section using slightly different techniques in aligning the planes of inclusions. First a diagram was prepared by plotting only those portions of the planes that were actually planar. A later diagram from the same section, made by approximating the general strike of the planes in the microscope field gave a similar diagram. Figures 3 and 4 illustrate the magnitude of the difference using the two methods. The differences illustrated indicate that some detail is lost by the second method of measurement; however, for the present reconnaissance work the second method is entirely adequate.

A more important source of error in this type of measurement is introduced through improper orientation of the thin sections with respect to the planes of inclusions. Figure 5 illustrates this error. In making the traverse AA' nine planes of inclusions would be recorded, representing the vertical set of planes, with no recordings of the equally numerous horizontal planes. If the traverse were made along BB' seven planes of each orientation would be recorded, this being the correct relation provided both sets of planes were perpendicular to the surface measured. If one set of the planes were nearly vertical while the other dipped steeply neither traverse method would be correct (CC' - DD').

A mathematical expression can be derived for corrections where the thin section is not approximately perpendicular to the planes of inclusions. However, it was found to be much less time-consuming merely to cut sections perpendicular to each set of planes as determined in an initial section. Billings and Sharp (11) have discussed similar problems encountered in making statistical studies of micas.

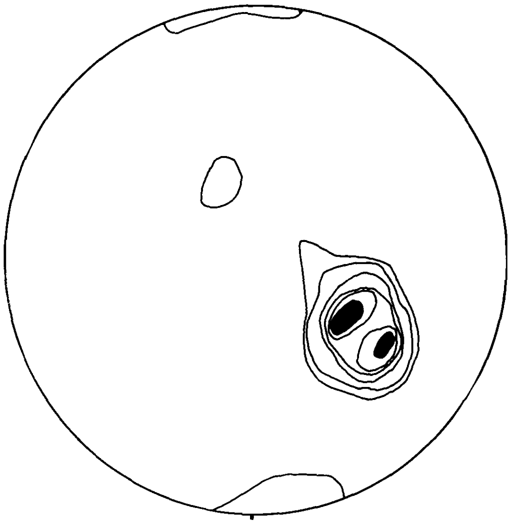


Figure 3. Locality 19. (See Figure 32.) 98 poles to planes of liquid inclusions measured by carefully aligning only those portions of each plane that are essentially planar. Contours 25-20-15-10-5-2-0 %.

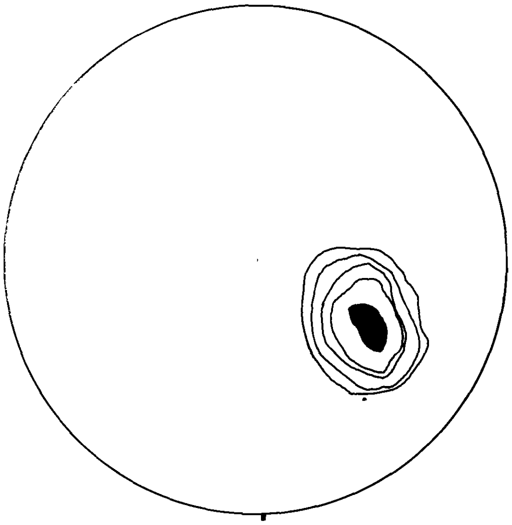


Figure 4. Locality 19. 100 poles to planes of liquid inclusions from the same thin section as figure 3. Measured by approximating the strike and dip of each plane. There is a slight loss in detail using this method which is similar to that used in measuring a rough joint or foliation plane in the field.

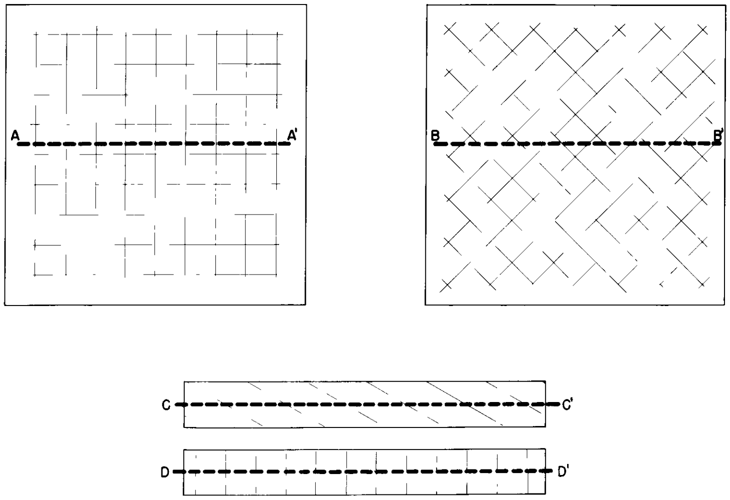
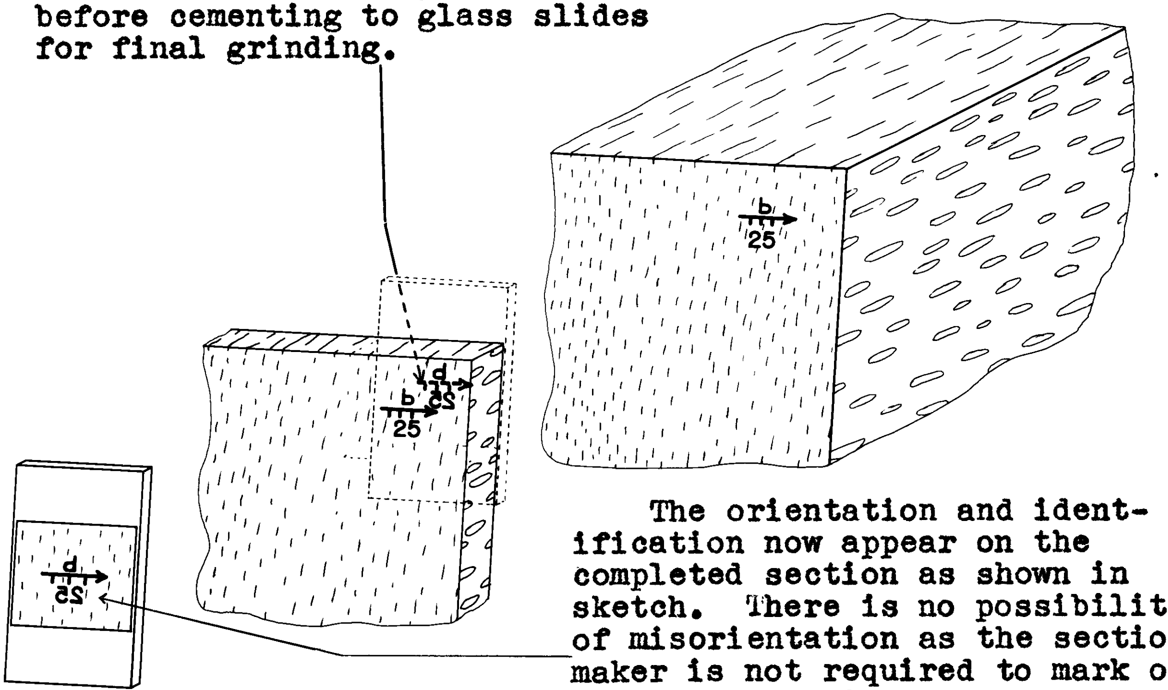


Figure 5. Schematic diagram illustrating some problems in traverse methods encountered when making statistical analysis of two or more sets of planes of liquid inclusions.

PREPARATION OF ORIENTED THIN SECTIONS

The difficulties encountered in properly marking rough hand specimens so that the thin section maker can prepare sections of the proper orientation are well known. Early in this work some hand specimens were sent to a commercial laboratory for sectioning and the orientation of the resulting sections were so often in doubt that the following technique was devised to prevent misorientation. All of the oriented sections used in this work were prepared by the author using the technique described below.

The first step in preparing the thin sections was to cut thin slices of the proper orientation from the hand specimen. In all cases two slices cut mutually perpendicular were prepared. The slices were then fitted back on the hand specimen in their original position and were marked with india ink on both sides as shown in figure 6. Next, one side of the slice was ground to the proper smoothness for thin section preparation and the center of this finely ground surface was remarked with a fine hard pencil. This ground and marked surface was then cemented onto a conventional thin-section glass and the section prepared as usual. The final section has the original markings in hard pencil in the center and there is no doubt of the proper orientation of the thin section. The surface from which the slice was cut is, then, essentially the surface of the thin section.



The orientation arrow, number of the specimen, and orientation of the section (b-section) are placed on the finely ground surface with a fine pointed hard pencil before cementing to glass slides for final grinding.

The orientation and identification now appear on the completed section as shown in sketch. There is no possibility of misorientation as the section maker is not required to mark or label the specimen.

Figure 6. Sketch illustrating the method used for marking rock specimens to prevent loss of orientation during preparation of thin sections.

ORIENTATION IN INDIVIDUAL QUARTZ GRAINS

The most striking feature of the planes of liquid inclusions in single quartz grains is the lack of crystallographic control of their orientation. This can be readily seen by crossing nicols and observing the planes extending across many quartz grains of different orientation with no deflection at the grain boundaries. A single plane within a quartz grain is usually nearly planar. However, the planes undulate considerably within a single grain, indicating again the lack of influence of crystallographic planes in the quartz.

Figures 7 and 8 illustrate the general character of the planes of liquid inclusions. The dark lines or rows of specks are planes of liquid inclusions. The planes are essentially vertical and appear to be continuous rather than made up of separate liquid inclusions. Figure 9 is a photomicrograph of the large grain in the center of figure 7. The undulating nature of the planes of liquid inclusions within a single grain can be seen at this magnification.

Figure 10 is a plot of the poles to planes of liquid inclusions in large single quartz grains. Where the planes were appreciably undulatory several measurements were made at intervals along the plane and the resulting plot of the poles connected by a line. These three diagrams were made from three different quartz grains in the same thin section. The lack of crystallographic control is well illustrated here as the three c-axes of the grains have considerably different

Figure 7. Photomicrograph of thin-section of gneiss showing planes of liquid inclusions as lines or rows of dark specks in quartz grains. x 30.

Figure 8. Same as figure 7 with crossed nicols. The planes of liquid inclusions can be seen to pass from one grain to another of different orientation without deflection at the boundary. x 30.

Figure 9. Center portion of figure 7 at higher magnification. The planes of liquid inclusions are nearly vertical, hence they appear as lines. The undulatory nature of the planes can be seen here. Some individual inclusions can be seen along each plane at this magnification. x 100.

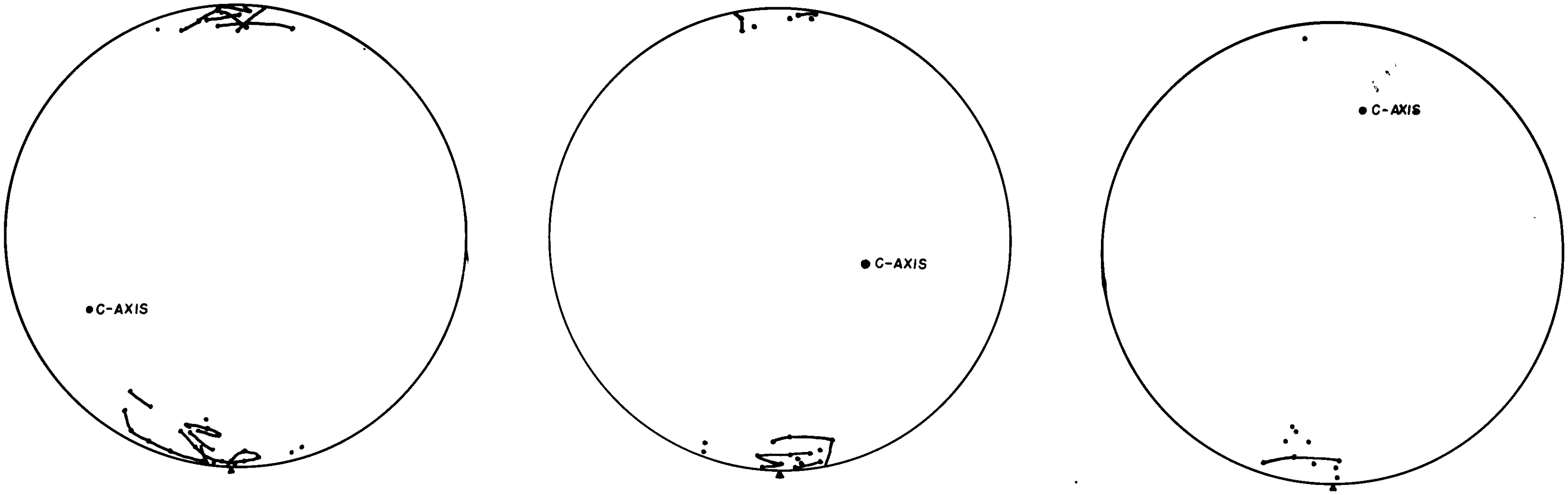


Figure 10. Orientation of planes of liquid inclusions in single quartz grains. Lines connecting poles illustrate the undulatory character of many of the planes. All three quartz grains are from the same thin section. The lack of crystallographic control of the orientation of the planes is apparent.

orientation, whereas the poles to the planes of liquid inclusions all have essentially the same orientation. This is further illustrated in figure 11 which was prepared by traversing the same thin section and plotting the c-axes of quartz grains together with the poles to planes of liquid inclusions. The high degree of preferred orientation of the planes of liquid inclusions with respect to the almost random orientation of the c-axes of the quartz grains further indicates the lack of control of the planes of liquid inclusions by crystallographic directions.

The planes of liquid inclusions in one quartz vein from the Washington, D. C. area are so unusual and informative that a detailed description and discussion is worthwhile. The usual shear planes of inclusions (see page 33) locally deviate toward the direction of tensional rupture. A single plane of inclusions curves into short en-echelon breaks with the trend of the tensional breaks along the same direction as the original shear break (figures 12 and 13). This resembles, on a small scale, shear faults (Newhouse 12) locally deviating toward the direction of tensional rupture. This has taken place <u>within</u> single quartz grains, indicating, perhaps, that the quartz behaved more like an isotropic material than like an anisotropic crystalline substance.

Planes of liquid inclusions vary greatly in their abundance in quartz grains. Thin sections of a specimen from locality 33 (see figures 7 and 32) for example, has planes spaced approximately at 0.06 mm., so that a traverse of 3 mm. perpendicular to the planes gave 50 measurements for a fabric

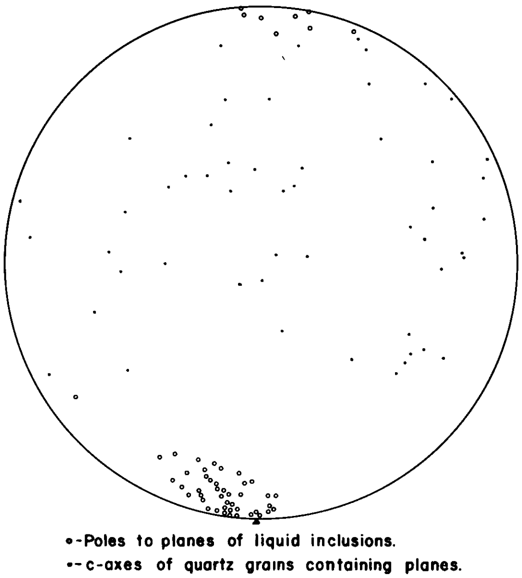


Figure 11. Diagram illustrating the relation between poles to planes of liquid inclusions and c-axes of quartz. Prepared from the same thin section as figure 10. The lack of crystal structure control of the orientation of the planes of liquid inclusions is illustrated here.

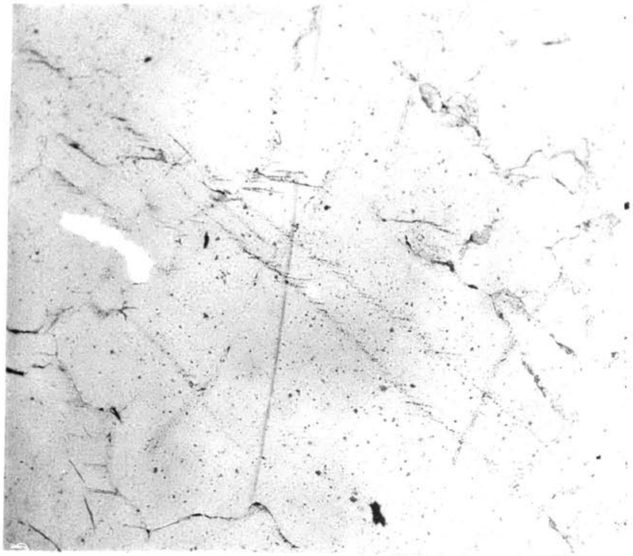


Figure 12. Photograph of planes of liquid inclusions in a single quartz grain. Sketch below illustrates an interpretation of this unusual type of structure. x 30.

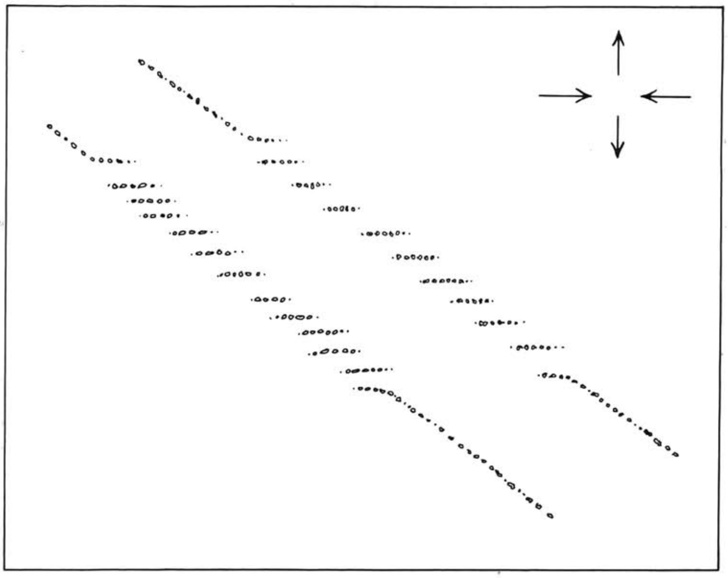


Figure 13. Sketch of the planes of liquid inclusions in the above photograph. The sketch is somewhat idealized. The planes of inclusions are perpendicular to the plane of the paper and the rows of irregular circles and dots represent the trace of the planes on the surface sketched. The short en-echelon planes are believed to be tensional breaks as indicated by the arrows. The trend of the en-echelon planes is believed to be the shear direction of the deforming stress pattern.

diagram (figure 68). This is one of the most abundant occurrances encountered. On the other hand, thin sections from locality 12 had only four or five planes that could be identified in completely traversing two large thin sections.

In general, planes of liquid inclusions appear to be most abundant in rocks containing a high percentage of quartz (i. e. quartzites). In some specimens showing a dearth of planes of liquid inclusions the foliation had nearly the same orientation as the planes elsewhere. It is suspected that movement which might have produced fractures that subsequently would become planes of inclusions was taken up by the mica which was responsible for the foliation.

The average thin section from the Washington, D. C. area contained enough planes to prepare a representative fabric diagram on traversing the section four or five times.

In summary, the planes of liquid inclusions in individual quartz crystals show little or no relation to crystallographic directions in the quartz. In many respects the planes appear to have formed by rupture with the directions of the rupture being controlled directly by the deforming stress uninfluenced by crystal structural planes within the quartz.

ORIENTATION IN SINGLE HAND SPECIMENS

One of the most striking features of fabric diagrams of planes of liquid inclusions is their high degree of orientation. Maxima up to 45% in a 1% area are not unusual and 20% maxima are very common. The diagrams look very much like mica diagrams from a well foliated schist (figure 4).

In the Washington, D. C. area diagrams of planes of liquid inclusions commonly have only one strong maximum, as illustrated in figures 14 and 15. The planes of inclusions, then, usually occur in a single orientation with only slight deviation from that orientation. Figures 16 and 17 are characterized by "split" maxima. This type has been found repeatedly in the Washington area (see page 15). The genetic significance of these split maxima is not known. They may represent some slight crystallographic influence, or possibly they represent a slight change in the over-all stress relations at the time of their formation. If the latter, they should be characteristic of the area. It will be interesting to see what further work of this nature elsewhere discloses.

In contrast to the single strong maximum found in the foliated rocks of the area two or more distinct maxima have been found in some quartz veins (figures 18 and 19). The planes of inclusions responsible for the single maximum in the foliated rocks do not continue into the quartz veins. This might indicate that the quartz veins were introduced later than the fracturing that subsequently became planes of liquid inclusions (see page 22).

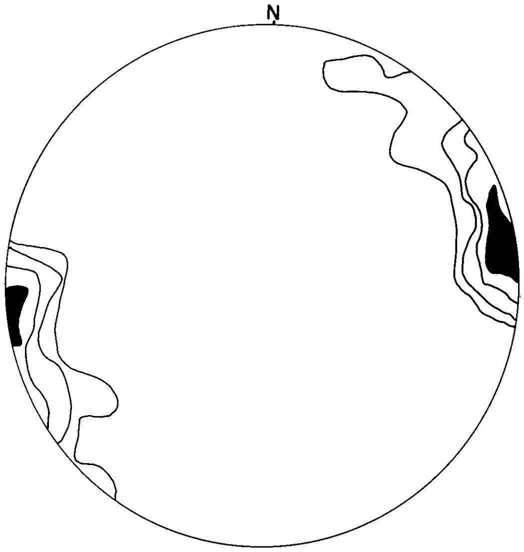


Figure 14. Locality 28
50 poles to planes of liquid inclusions. Contours (20-16)-10-5-2-0 %.

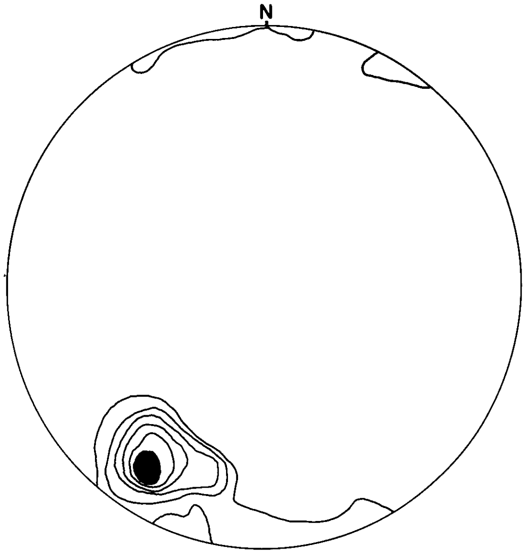


Figure 15. Locality 23.
50 poles to planes of liquid inclusions. Contours 24-20-16-12-8-4-0 %.

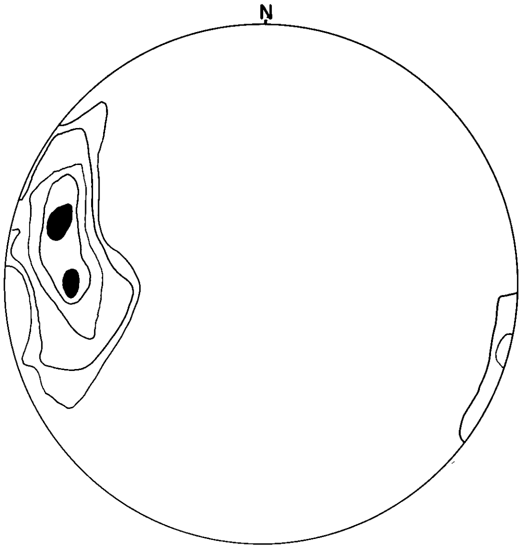


Figure 16. Locality 32.
50 poles to planes of liquid inclusions. Contours 22-16-10-4-2-0 %.

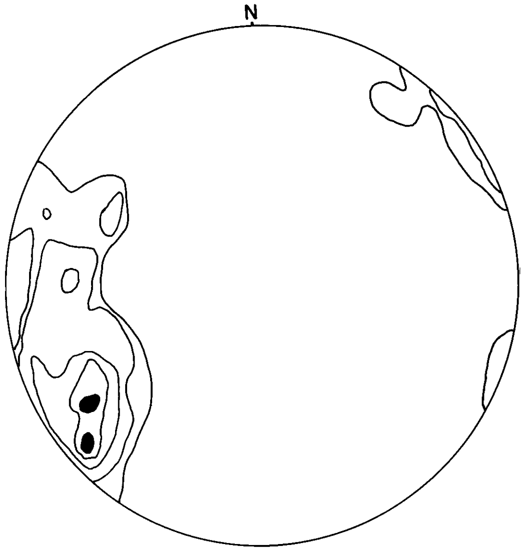


Figure 17. Locality 31.
50 poles to planes of liquid inclusions. Contours 22-16-10-4-2-0 %.

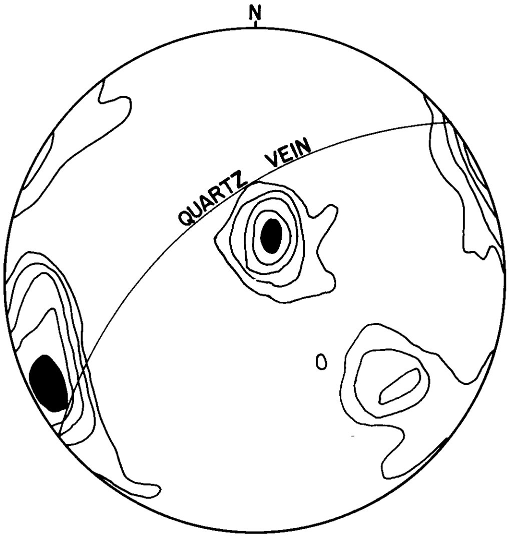


Figure 18. Locality 17.
175 poles to planes of liquid
inclusions in quartz vein.
Contours 15-11-7-3-1-0 %.

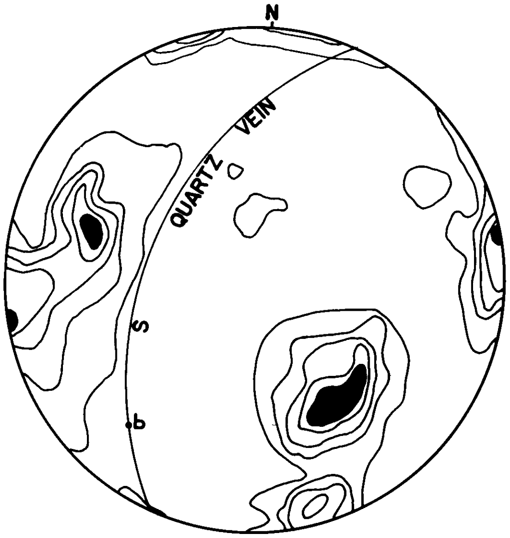


Figure 19. Locality 18.
221 poles to planes of liquid
inclusions in quartz vein.
Contours (6-5)-4-3-2-1-0 %.

Descriptions of planes of liquid inclusions from other areas frequently report "two sets of planes nearly at right angles." To check these observations ten thin sections with a wide geographic distribution were selected and the orientation of planes of inclusions measured. The results are illustrated in figures 20-29 inclusive. As only one section was available in all cases the diagrams are incomplete in that other concentrations of poles to planes of inclusions may occur near the center of the diagrams (planar structures cannot be measured when nearly parallel to the section). Five of these ten sections show two sets of planes "nearly at right angles" (figures 20, 21, 22, 23, 27). Three of the diagrams (figures 25, 26, 28) have maxima similar to those found in the Washington, D. C. area.

Many fabric diagrams of the poles to planes of liquid inclusions may have incomplete girdles. One specimen (figure 29) has a complete girdle. It appears that the girdles occur about the fold axis, indicating that the planes are intersecting at the <u>b</u> fabric axis.

ORIENTATION IN SINGLE OUTCROPS

In a single outcrop planes of liquid inclusions do not deviate to a measurable extent in hand specimens collected across the outcrop. Figure 30 illustrates this uniform orientation. (The slight difference in orientation of the maxima is within the experimental errors introduced during collecting, preparing the section, etc.) The planes cut across composition-

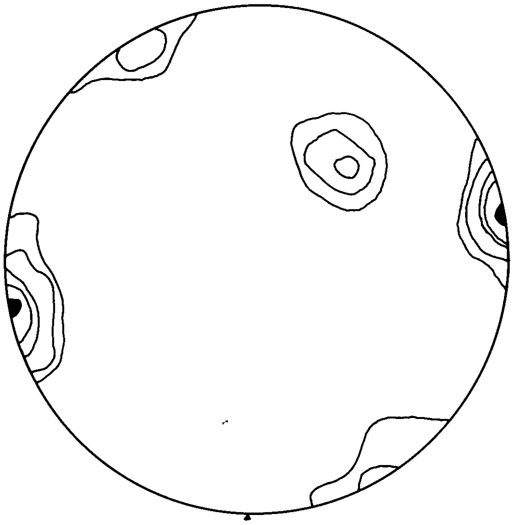


Figure 20. 168 poles to planes of liquid inclusions from Archean schist from the Grand Canyon. Contours 20-15-10-5-2-0 %.

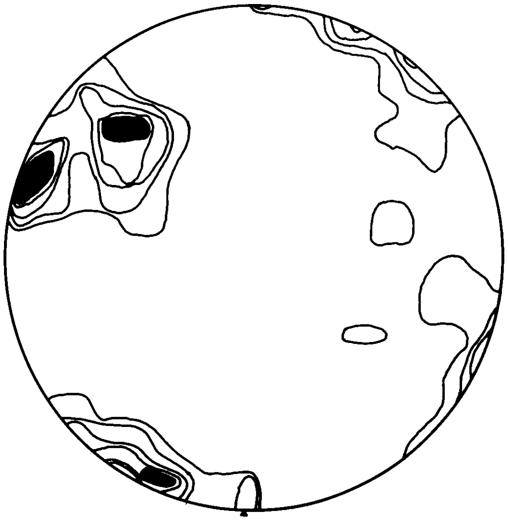


Figure 21. 50 poles to planes of liquid inclusions in a granite from Christiana, Norway. Contours 10-8-6-4-2-0 %.

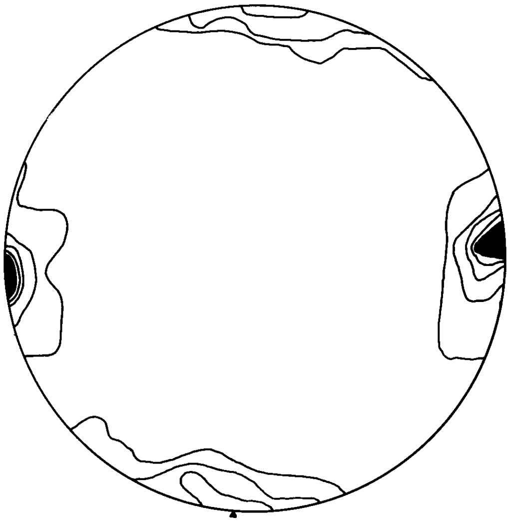


Figure 22. 54 poles to planes of liquid inclusions in granite from Schlesien, Germany. Contours 20-15-10-5-2-0 %.

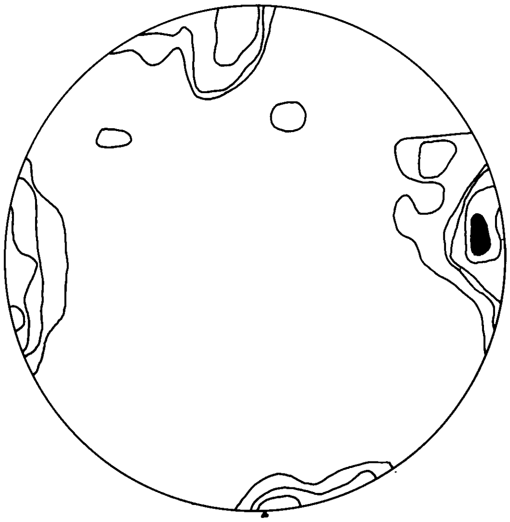


Figure 23. 50 poles to planes of liquid inclusions in Rapakiwi granite from Wiborg, Finland. Contours (18-14)-12-8-4-2-0 %.

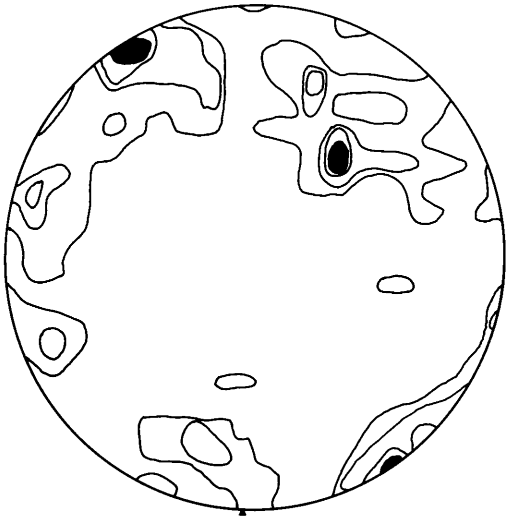


Figure 24. 50 poles to planes of liquid inclusions in granite from Cape Ann, Mass. Contours 8-6-4-2-0 %.

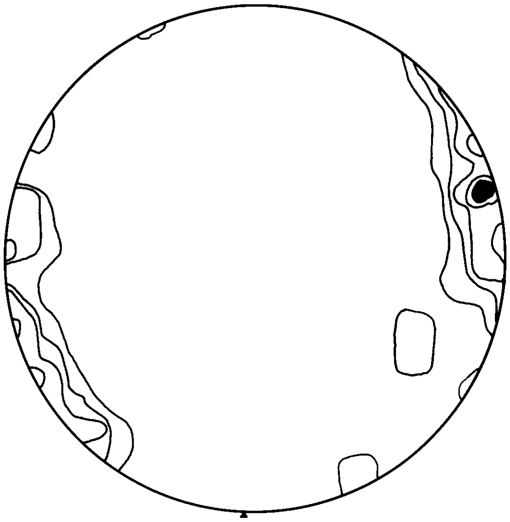


Figure 25. 50 poles to planes of liquid inclusions in a greisen from Zinnwald, Germany. Contours 20-15-10-5-2-0 %.

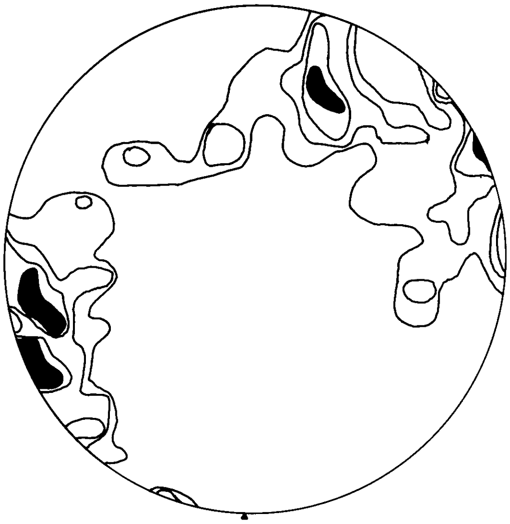


Figure 26. 56 poles to planes of liquid inclusions in a greisen from Altenberg, Germany. Contours 8-6-4-2-0 %.

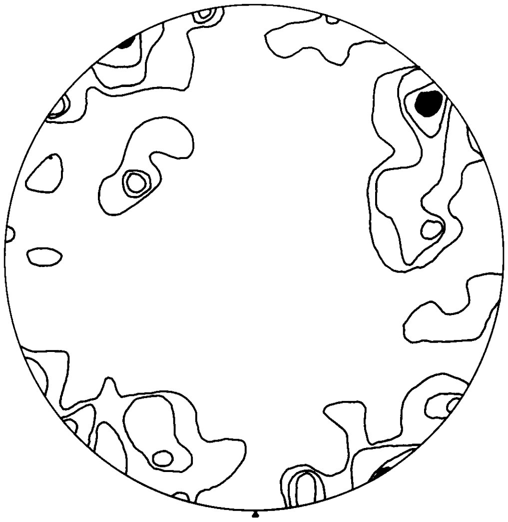


Figure 27. 55 poles to planes of liquid inclusions in a granite from Hohwald, Germany. Contours 8-6-4-2-0 %.

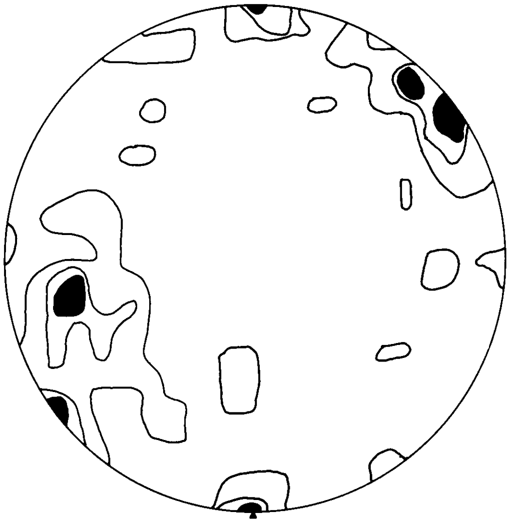


Figure 28. 50 poles to planes of liquid inclusions in granite from Markirch, Ober Elsass. Contours (8-6)-4-2-0 %.

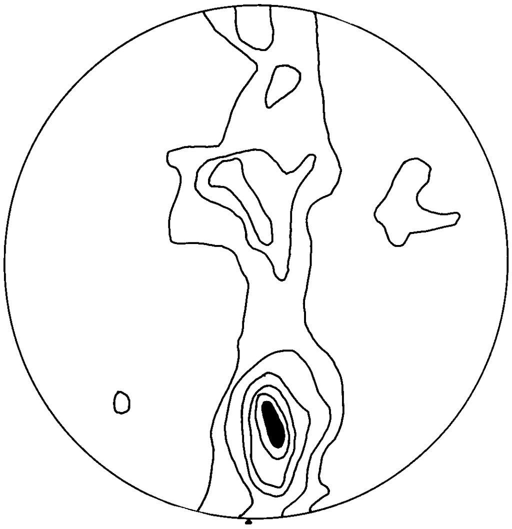
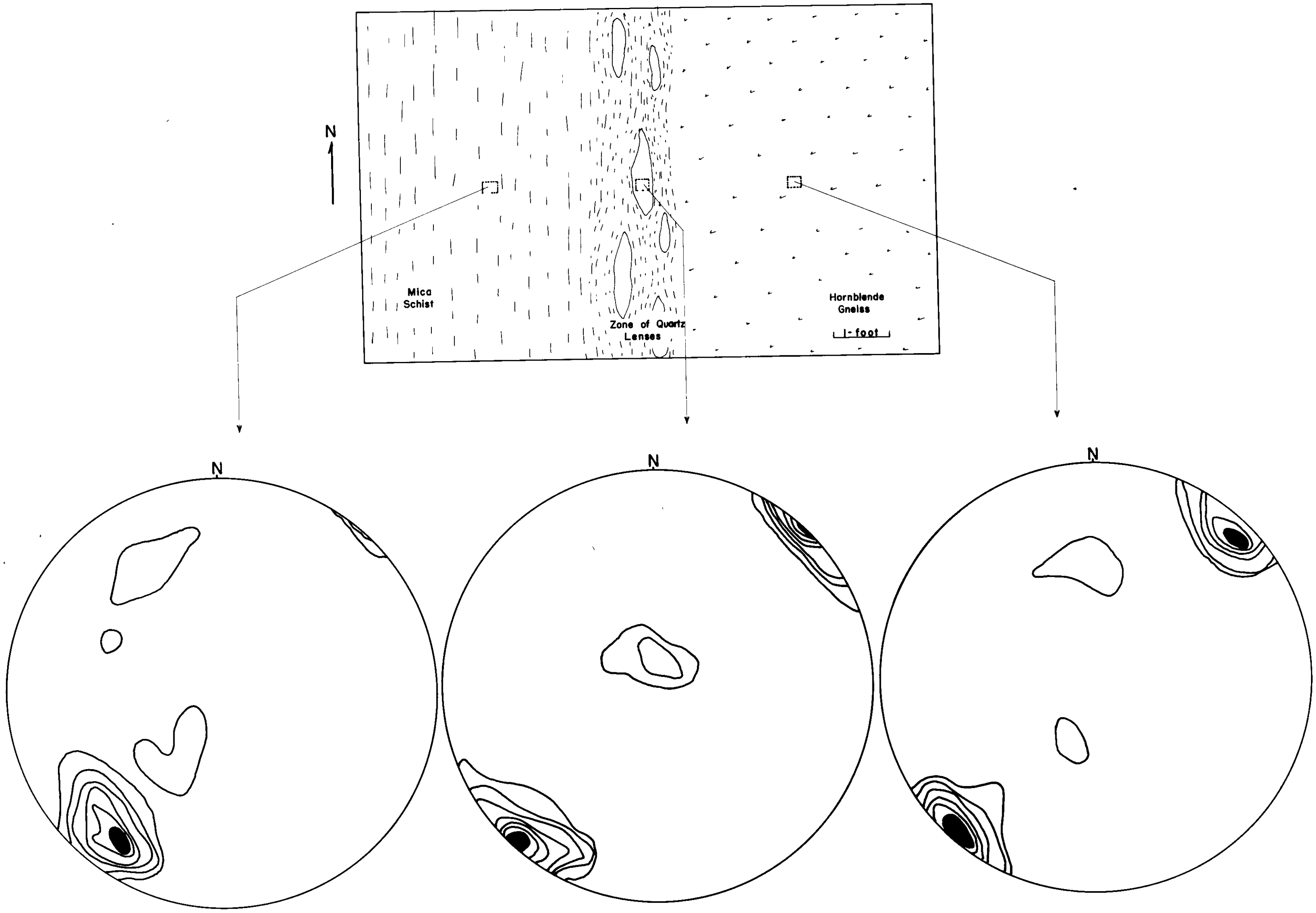


Figure 29. 154 poles to planes of liquid inclusions in quartzite 1 mile south of Highland, Maryland. Contours (14-11)-9-7-5-3-1-0 %.



150 Poles to planes of liquid inclusions
Contours- 25,20,15,10,5,2.

68 Poles to planes of liquid inclusions
Contours- (35-30),25,20,15,10,5,2

98 Poles to planes of liquid inclusions
Contours- 25,20,15,10,5,2.

Figure 30. Sketch of an outcrop showing the orientation of planes of liquid inclusions in the different rock types.

al boundaries with no deflection. For example, in figure 30 the planes have exactly the same orientation in the hornblende gneiss, the quartz lenses, and the biotite schist. However, the number of planes per unit volume may vary considerably (see page 18). A one centimeter traverse across the planes in the quartz lenses may cross fifty planes whereas only ten or fifteen may be encountered in the same length traverse in the biotite schist or the hornblende gneiss.

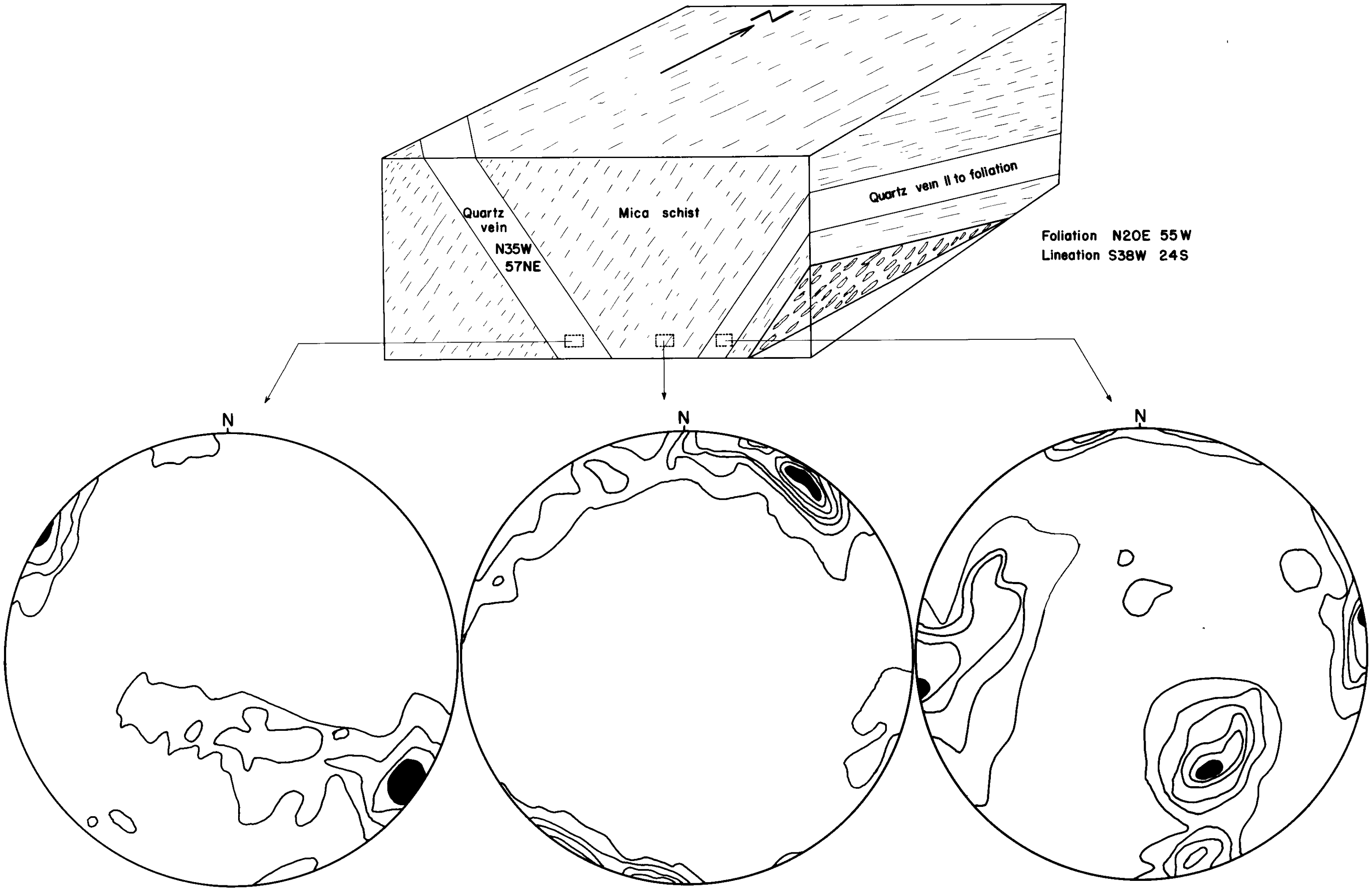
This uniform orientation within a single outcrop has been found at numerous localities in the area studied.

In contrast with this uniform orientation in various foliated rocks, the quartz veins of the area present an entirely different problem. Figure 31 illustrates the orientation of the planes in two quartz veins and the enclosing mica schist. The planes of liquid inclusions in these veins show no obvious symmetrical relation to the planes in the schist. This suggests that the planes in the quartz veins are late, and post-date the planes of inclusions in the surrounding rocks.

ORIENTATION IN WASHINGTON, D. C. AREA

Areal Geology

The rocks of the area investigated are largely metamorphic and igneous, the only exception being a thin veneer of flat lying coastal plain sedimentary rocks in the southeast portion. The metamorphic rocks are highly foliated with well developed lineation. Lithologically the rocks are



250 Poles to planes of liquid inclusions
Contours 9,7,5,3,1.

150 Poles to planes of liquid inclusions
Contours (16-14),12,10,8,6,4,2.

221 Poles to planes of liquid inclusions.
Contours 6,5,4,3,2,1.

Figure 31. Sketch of outcrop relations of mica schist and quartz veins with fabric diagrams showing the orientation of planes of liquid inclusions. The quartz vein parallel to the foliation is approximately 1 foot thick where exposed’and the cross-cutting vein is approximately 2 feet in thickness.

extremely diverse. This diversity is so pronounced that it seems certain that if several different geological parties mapped the area the resulting maps would show little if any uniformity of areal distribution of formational units.

Most of the southern half of the metamorphic belt was mapped by Williams and Keith (13) in 1893-99. The metamorphic rocks are classified as Archean and the following types described: granite, granite gneiss, diorite, diorite gneiss, gabbro, metagabbro, metadiorite, serpentine, and soapstone.

Over 90% of the area studied (figure 32) is composed of rock types that were called granite gneiss or diorite gneiss by Williams and Keith (13). These rocks are divided into two areas by a biotite granite which occurs in a narrow belt about one mile wide running north-south through the entire region studied (figure 32).

The granite and diorite gneisses are characterized by the almost universal presence of rock inclusions. The inclusions are usually lenticular with their planar direction parallel to the foliation. They range in size from a few millimeters to a few meters in largest dimension. The smaller inclusions are usually quartz, although micaceous, chloritic, and pyritiferous inclusions are seen in places. The inclusions commonly have a blade-like habit with the long axis parallel to the (b) lineation of the enclosing gneiss. The large inclusions commonly show structures that appear to be remnants of bedding or schistosity, which is usually parallel to the foliation of the enclosing gneiss. However, in some cases divergence from parallelism is pronounced.

These large inclusions would doubtless be called xenoliths by one disposed to calling this type of rock intrusive igneous, whereas an advocate of granitization would probably interpret them as remnants of the original rock that had escaped the granitization.

The biotite granite is characterized by the absence of inclusions and by its uniformly light color. The biotite occurs in large wavy flakes that give the rock a pronounced speckled appearance. Foliation is not as pronounced as in the surrounding gneisses, except near the contacts and in the northern portion of the area. Lineation is poorly developed except in the northern part of the area.

Structural Features

Perhaps the most prominent structural feature of the region is the foliation (figure 33). With the exception of a few minor areas all of the rock types encountered are well foliated. Non-foliated granite was found in only two small areas. The foliation is so pronounced that one is inclined to classify all of the rocks in the area as metamorphic rather than intrusive igneous. This tendency is enhanced by the scarcity of cross-cutting contacts. Although some contacts are discordant, in general they are parallel to the foliation, schistosity or banding. The contacts are also parallel to the planar direction of the ubiquitous inclusions in the granite and diorite gneisses. Some of the more schistose horizons in the granite gneiss show small, close, contorted folds. The

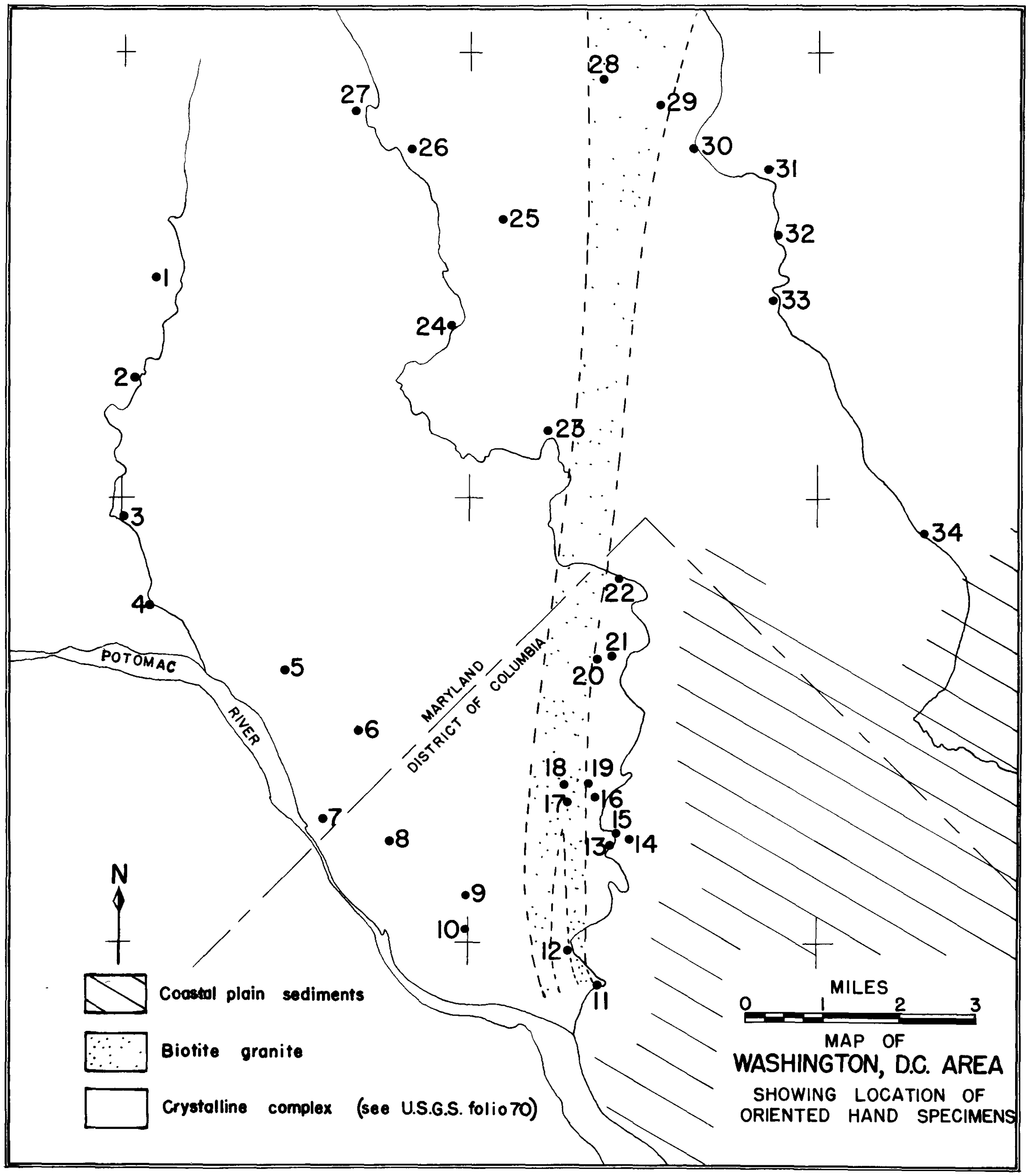


Figure 32. Map of the Washington, D. C. area showing the location of oriented hand specimens and the outcrop of biotite granite. All diagrams prepared from oriented specimens from this area are numbered to correspond with the above localities.

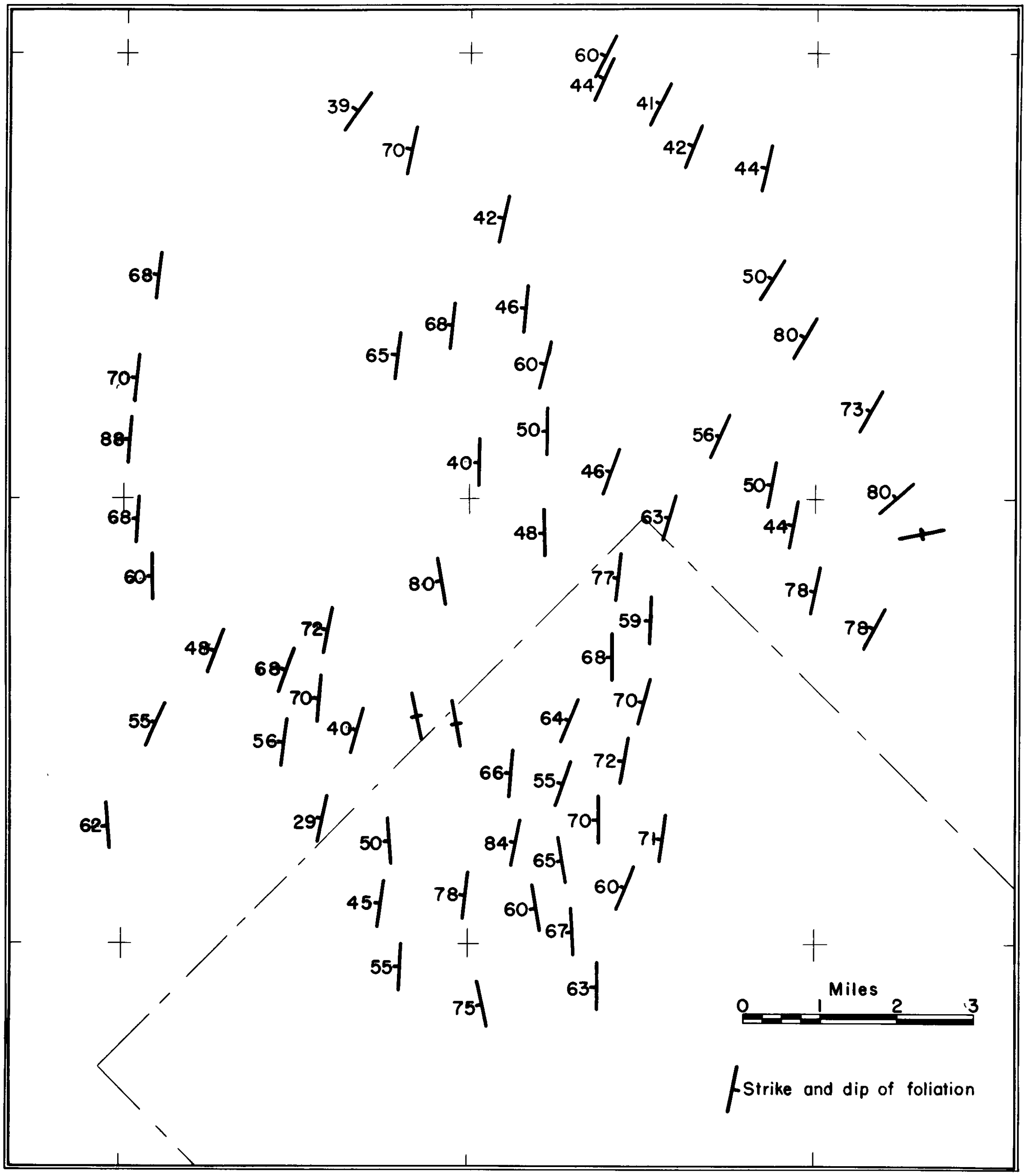


Figure 33. Map of the Washington, D. C. area showing the orientation of the foliation.

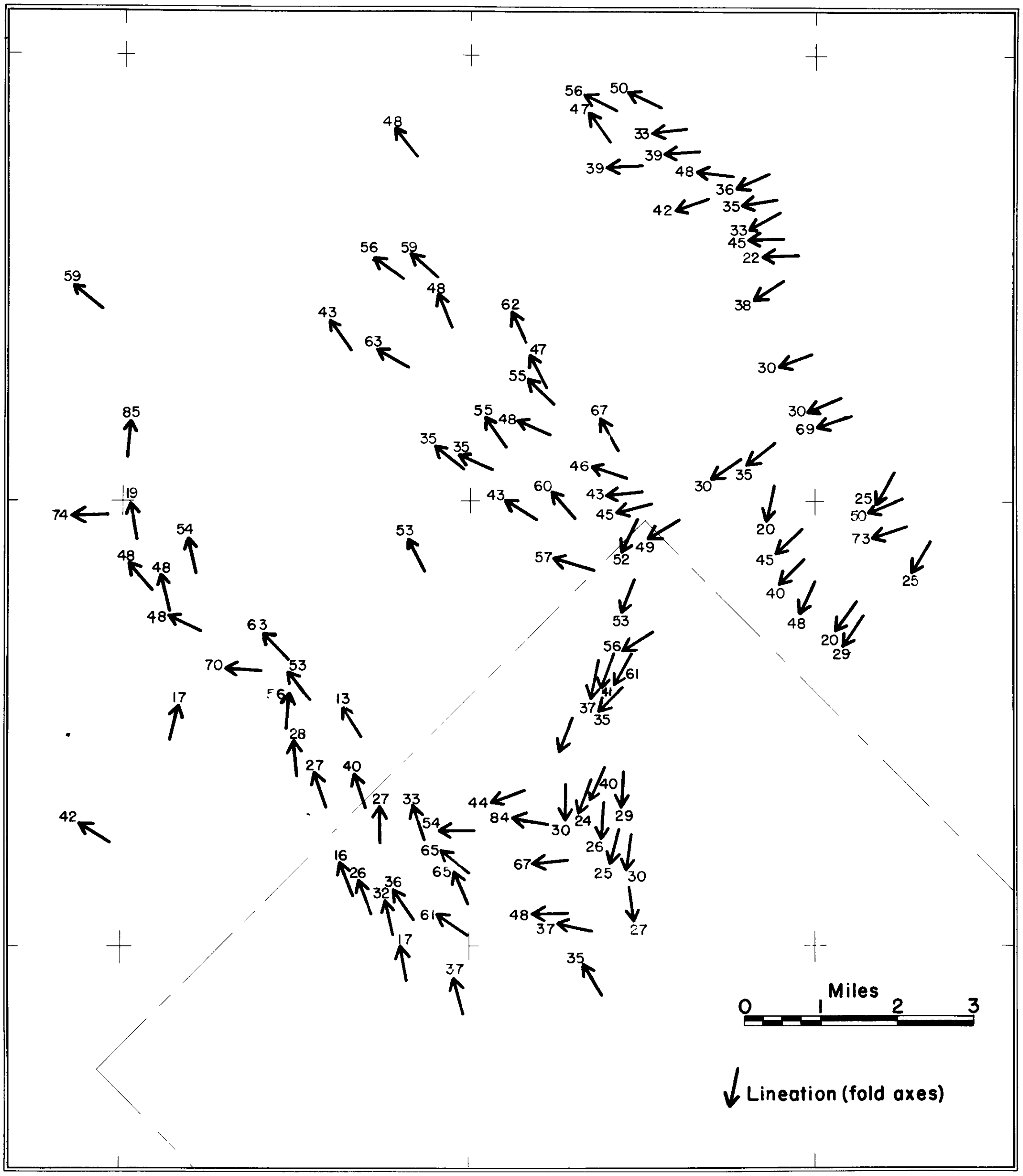


Figure 34. Map of the Washington, D. C. area showing the orientation of the lineation. These linear elements lie in the foliation planes and are the fold axis type of element (parallel to axial lines of folds).

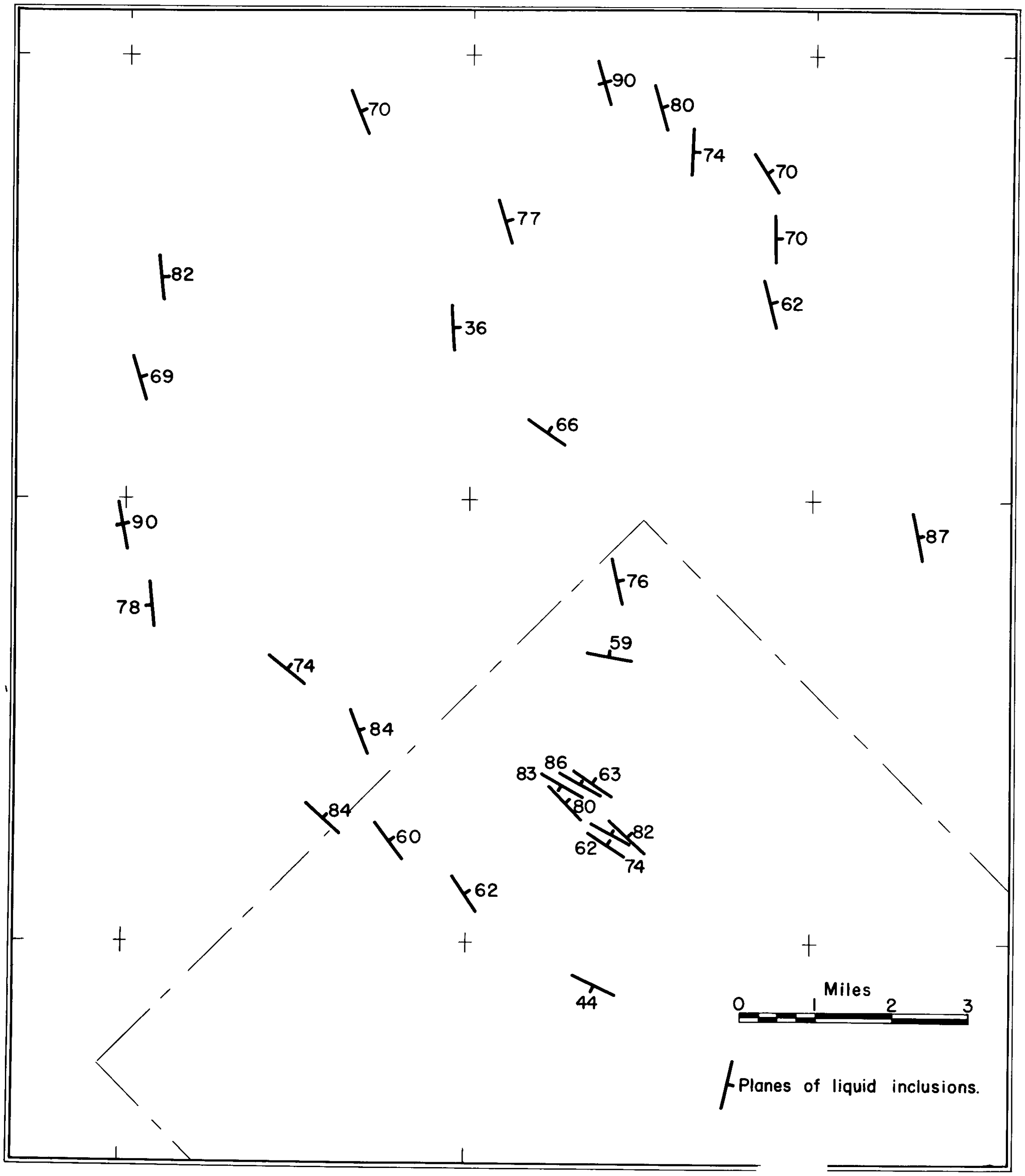


Figure 35. Map of the Washington, D. C. area illustrating the orientation of planes of liquid inclusions. Each value shown is approximately the maximum of a statistical fabric diagram. The diagrams from which these values were taken can be seen by locating the specimen number on index map (figure 32) and looking up the corresponding diagram. See also figure 37.

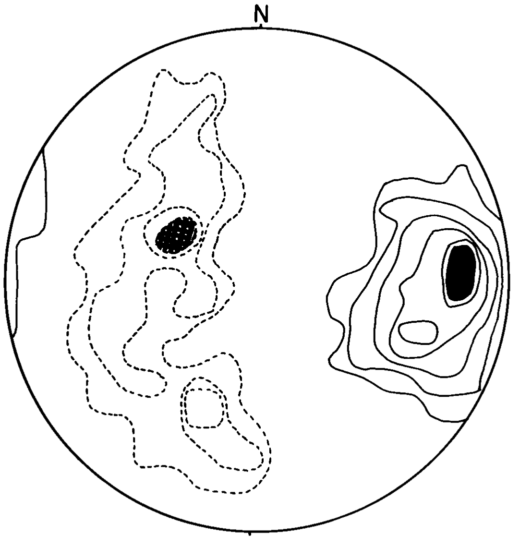


Figure 36. Compilation of field measurements of the orientation of foliation and lineation. ----151 lineation measurements. Contours 8-6-4-2-0 %. ——210 poles to foliation. Contours (16-15)-12-9-6-3-1-0 %.

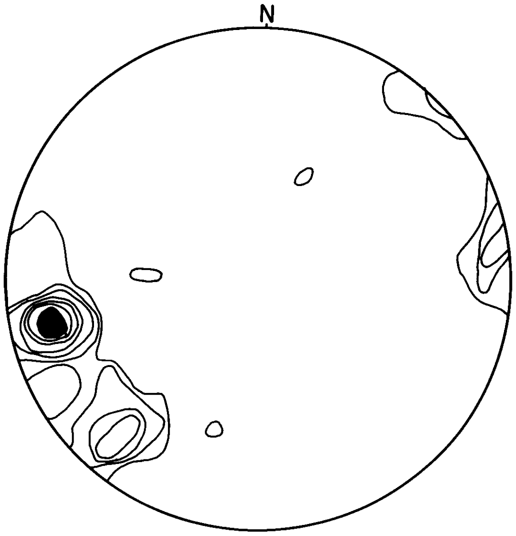


Figure 37. Compilation of the orientation of maxima from 30 statistical diagrams of poles to planes of liquid inclusions. Contours 23-20-17-13-10-7-3-0 %.

axial line of these folds is parallel to the regional lineation and in general the axial planes appear parallel to the regional foliation. The "bedding" on the limbs of these small folds is also parallel to the regional foliation.

Locally the contact between, say, the granite gneiss and a schistose horizon in the granite gneiss may have discordant relations measured in feet. Embayments occur in the schist and in some places blocks of it are apparently surrounded by the granite gneiss. Petrographic examination of the relations suggests a replacement origin for this type of contact, as fragments of the schist can be seen in thin section in all stages of digestion, with the smallest fragments showing unmistakable parallelism with the surrounding schist. If this were an intrusive contact one would expect to find some fragments of the schist rotated somewhat by the "intruding" granite gneiss.

Foliation - The most common type of foliation is a result of the alignment of mica flakes into sub-parallel orientation (figure 38). The foliation is locally intensified by segregation of mica into layers alternating with quartzose layers. In some places banding due to alternating layers of amphibole and quartz-feldspar gives a pronounced foliation. In others the foliation is a result of alternate layering of quartz-feldspar and chlorite or of quartz and epidote. Foliation in the biotite granite is made conspicuous by the large dark colored mica flakes, but on close examination it is seen that it is in part due to segregation into bands of the quartz and feldspar. Thus, although the rock has the

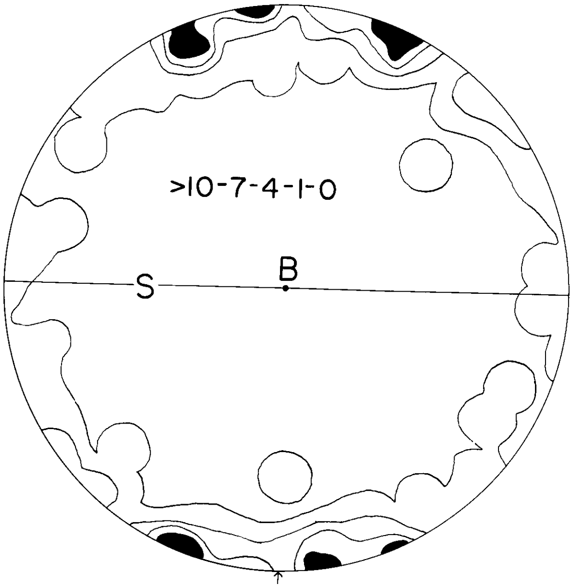


Figure 38. Locality 23.
100 poles to biotite cleavage. The maxima near a and the partial girdle about b are responsible for a lineation parallel to b.

mineral composition of a granite, texturally it is a gneiss.

Lineation - Five types of lineation have been observed in the Washington, D. C. area. Four of these are believed to be parallel to b (fold axis) and one perpendicular to b in the plane of foliation. The evidence that the four types are parallel to b is given by their parallelism with the axial lines of all the minor folds in the area (see page 24). The relation of these small folds to any major folds that may exist is not known. It is possible that the fold axes of the small folds may be either parallel or perpendicular to the regional fold axes. If they are parallel, the above mentioned four types of lineation would be parallel to b of both the small folds and the regional folds. However, if the fold axes of the small folds are perpendicular to large scale regional folds then the four types of lineation would be in b of the small folds and a of the regional folds.

The four fold axis types are: 1) Mica flakes in many of the rocks are so oriented that the poles to the cleavage have a maxima at c and a girdle about the b fabric axis. This gives a pronounced linear structure on the foliation (s) plane parallel to b because the traces of mica plates on a surface parallel to s are statistically parallel to b (see figure 38). 2) This type is the result of orientation of elongated amphibole or tourmaline crystals, and has been observed to be parallel to the fold axes of small folds throughout the area. 3) The third type is caused by pinching and swelling of alternate layers of different mineral composition (see page 25). This is a gross lineation best seen at a considerable distance from the outcrop and is parallel to the fold axis of the small folds. 4) The fourth type is the result of parallel orientation of the long axes of elongate inclusions. These are also parallel to the fold axes of small folds.

A fifth type, unrelated to fold axes, is seen in hand specimens as striae on cleavage surfaces. The striae are perpendicular to the four fold-axes types of lineation and hence are believed to lie in a of the small folds.

In addition to the above, several younger linear structures occur having variable relations with the fold-axes type. For example, one schistose horizon in the granite gneiss commonly has numerous small drag folds (see page 32) that are obviously later than the regional foliation. The fold axis of these small crenulations can be easily measured as a linear structure. Also, small but easily visible striae which are perpendicular to the fold axes of these drag folds can be seen at numerous localities.

Relation of Planes of Liquid Inclusions to Major Structures

The major structures as observed in the field are illustrated in figures 32, 33, and 34. The foliation strikes predominatly north-south and dips steeply to the west. This is, perhaps, best illustrated in the compilation of all measured values shown in figure 36. The linear structures shown in figure 36 all lie in the plane of the foliation and all those values illustrated are believed to be parallel to the fold axes of minor folds seen in several localities in the area. Therefore they are believed to represent lineation parallel to b of the small folds. Figure 36 is a compilation of one hundred fifty-one measurements of strike and pitch of linear structures.

The linear structures pitch generally south to southwest in the eastern part of the area whereas they pitch northwest in the western part of the area. The change from southwest to northwest pitch is gradual in the northern portion and surprisingly abrupt in the southern part. An explanation of the orientation of the linear structures will doubtless be obvious when the relations to similar structures over a much larger area are known.

The orientation of the planes of inclusions is illustrated in figure 35. Each orientation shown is the orientation of the maxima from a contoured fabric diagram. The planes of inclusions strike generally northwest and dip to the northeast. Figure 37 illustrates a compilation of all maxima and it can be seen that they are highly oriented (maxima up to 23% in a 1% area) throughout the area. In fact, they are more uniform in orientation than either the foliation (16% maxima) or the lineation (8% maxima). The planes of liquid inclusions cut across the primary structures (foliation and lineation) and bear no symmetrical relation to them. This in itself would indicate that the planes of inclusions are later than the foliation and lineation and therefore are not genetically related.

It must be emphasized that any one of the maxima shown on figure 35 may be in error by as much as twenty degrees because of the many manipulations that must be made in determining the orientation (i.e. orientation of hand specimen, orientation of thin sections, rotation of diagrams, etc.); however, in most cases it is believed that the errors are not more than ±5 degrees. It is believed that the orientation of the planes may be considerably more uniform than illustrated because when special precautions were taken to eliminate errors no differences in orientation could be recognized between hand specimens from the same outcrop. This is illustrated in figure 30.

In considering the distribution of the planes of inclusions it is remarkable that no macroscopic structures could be found that were related to the planes. One would think that an orogenic stress that could produce such a structure throughout an area of two hundred square miles would manifest itself in some other way. After the orientation of the planes throughout the area was known, considerable time was spent in the field revisiting many outcrops in an effort to find some macroscopic structure that could be related to the planes. None was discovered. It is hoped that workers in other areas, where auxillary structures may be developed, will be able to make some correlation.

The relation of the quartz orientation to the planes of inclusions is illustrated in figures 74 to 85. As might be expected there is no consistant relation between the two, since the environment of the planes of inclusions merely indicates fracturing. Such an environment could hardly be expected to reorient the quartz. The quartz is in most cases related to the primary foliation (s) and lineation (b). This again

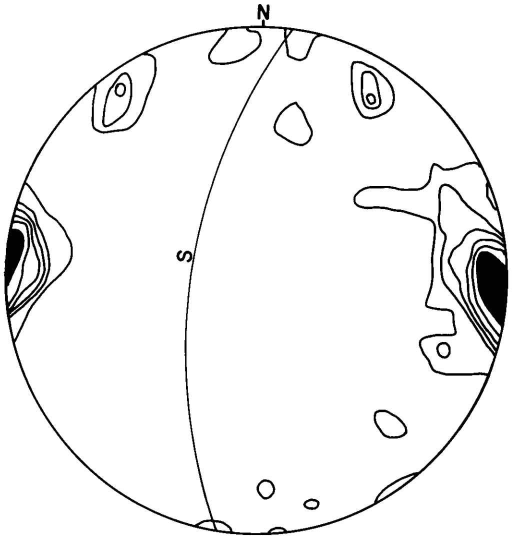


Figure 39. Locality 1
36 poles to planes of liquid inclusions. Contours 16-14-11-8-6-3-0 %.

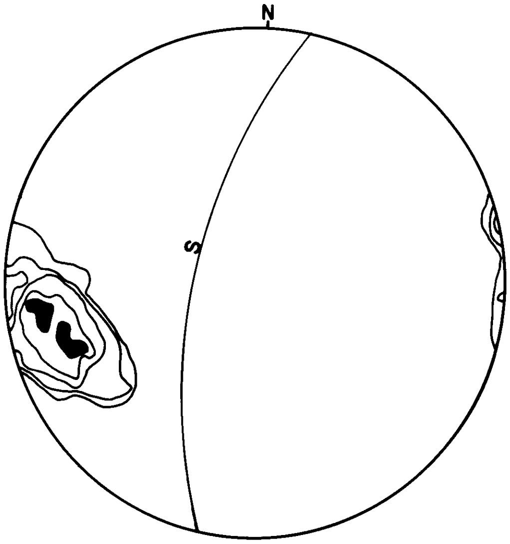


Figure 40. Locality 2.
33 poles to planes of liquid inclusions. Contours 30-21-12-6-3-0 %.

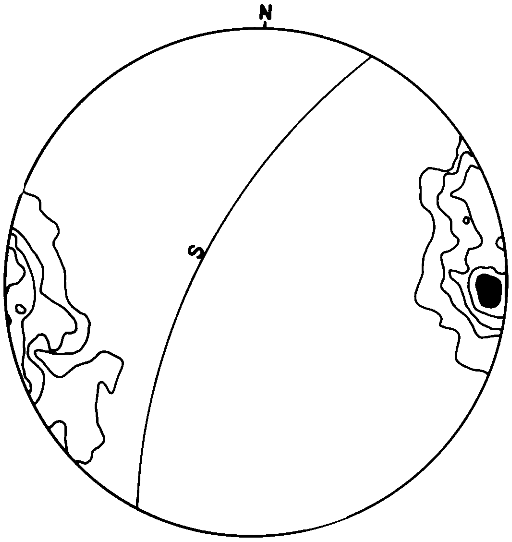


Figure 41. Locality 3.
50 poles to planes of liquid inclusions. Contours 18-14-10-6-2-0 %.

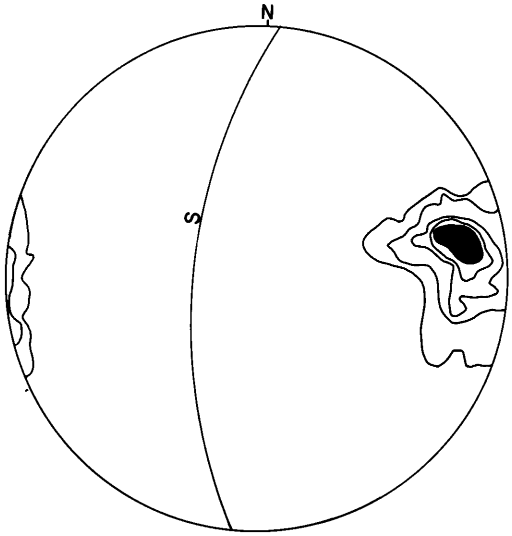


Figure 42. Locality 4.
40 poles to planes of liquid inclusions. Contours (30-26)-20-14-8-2-0 %.

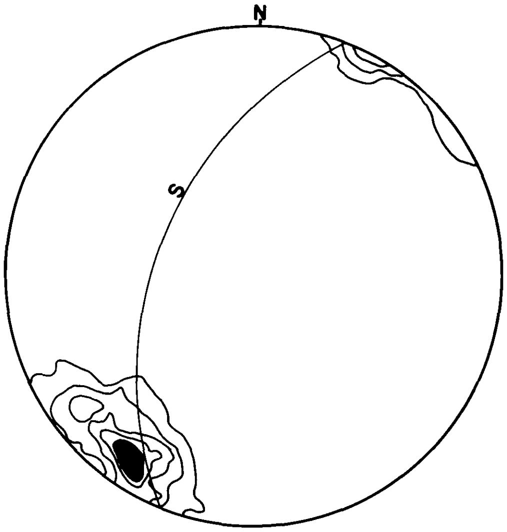


Figure 43. Locality 5. 50 poles to planes of liquid inclusions. Contours 32-24-16-8-2-0 %.

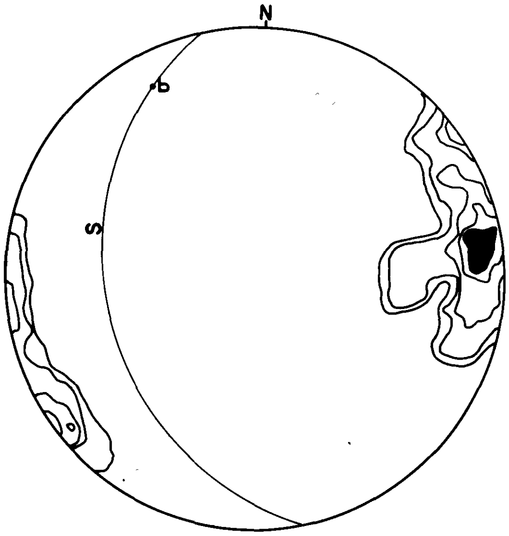


Figure 44. Locality 6. 50 poles to planes of liquid inclusions. Contours 22-16-10-4-2-0 %.

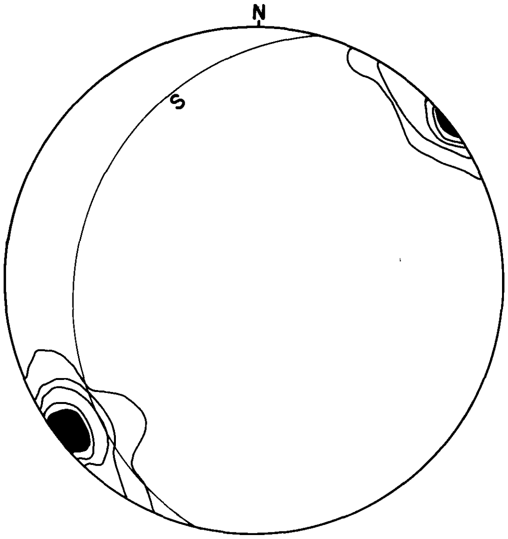


Figure 45. Locality 7. 50 poles to planes of liquid inclusions. Contours 28-22-16-10-4-0 %.

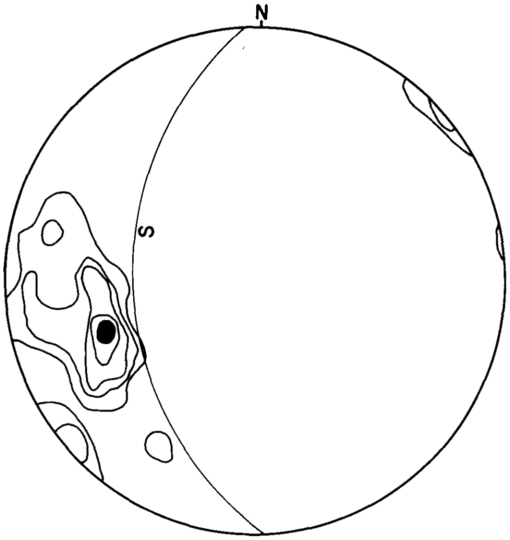


Figure 46. Locality 8. 50 poles to planes of liquid inclusions. Contours 20-16-12-8-4-0 %.

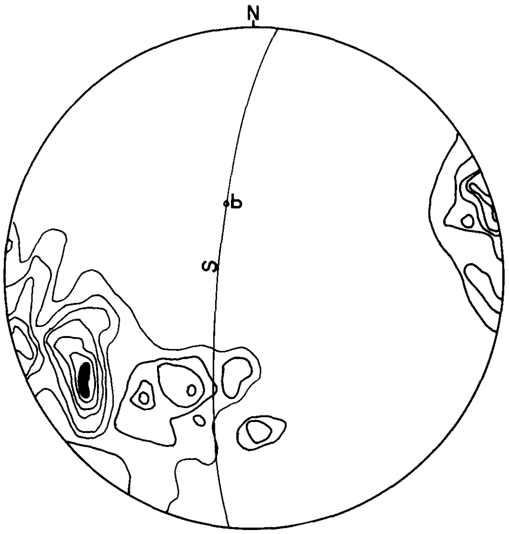


Figure 47. Locality 9.
50 poles to planes of liquid inclusions. Contours 14-12-10-8-6-4-2-0 %.

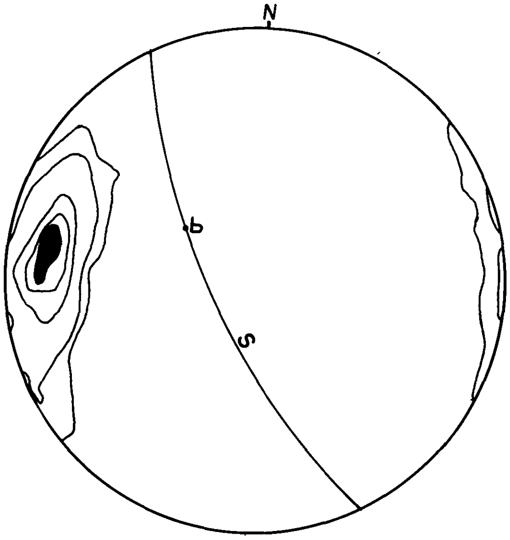


Figure 48. Locality 10.
150 poles to planes of liquid inclusions. Contours 20-15-10-4-2-0 %.

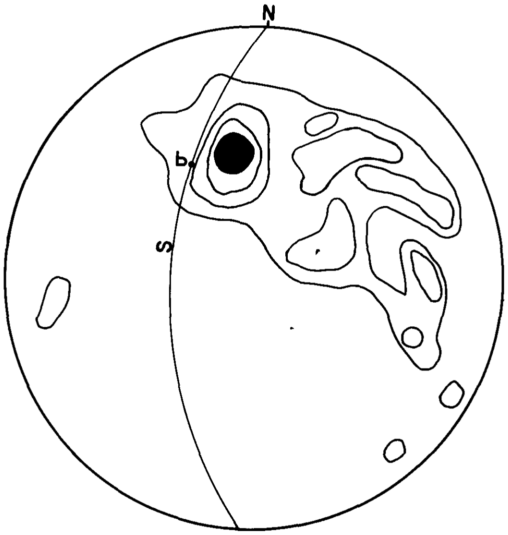


Figure 49. Locality 11.
86 poles to planes of liquid inclusions. Contours (10-8)-6-4-2-0 %.

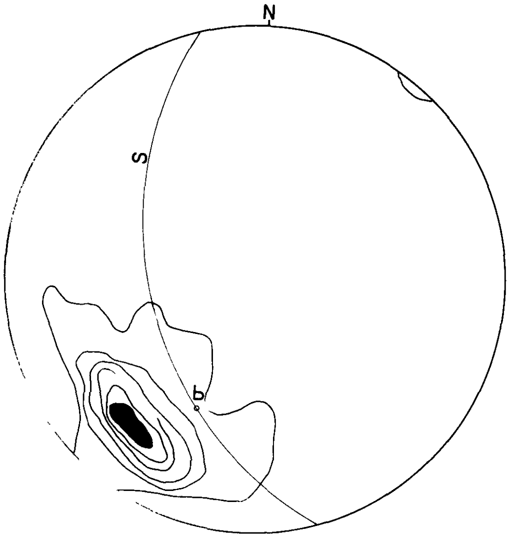


Figure 50. Locality 13.
140 poles to planes of liquid inclusions. Contours 25-20-15-10-5-1-0 %.

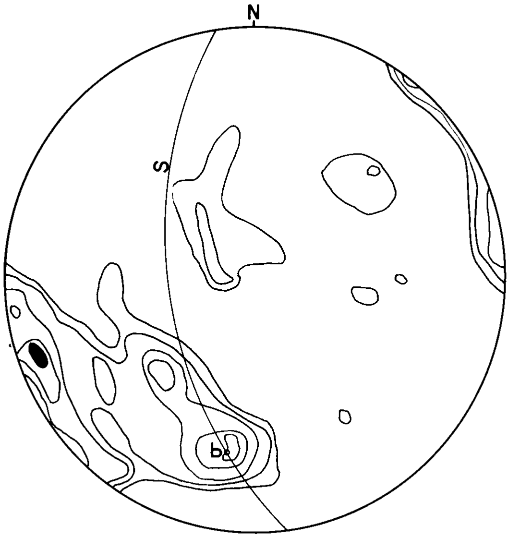


Figure 51. Locality 14. 126 poles to planes of liquid inclusions. Contours 8-6-4-2-1-0 %.

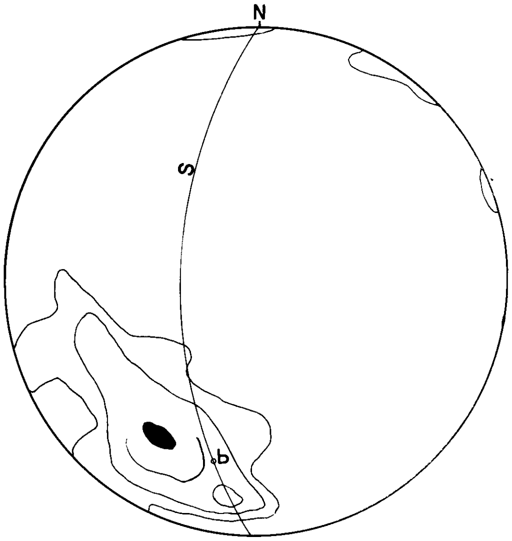


Figure 52. Locality 15. 146 poles to planes of liquid inclusions. Contours 15-10-5-2-0 %.

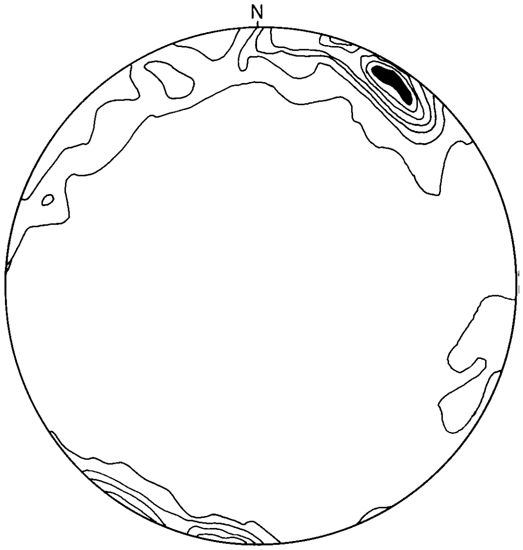


Figure 53. Locality 18. 150 poles to planes of liquid inclusions. Contours (16-14)-12-10-8-6-4-2-0 %.

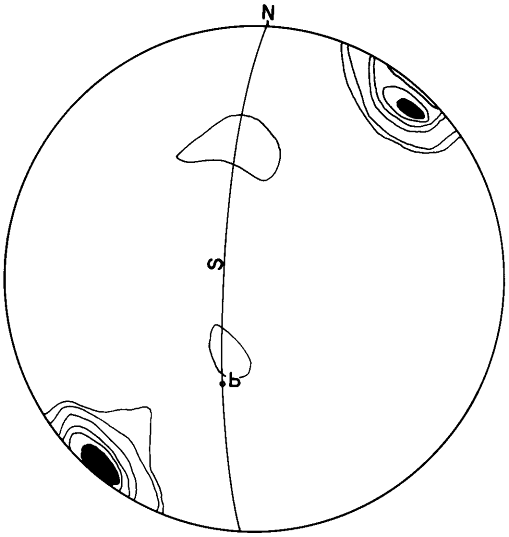


Figure 54. Locality 19. 98 poles to planes of liquid inclusions. Contours 25-20-10-5-2-0 %.

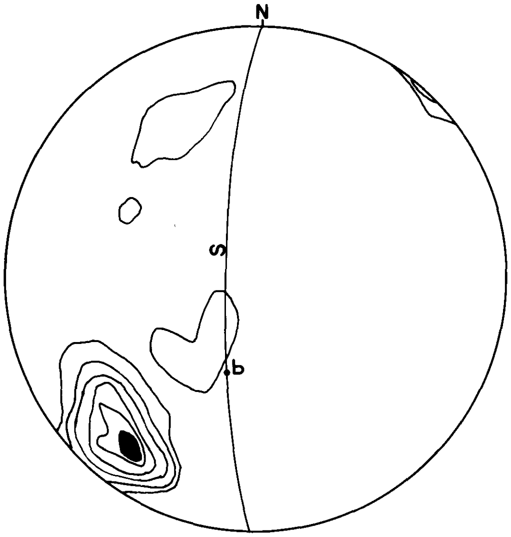


Figure 55. Locality 19. 150 poles to planes of liquid inclusions. Contours 25-20-10-5-2-0 %.

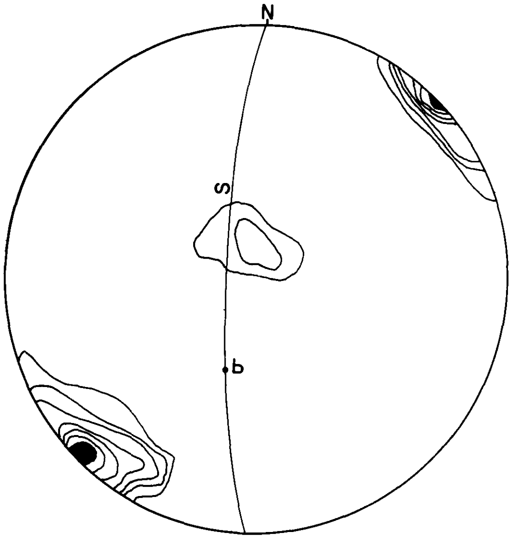


Figure 56. Locality 19. 68 poles to planes of liquid inclusions. Contours (35-30)-25-20-15-10-5-2-0 %.

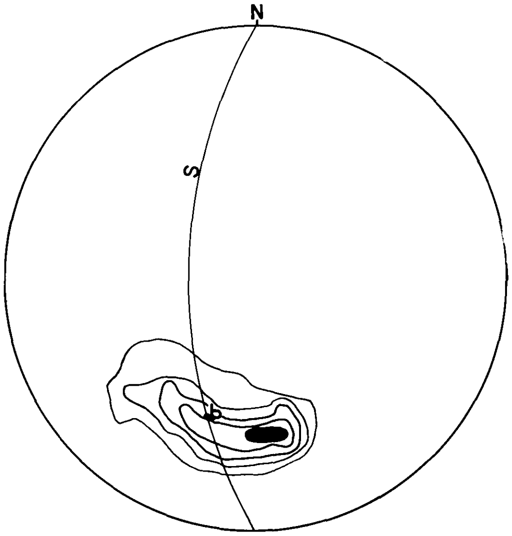


Figure 57. Locality 21. 50 poles to planes of liquid inclusions. Contours 20-16-12-8-4-0 %.

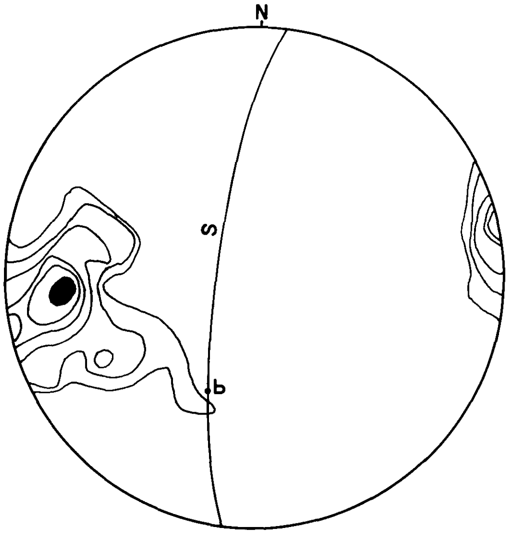


Figure 58. Locality 22. 50 poles to planes of liquid inclusions. Contours 20-16-12-8-4-0 %.

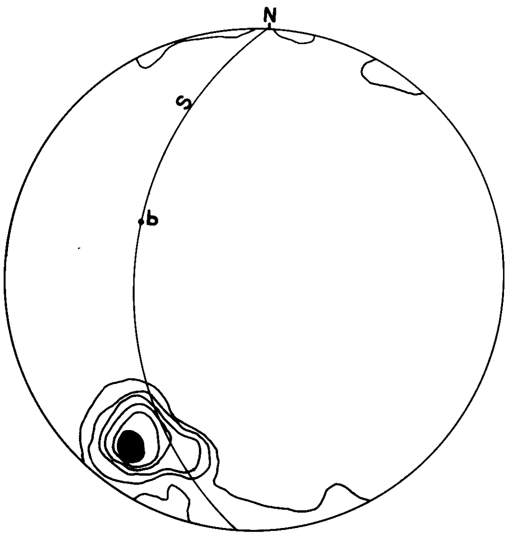


Figure 59. Locality 23. 60 poles to planes of liquid inclusions. Contours 24-20-18-12-8-4-0 %.

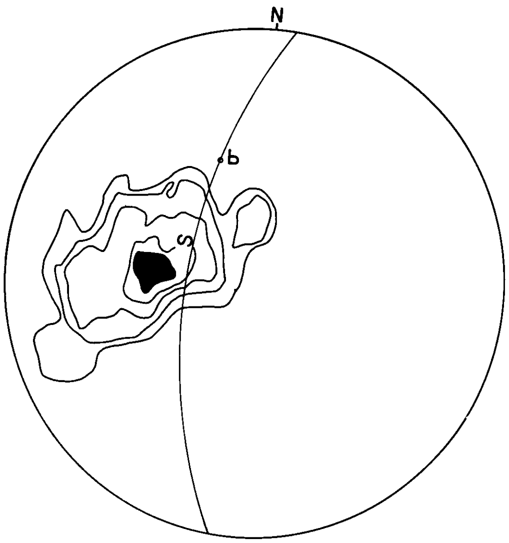


Figure 60. Locality 24. 50 poles to planes of liquid inclusions. Contours 20-14-8-4-2-0 %.

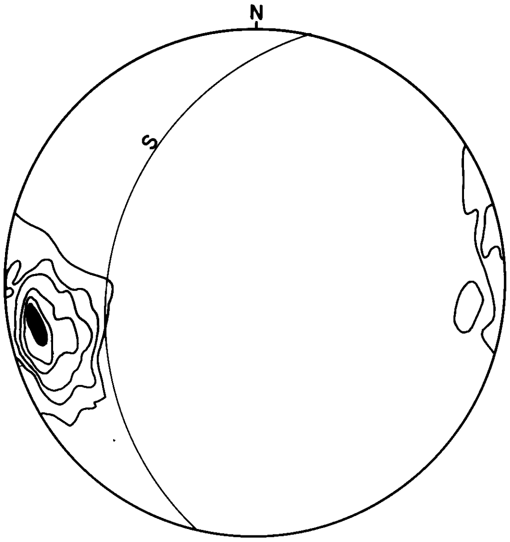


Figure 61. Locality 25. 50 poles to planes of liquid inclusions. Contours 32-26-20-14-8-2-0 %.

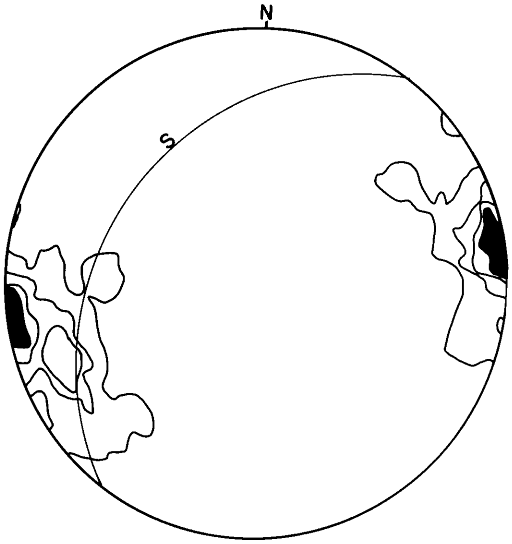


Figure 62. Locality 27. 50 poles to planes of liquid inclusions. Contours 20-16-12-8-2-0 %.

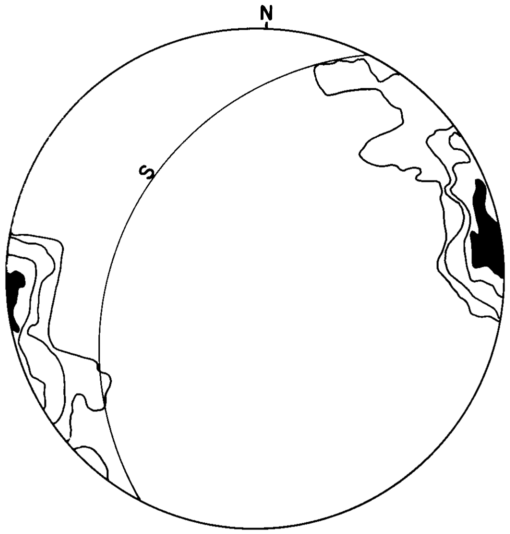


Figure 63. Locality 28. 56 poles to planes of liquid inclusions. Contours 20-16-10-5-2-0 %.

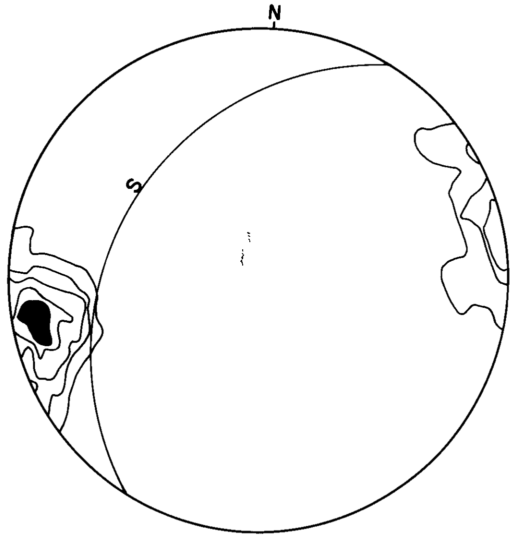


Figure 64. Locality 29. 50 poles to planes of liquid inclusions. Contours 24-18-12-6-2-0 %.

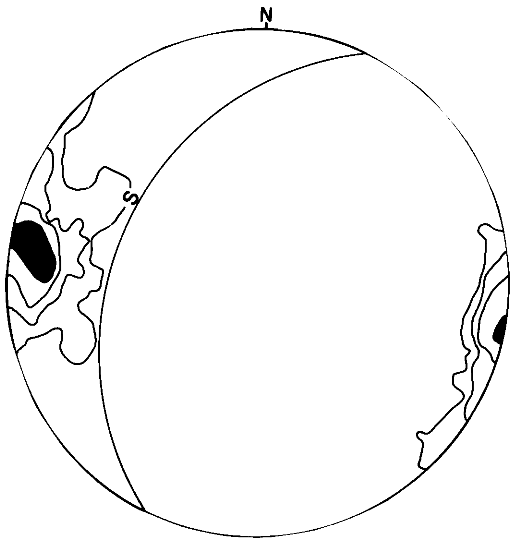


Figure 65. Locality 30. 50 poles to planes of liquid inclusions. Contours 30-22-12-6-2-0 %.

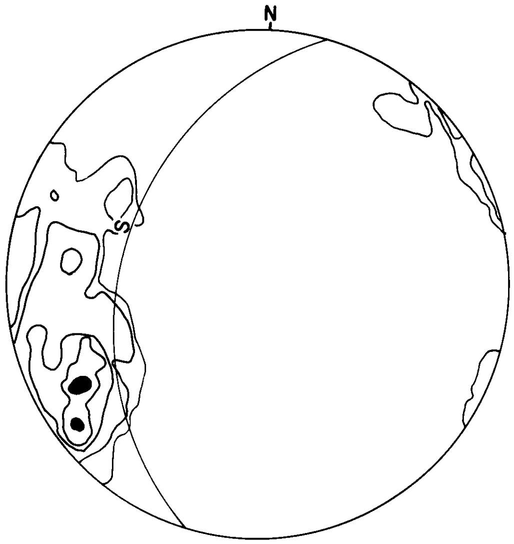


Figure 66. Locality 31. 50 poles to planes of liquid inclusions. Contours 22-16-10-4-2-0 %.

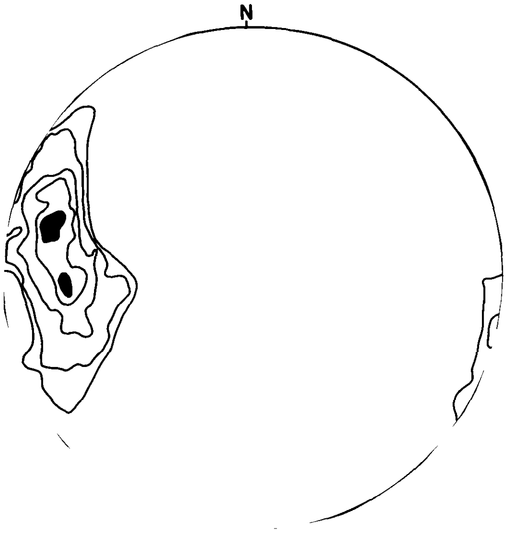


Figure 67. Locality 32. 50 poles to planes of liquid inclusions. Contours 22-16-10-4-2-0 %.

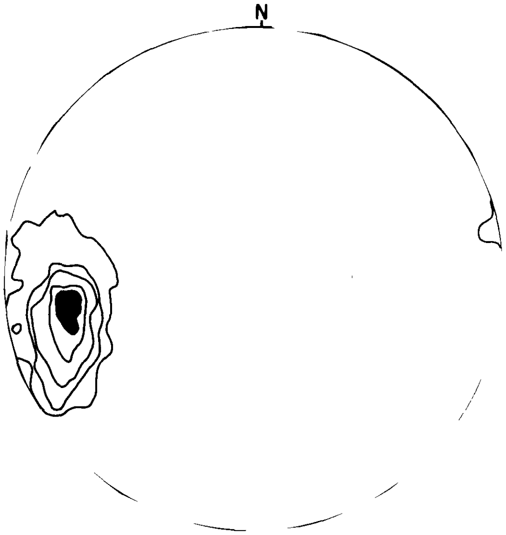


Figure 68. Locality 33. 50 poles to planes of liquid inclusions. Contours 18-14-10-6-2-0 %.

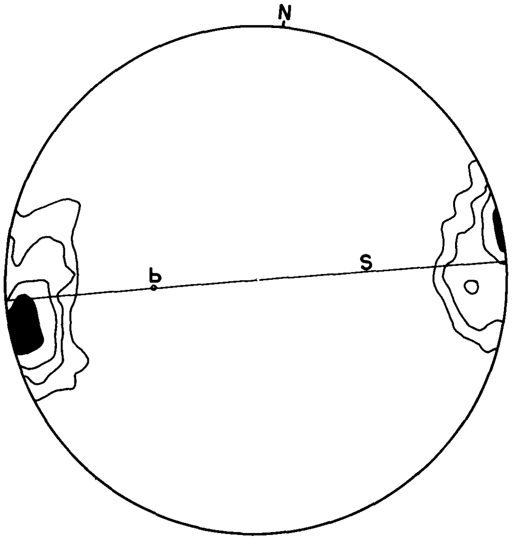


Figure 69. Locality 34. 50 poles to planes of liquid inclusions. Contours 30-22-14-6-2-0 %.

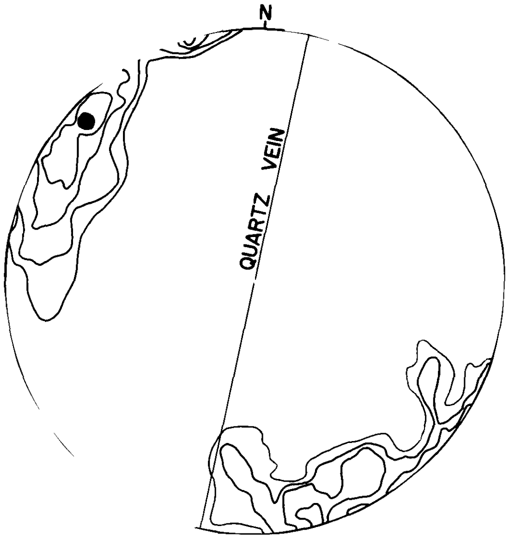


Figure 70. Locality 8. Quartz vein. 53 poles to planes of liquid inclusions. Contours 20-16-12-8-4-0 %.

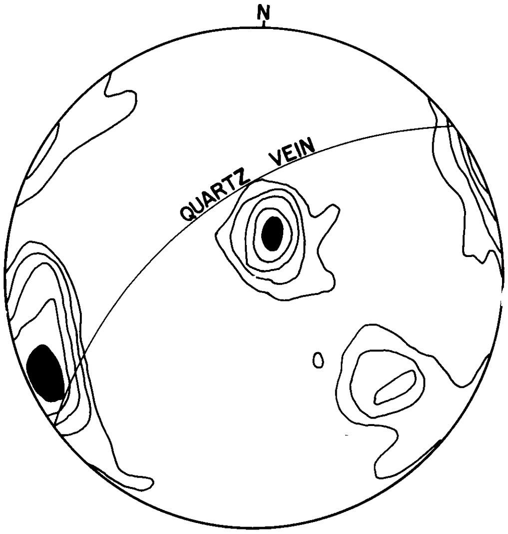


Figure 71. Locality 17. Quartz vein. 175 poles to planes of liquid inclusions. Contours 15-11-7-3-1-0 %.

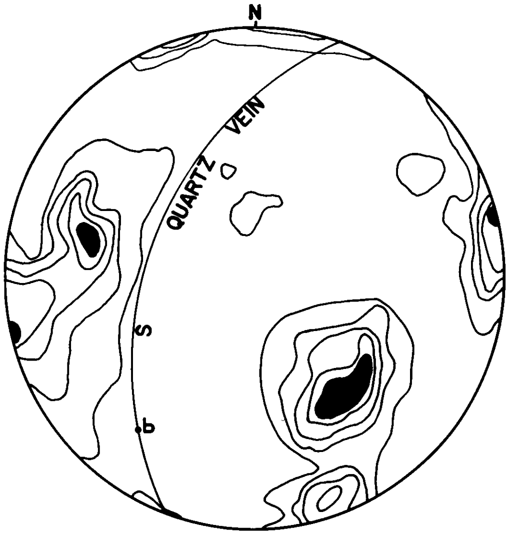


Figure 72. Locality 18. Quartz vein. 221 poles to planes of liquid inclusions. Contours (6-5)-4-3-2-1-0 %.

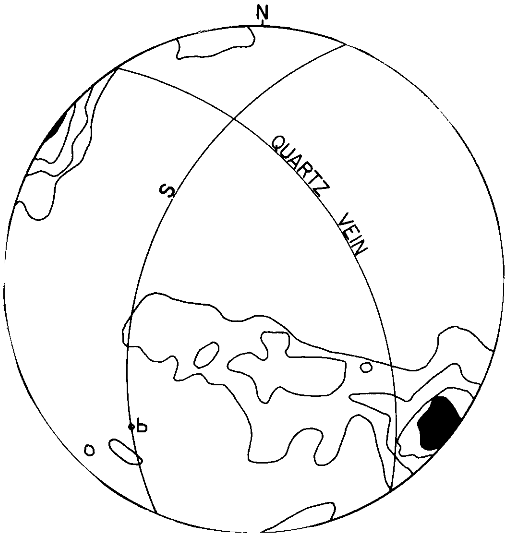


Figure 73. Locality 18. Quartz vein. 352 poles to planes of liquid inclusions. Contours (10-8)-6-4-2-0 %.

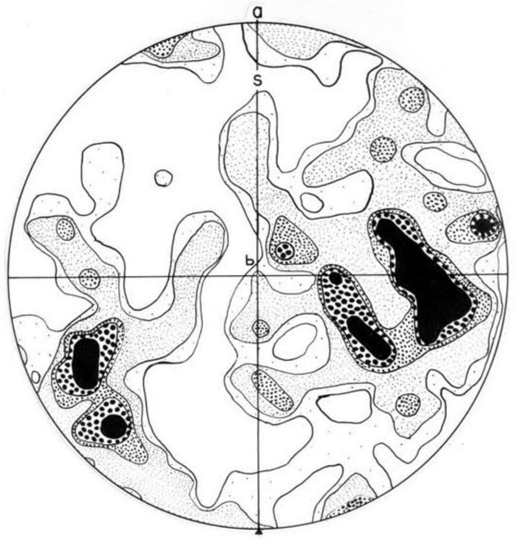


Figure 74. Locality 1. 245 C_v quartz. Planes of liquid inclusions from same thin sections shown in figure 75. Contours 3-2.5-2-1.5-1-0 %.

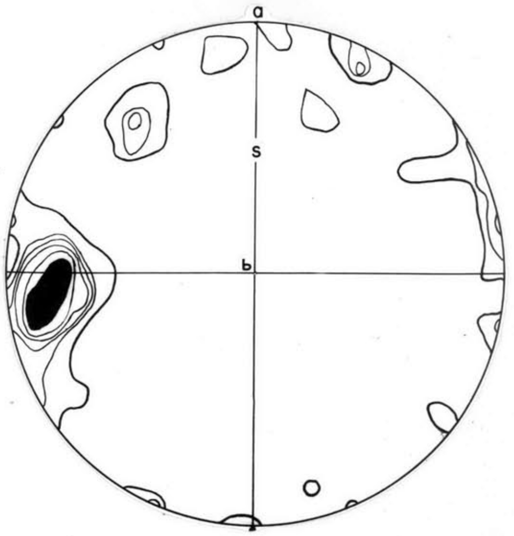


Figure 75. Locality 1. 36 poles to planes of liquid inclusions. Quartz orientation shown in figure 74. Contours 16-14-11-8-6-3-0 %.

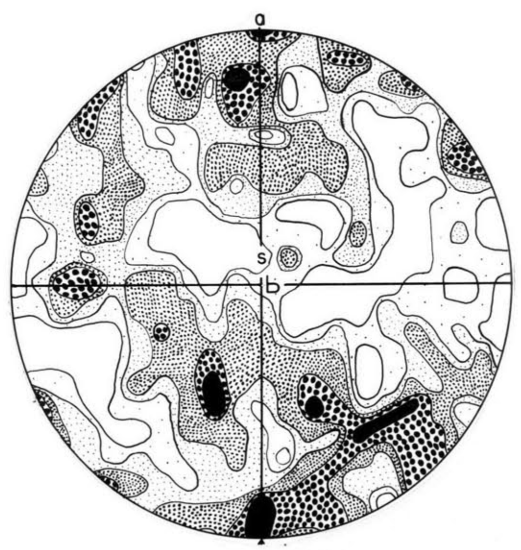


Figure 76. Locality 2. 300 C_v quartz. Poles to planes of liquid inclusions from same thin sections shown in figure 77. Contours 3-2.5-2-1.5-1-0 %.

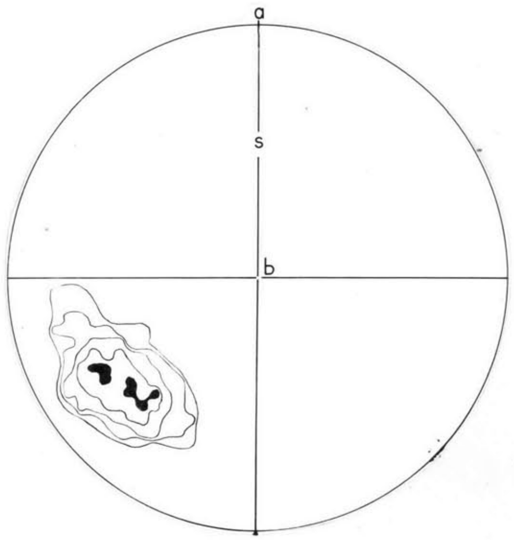


Figure 77. Locality 2. 33 poles to planes of liquid inclusions. Quartz orientation shown in figure 76. Contours 30-21-12-6-3-0- %.

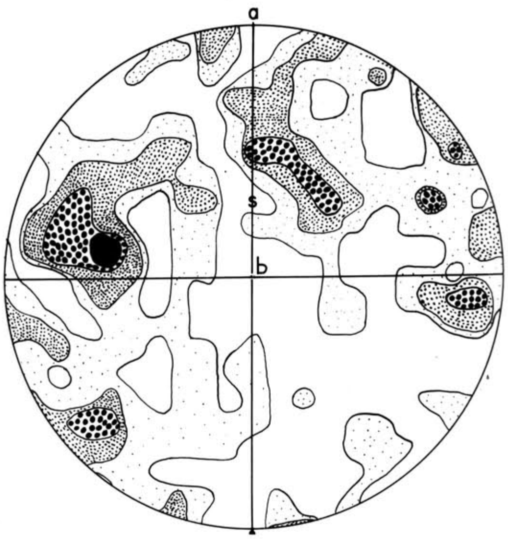


Figure 78. Locality 3. 213 C_v quartz. Planes of liquid inclusions from same thin sections shown in figure 79. Contours 4-3-2-1-0 %.

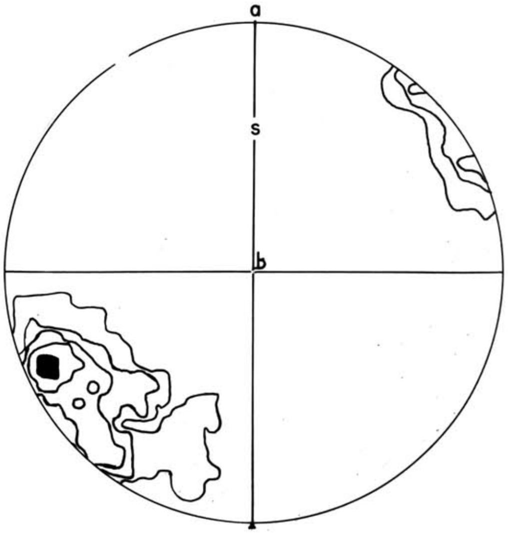


Figure 79. Locality 3. 50 poles to planes of liquid inclusions. Quartz orientation shown in figure 78. Contours 18-14-10-6-2-0 %.

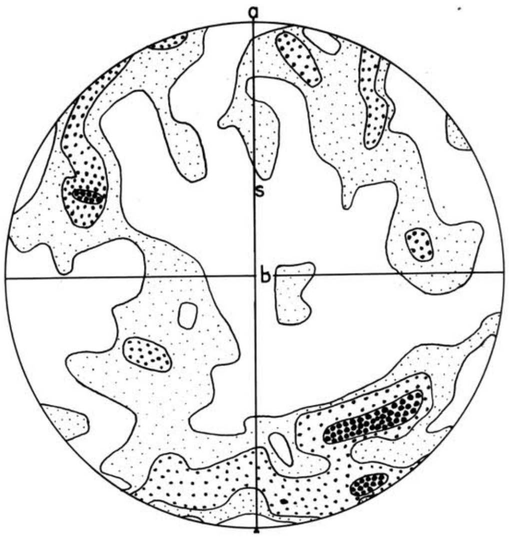


Figure 80. Locality 14. 300 C_v quartz. Planes of liquid inclusions from same thin sections shown in figure 81. Contours (4-3)-2-1-0 %.

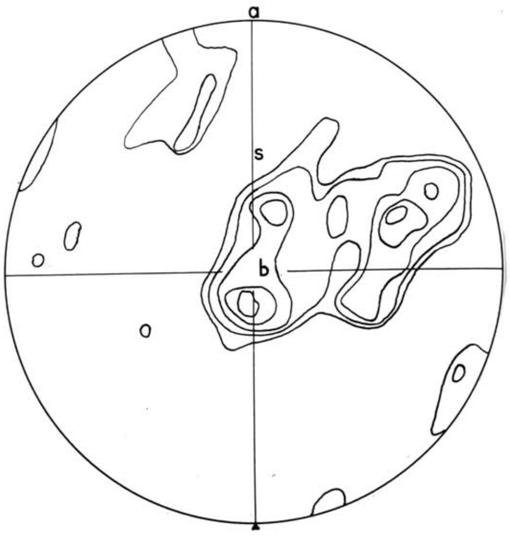


Figure 81. Locality 14. 126 poles to planes of liquid inclusions. Quartz orientation shown in figure 80. Contours 8-6-4-2-1-0 %.

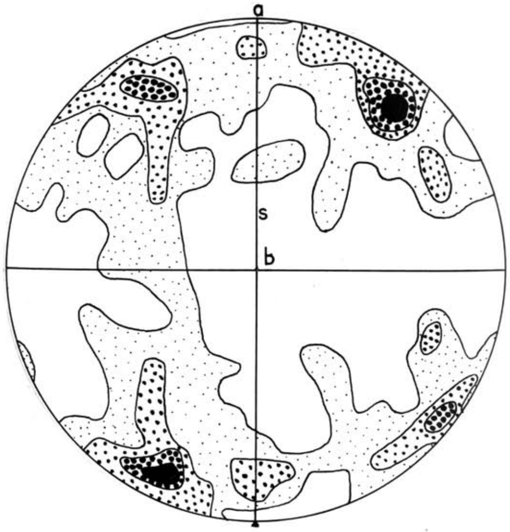


Figure 82. Locality 19. 429 C_v quartz. Planes of liquid inclusions from same thin sections shown in figure 83. Contours 4-3-2-1-0 %.

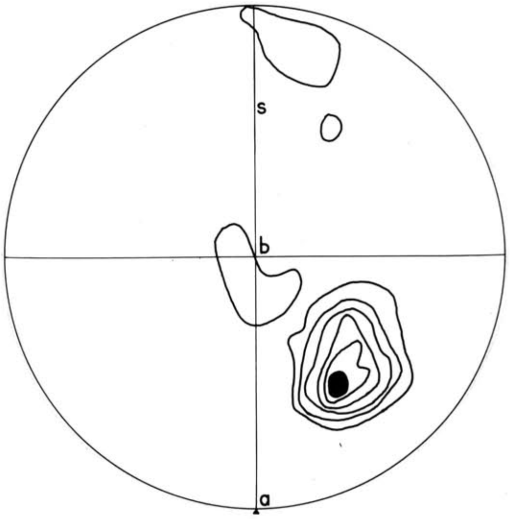


Figure 83. Locality 19. 150 poles to planes of liquid inclusions. Quartz orientation shown in figure 82. Contours 25-20-15-10-5-2-0 %.

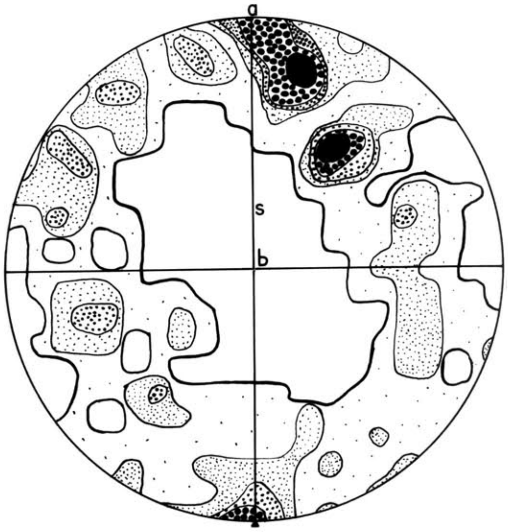


Figure 84. Locality 31. 173 C_v quartz. Planes of liquid inclusions from same thin sections shown in figure 85. Contours (6-5)-4-3-2-1-0 %

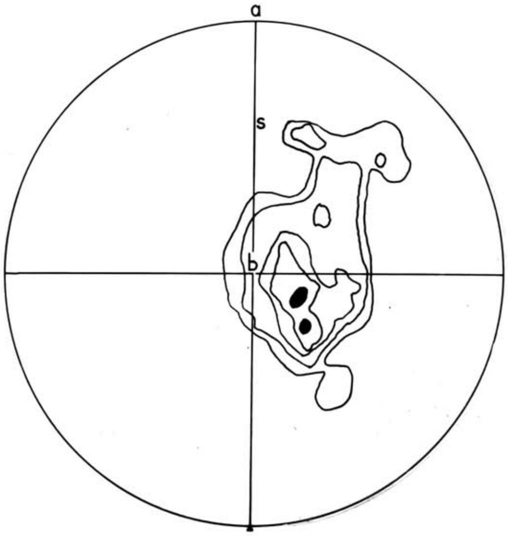


Figure 85. Locality 31. 30 poles to planes of liquid inclusions. Quartz orientation shown in figure 84. Contours 22-16-10-4-2-0 %.

indicates that the planes of inclusions are later than the primary regional structures.

Late Structural History of the Washington, D. C. Area

After the metamorphism that produced the foliation and quartz orientation, the entire region was subjected to orogenic movements that induced fracturing in the quartz grains of all the rock types. These fractures were strongly developed in a northwest southeast direction with a steep eastward dip. The fractures were filled with solution, either interstitial or hydrothermal, which subsequently became trapped as minute liquid inclusions in the quartz. The initial thin layer of liquid along each fracture became disseminated into numerous isolated inclusions by a process of solution and deposition of silica. This process of solution and deposition apparently continued for a relatively long period since the liquid inclusions had begun to develop crystallographic planes as boundaries before the next orogenic disturbance. The next orogenic disturbance manifested itself as numerous small drag folds in the less competent horizons of the area. During the drag folding the quartz was locally reoriented in part and deformed subparallel to the shear directions of the deforming stress as deformation lamellae (see page 34). The lamellae are believed to have formed while the folding was in process as they occur as a partial girdle about the fold axis. After this period of deformation the quartz was again fractured locally, and again liquid filled the fractures. These latest fractures still remain as thin sheet-like liquid inclusions, indicating that they are relatively young compared to the other structural features described.

Sometime during the above described events quartz veins and pegmatites were introduced. They are, in part at least, later than the foliation; but otherwise no evidence has been discovered to fit them more closely into the sequence of structural events.

GEOLOGICAL SIGNIFICANCE OF PLANES OF LIQUID INCLUSIONS

General

Planes of liquid inclusions have not been identified megascopically, nor have they been related to any megascopic structures such as joints and fractures. The commonly described ac and BC fractures, both of which can usually, if not always, be recognized in the field, have not been recognized in the Washington, D. C. area; therefore it is not possible to compare them directly with the planes of liquid inclusions. The most important distinction between the fractures and planes of liquid inclusions is that the latter are confined to the quartz grains of the rock, whereas joints and fractures usually represent failure of all the minerals in the rock. It is possible that megascopic jointing and fracturing are a relatively shallow zone manifestation of the same stress environment that produces planes of liquid inclusions at greater depths.

Heretofore the only suggestion of the orientation of the planes of liquid inclusions with respect to a direction in the deforming stress pattern has been the en-echelon tension-like planes described on page 18 (see also figures 12 and 13). These planes would seem to indicate that either the shear or tensional direction in the deforming stress pattern may be favorable for the development of fractures that subsequently become planes of liquid inclusions. It has been mentioned (page 21) that the poles to planes of liquid inclusions commonly lie in incomplete girdles. These may be perpendicular to the fold axes. The evidence for this belief, presented in the next section, is the relation of a set of extremely thin sheet-like planes of inclusions to small drag folds found in a schistose horizon in the granite gneiss.

Planes of Liquid Inclusions in Small Drag Folds

The drag folds are younger than the foliation, as the mica flakes are bent around the folds with no evidence of recrystallization. The planes of liquid inclusions previously described are rotated by this folding and therefore antedate it. The maximum in diagram A of figure 86 shows the orientation of these planes in the portion of the schist that has not been rotated. Only a few of these planes could be found in the rotated portion of the fold, but all were obviously rotated during the folding. These planes of inclusions are therefore older than the drag folds and are not genetically related. In addition to these planes, characterized by a broad plane of nearly equidimensional inclusions, another type is present in sections of the drag folds. This type is characterized by extremely thin planes of sheet-like inclusions. Diagrams B and

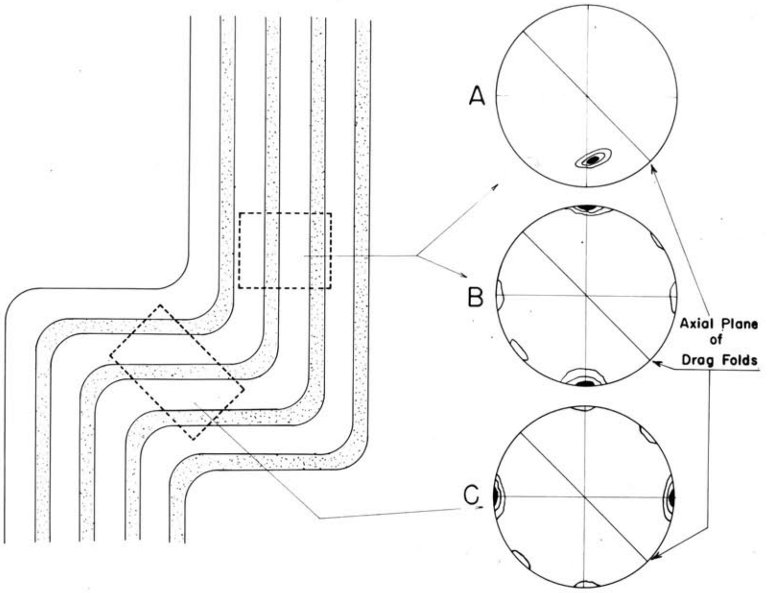


Figure 86. Diagrammatic cross section of drag fold with schematic fabric diagrams illustrating the orientation of planes of liquid inclusions in the fold. (A) Poles to planes of liquid inclusions characterized by a broad plane of nearly equi-deminsional inclusions. (B-C) Poles to planes of liquid inclusions characterized by extremely thin planes of sheet-like inclusions.

C of figure 86 illustrate their orientation with respect to the drag folds. They are symmetrically related to the drag folds and are believed to be also genetically related. They are essentially in the shear direction of the conventional stress pattern. In diagram B of figure 86 most of the planes are perpendicular to the foliation, which is one of the shear directions of the drag fold. In diagram C of figure 86 most of the planes are again nearly perpendicular to the rotated foliation, but this is also a shear direction of the drag fold. In both B and C there are some planes of inclusions in both shear directions, but one of the directions predominates in each case; hence providing a possible explanation of why only single-maximum diagrams are found in most specimens in the area. The drag fold is composed of alternating layers of mica and quartz and in all probability the movement which theoretically should have produced two equally dense maxima in B of figure 86 was partially taken up by the less competent mica layers when the shear was along the plane of the mica layers. It should also be noted that a few planes were found that were in the tensional direction in the drag folds.

Diagrams B and C are sketches of what is believed to be the correct interpretation of the orientation of the thin sheet-like planes. Conventional contoured diagrams were not prepared because only a few planes were found in the thin sections available. Measurement of these planes is extremely tedious because they can be seen only when nearly parallel to the microscope axis and only a few were found in carefully traversing several large thin sections.

Relation Between Deformation Lamellae and Planes of Liquid Inclusions in Quartz

Deformation lamellae have previously been described (Ingerson and Tuttle 14) in the quartz grains of these drag folds. They were found to occur in the shear directions of the deforming stress pattern and it was shown that the orientation of the lamellae is unrelated to definite crystallographic directions.

Lamellae in quartz were first described in detail by Böhm (3), and it is interesting to note that Böhm believed the lamellae to be planes of inclusions. Where the inclusions could not be seen, Böhm suggested that they were merely ultramicroscopic in size. A somewhat different explanation has been offered by other observers (Kalkowsky 2, Ingerson and Tuttle 14, and Fairbairn 15). Lamellae are believed to be an entirely different type of structure from planes of inclusions, and the confusion has been brought about by the fact that planes of inclusions commonly occur with the lamellae. Lamellae (see photograph figure 88) are planar structures manifested by a slight difference in refractive index between the lamella and the surrounding area. In some cases the birefringence serves to distinguish their presence. They can be seen in thin section only when they are nearly parallel to the axis of the microscope. In many cases it is necessary to have sections several times the normal thickness to recognize them. They are not definite breaks in the quartz grains and do not pass uninterrupted from one grain to another of different

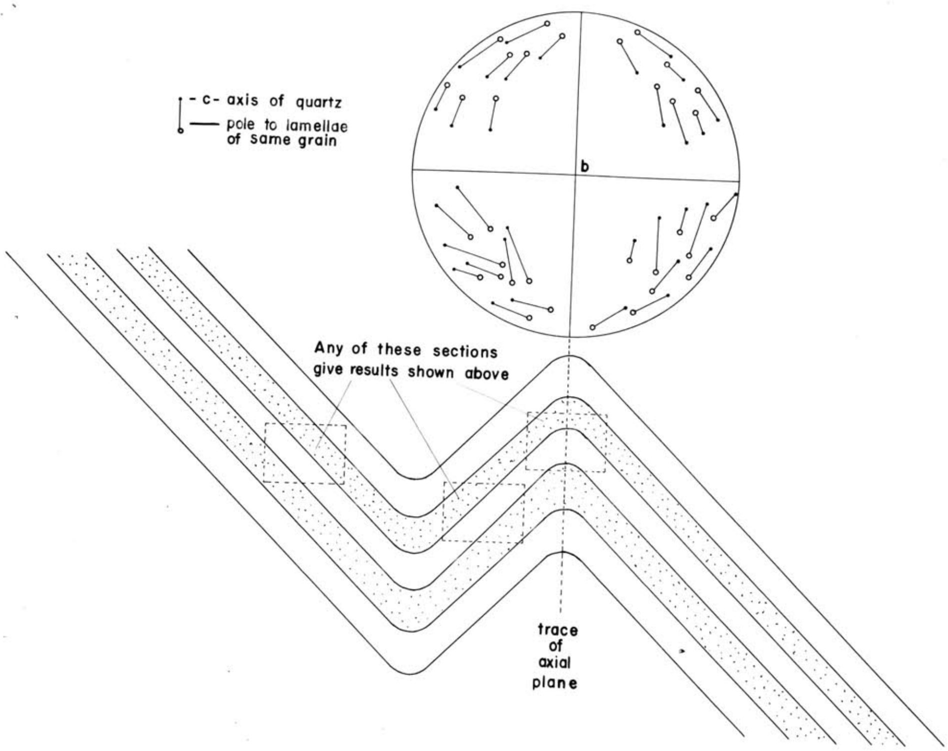


Figure 87. Diagram illustrating the relation between c-axes, poles to lamellae, and fold axis of a small drag fold in mica schist. Note that the lamellae have the same orientation as the planes of liquid inclusions in figure 86.

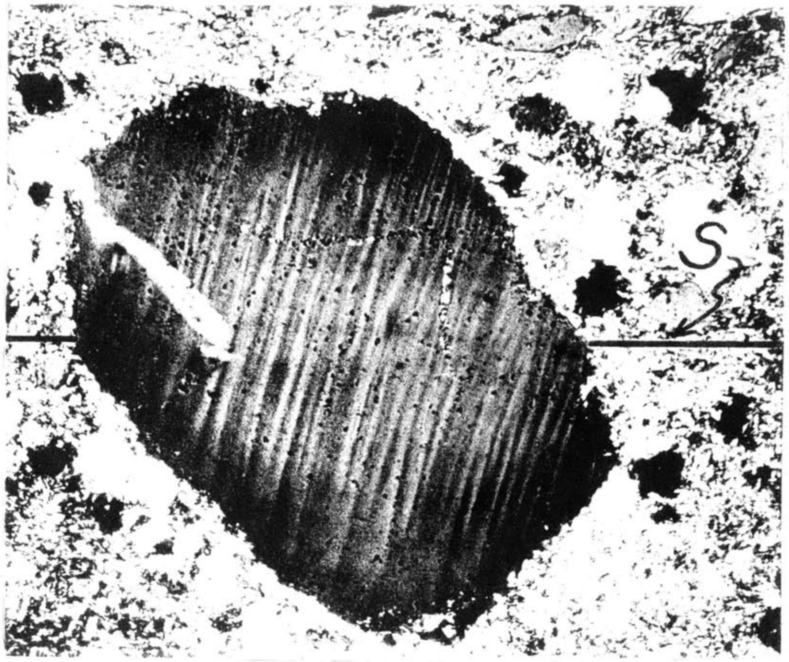


Figure 88. Quartz grain from Ajibik quartzite showing numerous lamellae (photomicrograph by Fairbairn 20).

orientation as do planes of liquid inclusions. In general, lamellae are more common within a zone from 10-30° of the base, although they have been observed in all positions from 0-90° of the base.

Lamellae have been interpreted as translation-gliding planes by some observers (Mügge 16, Sander 17). Fairbairn (15) suggested that a glide-line (m:r) was operative rather than one or more glide-planes. Ingerson and Tuttle (14) concluded that the lamellae are not controlled by definite crystallographic planes or zones. They suggested that the quartz had failed more nearly like an isotropic material than a crystalline substance.

The orientation of the lamellae in the quartz of the drag folds previously described (page 32) is illustrated in figure 87. The relation between the orientation of these lamellae and the planes of liquid inclusions can be seen by comparing figure 86. Both structures are related to the shear direction of the deforming stress. This suggests that the two structures are produced in similar stress environments. The deformation lamellae tend to be less highly oriented than the planes of inclusions, indicating, perhaps, that they were formed at an earlier stage while the quartz grains were still being rotated by the deforming stress. Rotation of individual quartz grains did not occur during or after the fracturing that produced the planes of inclusions because a single plane can be seen crossing many quartz grains of different orientation without deflection at the boundaries.

Relations Between Planes of Liquid Inclusions and the Rift, Grain, and Hardway of Granites

Planes of liquid inclusions have been reported as being parallel to the rift, grain, and hardway of granites. Some investigators have reported parallelism between planes of inclusions and one of these directions, and others between planes of inclusions and two of these directions. In all cases the relation between the two structures was apparently investigated by inspection of thin sections without the aid of the universal stage, and orientation of the planes could not be accurately determined. For example, figure 89 (taken from Dale (8) page 18) is a camera lucida drawing of a section parallel to the hardway of a granite and is intended to illustrate that the planes of inclusions are parallel to the rift and grain. It can be stated with certainty that neither set of planes of inclusions illustrated is parallel to the rift or grain of the granite. The "strike" of the two sets of planes with respect to the thin section surface is nearly parallel to the rift and grain directions, but the "dip," in both sets obviously does not coincide with the rift or grain in either case.

The interpretation placed on this example throws doubt on other observations made without the universal stage and emphasizes the need for careful statistical study of such structures. For example, planes of liquid inclusions are reported to be parallel to the rift of some Pre-Cambrian granites of Quebec (Osborn 24). However, the method of

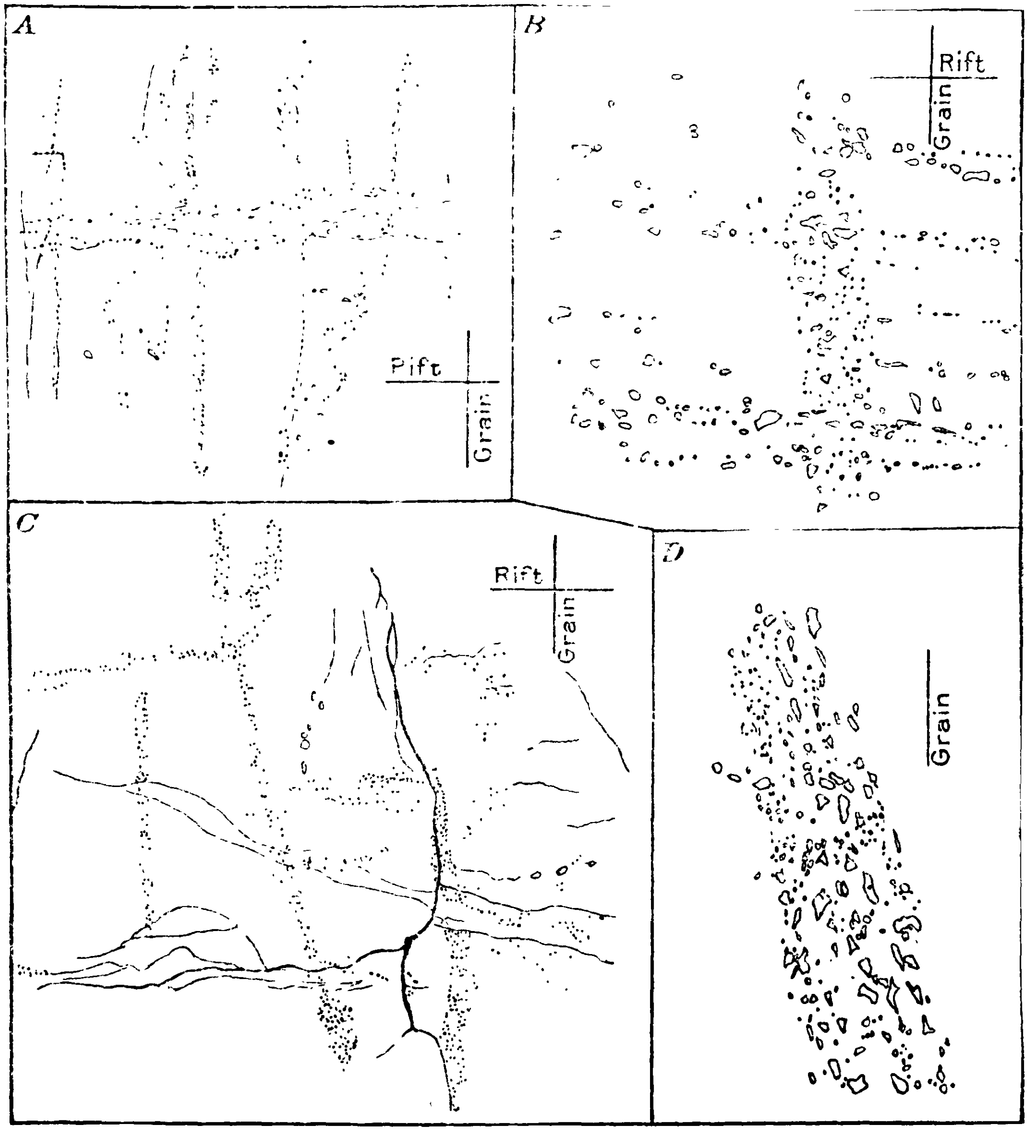


Figure 89. From Dale(8). "Camera lucida drawings of quartz areas in an enlarged thin section of biotite granite from the Redstone quarry in Conway, N. H., cut parallel to the "hard way." A, enlarged 62½ diameters, shows sheets of cavities and incipient cracks in both rift and grain directions. B, from a different quartz area, enlarged 175 diameters, shows the variation in the size of the cavities and their arrangements in both rift and grain directions. C, from still another quartz area, enlarged 23½ diameters, shows conspicuous rift and grain cracks, filled with fibrous white mica, coinciding here and there with the sheets of cavities, also two parallel exceptional fractures crossing the rift and grain directions diagonally. D shows part of one of the grain sheets of cavities of C, enlarged 175 diameters in order to show the shapes of the cavities. As most of these sheets of cavities in the section appear to undulate in the direction of the line of vision when placed under the microscope the outlines of all the cavities become visible only by altering the focus."

determining the orientation is not given and the observation may be subject to the same misinterpretation as mentioned above.

Relation Between Shear and Tension Fractures and Planes of Liquid Inclusions

Sander (17) has studied and described the orientation of four types of fractures in quartz. Two of them (ac and BC) are tension and two, (intersecting in a and b) are shear fractures. Unfortunately detailed description of the fractures is unavailable to correlate them directly with planes of liquid inclusions. All four types are symmetrically related to the primary structures of the rocks and to the quartz orientation, whereas the planes of liquid inclusions considered here are not so related. At least two of the fracture types (BC and b) are megascopic structures, hence differing from the planes of inclusions in this respect. The four types of fractures have one important feature in common with planes of liquid inclusions, namely, the lack of control of their orientation by crystallographic directions in the quartz. This further emphasizes the isotropic nature of observable quartz failure in deformed rocks.

Environment for Production of Planes of Liquid Inclusions

Planes of liquid inclusions have been described by Anderson (9) as being related to crystallographic directions in quartz. The quartz studied by Anderson occurs in small veinlets in a quartzite and is believed to represent low grade metamorphism as it lacks secondary silica and contains much chlorite. The significance of this work is open to some question as only eight quartz grains were studied and statistical methods were not used. However, if it is assumed that the planes of liquid inclusions are related to crystallographic directions in some cases, then it seems reasonable to expect that a different stress environment is responsible for the control of fracturing by crystallographic planes in one case and the lack of control in another. The rocks in the Washington, D. C. area have been subjected to a very high grade metamorphism and probably were buried to a greater depth than the low rank chloritic rocks in the area investigated by Anderson. The speculation is therefore warranted that quartz may behave like an anisotropic material when deformed at relatively shallow depths, but at higher pressures (and temperatures ?) and greater depths the crystallographic control of fracturing is lost.

Planes of Liquid Inclusions and Hypotheses of Quartz Orientation in Deformed Rocks

Fairbairn (20) has critically discussed three hypotheses of quartz orientation in tectonites. They are based on twinning, translation, and fracture. The twinning hypothesis is considered least likely to apply because little direct evidence has been obtained to substantiate such a mechanism. The translation hypothesis is also considered unproven because of the lack of direct experimental evidence. Deformation lamellae may originate by translation-gliding, but the lack of control (Ingerson and Tuttle 14) of their orientation by crystallographic directions in the quartz makes this hypothesis even less acceptable. The third hypothesis, based on the crystallographic control of fracturing is considered most likely, and Fairbairn concluded (21 p. 1490), "All the known quartz maxima in tectonites may be correlated with the fracture hypothesis.....", however, "The common oblique and ac-girdles are not adequately explained by any of the three hypotheses."

The fracture hypothesis requires quartz to break into needle-like slivers which are parallel to prominent crystallographic directions. The bounding faces of the needles must be crystallographic planes. The hypothesis is based on experimental deformation of quartz by Griggs and Bell (18), who found that quartz broke into needle-like fragments bounded by prominent crystallographic planes when ruptured at elevated temperatures (450° C.) in the presence of sodium carbonate solutions. Quartz maxima are theoretically produced by rotation of the needles into shear planes with the prominent bounding plane parallel to ab.

It should be noted that the tendency for quartz to break into needle-like cleavage fragments was not encountered when the quartz was ruptured "dry" at room temperature with or without confining pressures. Thus the presence of solutions and the temperature may be important environmental factors controlling the behavior of quartz in tectonites.

The fracture hypothesis does not explain the ubiquitous girdles found in tectonites, and Billings (22, p. 352) criticizes the hypothesis because, "..... we should expect to find many rocks containing such slivers of quartz. Actually, they are very rare." The evidence presented here for the orientation of planes of liquid inclusions in quartz indicates that quartz fractures much like an isotropic material under the conditions prevailing during the development of the planes, and fails to give evidence for crystallographically controlled fractures in quartz. This fracture isotropism is further emphasized by Sander's (17) investigation of four different types of fractures in quartz. All four types show no lattice control of their orientation.

Thus the geological evidence of the isotropic nature of quartz failure appears to render the fracture hypothesis as untenable as the twinning and translation hypotheses. Some type of growth hypothesis may afford a more plausible explanation of quartz orientation where the environment does not permit lattice control of the failure of quartz. Such hypotheses have been proposed by several workers. Girggs and Bell (18, p. 1745), for example, suggest that differential solubility and the effect of the stress field on recrystallization might be operative to preserve certain orientations and obliterate others. Cloos (23, p. 39) has suggested growth to explain quartz orientations in primary igneous and metamorphic rocks. As quartz is the latest mineral to crystallize, its orientation may be controlled by the pre-existing mica, feldspar, and hornblende. Cloos writes, "Growth in a girdle plane may be in any rhombohedran or prism — a large array of possibilities, the only restriction being that the availability of many other minerals in a definite direction exerts an influence in the growth and orientation of quartz."

In conclusion, no completely satisfactory hypothesis of quartz orientation is known. Until quartz fabrics are synthesized and the orientation processes are better investigated this state of affairs will probably continue.

Planes of Liquid Inclusions as Evidence for Openings for Hydrothermal Solutions

Examination of a thin section of one granite (locality unknown) shows two sets of planes of liquid inclusions that differ in the character of the liquid. One set contains inclusions consisting of three phases - vapor, water, and liquid carbon dioxide - whereas the other set apparently contains only a vapor bubble and water. It is obvious that the two sets are of different age and that the character of the liquid available to fill the fractures changed with time. It is difficult to see how the composition of the liquid available to fill the fractures could change without introduction of material - therefore a hydrothermal source for one or both of the liquids is suggested. This introduces the possibility that the fractures may provide avenues for migration of hydrothermal solutions.

At first thought it would appear ridiculous to postulate that such minute fractures could provide channelways for any considerable amount of solution; however, when a specimen such as number 33 is examined and as many as two hundred planes are crossed in a traverse of only one centimeter it seems that the openings provided are worthy of consideration by geologists studying ore deposits. It should perhaps be emphasized here that no megascopic evidence has been discovered that will indicate the presence or orientation of the planes. Also, evidence of movement along the fractures has not been observed, although slight displacements would be difficult to establish.

SUMMARY

Planes of liquid inclusions are common in the quartz of igneous and metamorphic rocks. The planes consist of numerous individual inclusions which are commonly planar parallel to the plane. The liquid inclusions are believed to have originated as fractures in the quartz grains which subsequently became filled with solution. The solution-filled fracture is believed to change to numerous individual inclusions by a process of solution and deposition of silica. The process may have originated by a mechanism similar to that discussed by Riecke which requires that solution will take place in a stressed crystal in the area under greatest stress and precipitate in the area of least stress. Temperature oscillation would also be a contributing factor, as would the fact that an irregular inclusion does not represent the lowest possible energy level; hence the process of solution and deposition will continue until euhedral cavities are formed.

This constant change in the character of the planes of liquid inclusions suggests a method of estimating the relative ages of two or more sets of planes. "Young" planes are characterized by their sheet-like inclusions, whereas "old" planes are composed of inclusions that are more nearly equant and bounded, in part, by crystal planes. The relative age of two or more sets could also be determined by many of the methods used to establish the relative age between two or more sets of faults or joints.

Statistical studies of planes of liquid inclusions indicate that there is no control of the orientation of the planes by crystallographic directions in the quartz, suggesting that the quartz behaved like an isotropic material. Some evidence was found suggesting that the planes may be developed in the shear or tensional direction of the deforming stress pattern.

Statistical representation of the poles of planes of inclusions on a Schmidt equal area net gives diagrams that have maxima up to 45 per cent. Maxima of 20 per cent are very common. Strong single maxima are most common, but split maxima have been found repeatedly. In the Washington, D. C. area two or more distinct maxima occur in the quartz veins but not in the gneisses. In other areas two or more maxima are apparently common. Many fabric diagrams of planes of liquid inclusions have incomplete girdles that are believed to be oriented about the b axes. Occasionally complete girdles are found.

Planes of liquid inclusions have a remarkably uniform orientation throughout the Washington, D. C. area, striking northwest and dipping steeply to the northeast throughout an area of fifteen by twenty miles. Primary structures such as contacts, foliation, and banding strike predominantly north and dip steeply to the west. This nonsymmetrical relation is believed to indicate that the planes of inclusions are younger than the primary structures and therefore are not genetically related. No macroscopic structures could be found that were genetically related to them, although it is possible that some of the quartz veins are so related. The quartz orientation is in general believed to be genetically related to the primary foliation and lineation.

Detailed study of small drag-folds indicates that planes of inclusions may develop in the shear direction of the deformation, but that one set of planes parallel to one shear direction predominates.

Quartz deformation lamellae are present in the small drag folds. They also occur in the shear direction and are believed to be genetically related to the planes of liquid inclusions in the same folds. As lamellae are susceptible to recrystallization it is not surprising that they are not commonly found with planes of liquid inclusions.

One investigator has described planes of inclusions that are believed to be related to crystallographic directions in quartz. However, the material studied may represent deformation at relatively shallow depths and at low temperatures. If this is the correct interpretation, then planes of liquid inclusions that are not related to crystallographic directions may represent an environment characterized by high hydrostatic pressure and probably also high temperatures.

A study of planes of liquid inclusions may throw some light on the mechanism of quartz orientation in tectonites. It has been established that quartz fails like an isotropic material in certain environments and those theories of quartz orientation based on crystal structure control of failure are not applicable in such environments. Orientation by some growth process would appear to be more plausible.

Quartz may fail by shear or tensional rupture and in certain cases by deformation which produces lamellae that may be a type of translation-gliding. Failure by rupture along crystallographic directions has been noted by one observer and has been produced experimentally in the laboratory, These different phenomena are believed to represent failure under varying environmental conditions and the optimum development of any one type of failure depends on such factors as confining pressure, temperature, composition, and the presence (and character) of solutions.

As many as 200 planes of liquid inclusions have been found in a one centimeter traverse of a thin section of a quartzite. Although the openings are minute, their abundance suggests that they are worthy of consideration as a channelway for the movement of gases and solutions.

REFERENCES

(1) Buerger, M. J. "The significance of block structure in crystals." Am. Min., 17, p. 190, 1932.

(2) Kalkowsky, Ernst "Die Gneiss formation des Eulengebirges, Habitilationsschrift, Thesis, Leipzig, 1878.

(3) Böhm, August "Uber die Gesteine des Wechsels" Tech. Min. Pet. Mitt. N. F. 5, pp. 197-214, 1883.

(4) Hicks, H. "On the conglomerates etc." Geol. Soc. of London Quart. Jour. 40, 1884.

(5) Judd, J. W. "A contribution to the theory of schillerization." Min. Mag. 7, 1886.

(6) Van Hise, C. R. "Pre Cambrian of the Black Hills" G. S. A. Bull. 1, p. 218, 1890.

(7) Bastin, E. S. "Geology of the pegmatites and associated rocks of Maine" U. S. G. S. Bull. 445.

(8) Dale, T. M. "The commercial granites of New England" U. S. G. S. Bull. 738, 1923.

(9) Anderson, J. L. "Deformation planes and crystallographic directions in quartz" G. S. A. Bull. 56, pp. 409-430, 1945.

(10) Riecke, E. "Uber das Gleichgewicht etc." Ann.Physc 53, p. 731, 1895.

(11) Billings, M. P. and Sharp, R. P. "Petrofabric study of a fossiliferous schist, Mt. Clough, New Hampshire." Am. J. Sci. Vol. 34, pp. 277-292, 1937.

(12) Newhouse, W. H. "Ore deposits as related to structural features." p. 10.

(13) Williams, G. H. and Keith, Arthur U. S. G. S. Folio 70.

(14) Ingerson, Earl and Tuttle, O. F. "Relations of lamellae and crystallography of quartz and fabric directions in some deformed rocks." Trans. A. G. U. Vol. 26, pp. 95-105.

(15) Fairbairn, H. W. "Deformation lamellae in quartz from the Ajibik formation, Michigan. G. S. A. Bull. 52, pp. 1265-1277.

(16) Mügge, O. "Der Quarzporphyr der Bruchhäuser-Steine in Westfalen" N. Jahrb. Min. B. B. 10, p. 757, 1896.

(17) Sander, Bruno "Gefügekunde der Gesteine" Julius Springer, Vienna, 1930.

(18) Griggs, David and Bell, J. F. "Experiments bearing on the orientation of quartz in deformed rocks" G. S. A. Bull. 49, pp. 1723-1746.

(19) Griggs, David "Experimental flow of rocks under conditions favoring recrystallization" G. S. A. Bull. 51, pp. 1001-1034.

(20) Fairbairn, H. W. "Structural Petrology" Addison-Wesley Press, 1942.

(21) Fairbairn, H. W. "Hypotheses of Quartz orientation in tectonites" G. S. A. Bull. 50, pp. 1475-1492, 1939.

(22) Billings, M. P. "Structural geology" Prentice-Hall, 1942.

(23) Cloos, Ernst "Lineation ......" G. S. A. Memoir 18.

(24) Osborn, F. F. "Rift, grain, and hardway in some Pre-Cambrian granites, Quebec" Ec. Geol. 30, p. 540, 1935.

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Tuttle, O. F. Heavy Minerals of the Ordovician-Silurian Boundary in Central Pennsylvania. Proc. Penna. Acad. Sci. Vol. XIV 1940 pp. 55-59

______ and Krynine, P. D. Bellefonte Sandstone: Example of Tectonic Sedimentation. (abstract) Co. S. A. Bull. 52 1941 p. 1918

______ and Krynine, P. D. Petrology of the Ordovician-Silurian Boundary in Central Pennsylvania. (abstract) Co. S. A. Bull. 52 1941 p. 1917

______ Orientation of Ilmenite and Andesine from the St. Urbain Quebec Titaniferous Iron-ore Deposit. (abstract) Trans. Am. Geophysical Union Pt. I 1943 p. 280

______ and Ingerson, Earl A Graph for Determining Angle and Direction of Pitch of Lineation in the Field. Am. Min. Vol. 28 1943 pp. 209-210

______ Structural Relations of Planes of Liquid Inclusions in the Crystalline Rocks of the Washington, D. C. Area. Trans. Am. Geophysical Union Vol. 26 No. 2 1945 p. 301

______ and Ingerson, Earl Relations of Lamellae and Crystallography of Quartz and Fabric Directions in Some Deformed Rocks. Trans. Am. Geophysical Union Vol. 26 Pt. 1 1945 pp. 95-105

______ and Twenhofel, W. S. Effect of Temperature on Lineage Structure in Some Synthetic Crystals. Am. Min. Vol. 31 1946 pp. 569-573

______ and Egli, P. H. The Preparation of Mixed Thallium Bromide-Iodide for Infrared Transmissions. J. Chem. Phys. 14, 1946 p. 571

Tuttle, O. F. and Ingerson, Earl Artificial Willemite Needles. Am. Jour. Sci. Vol. 245, May 1947 pp. 313-319

———— and Morey, G. W. and Ingerson, Earl The Systems K_2O, ZnO,-SiO_2, ZnO-B_2O_3-SiO_2 and Zn_2SiO4-Zn_2GeO_4 Am. Jour. Sci. Vol. 246 Jan. 1948, pp. 31-40

———— and Bowen, N. L. The System MgO-SiO_2-H_2O (abstract) Am. Min. Vol. 33 1948 p. 193

———— and Bowen, N. L. Serpentine and Talc Equilibria. To be presented at the International Geological Congress, London, 1948.

———— and Friedman, I. I. Liquid Immiscibility in the System H_2O-Na_2O-SiO_2 Jour. Am. Chem. Soc. Vol. 70. 1948 pp. 919-927

———— A New Hydrothermal Quenching Apparatus. Manuscript now in hands of the editor Am. Jour. Sci.