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COMPARISON OF THE FABRICS OF INCLUSIONS AND THE ADJACENT INTRUSIVE ROCK

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INTRODUCTION

Fabric studies are being used more and more in interpreting the history of metamorphic areas and have been used a few times to obtain from igneous and sedimentary rocks information not available by other means. The use of such studies is by no means confined to making large-scale tectonic interpretations; they can aid in attacking many kinds of geological and mineralogical problems. For example, statistical grain orientation studies can aid in determining the origin of inclusions in igneous rocks and of included minerals[1] within individual grains of other minerals; also whether or not metamorphism has affected inclusion and host together.

Before such fabric criteria of origin can be very useful or reliable it will be necessary to make numerous studies of actual examples. This paper is such a study and has to do with three[2] intrusions that have numerous inclusions: (1) The Port Deposit granodiorite of Northeastern Maryland, (2) the Uncle Sam quartz monzonite porphyry, which is just southwest of Tombstone, Arizona, and (3) the Val Verde tonalite

[1] Ingerson, E., Albite trends in some rocks of the Piedmont: *Am. Jour. Sci.*, **35A**, 127–141 (1938). In this paper the following paragraph appears:

"These albite trends are most striking where mica is the included mineral, but many consist of other minerals such as quartz, epidote, or garnet. These trends of other minerals are more difficult to study quantitatively, but where they are present in the same feldspar grain with mica they appear to be parallel to the mica and presumably have the same origin and significance."

Since the appearance of this paper several quartz trends in albite grains have been measured accurately and they correspond to crystallographic planes of the albite porphyroblasts quite as closely as do the mica trends. Five of them were measured in five different albite grains and were found to be parallel to the following planes, (010), (010), (001), (110), and $(1\bar{1}0)$.

[2] The first two of these were studied by the writer. The Val Verde tonalite was studied by Dr. E. F. Osborn, who very kindly lent specimens for fabric comparison.

of Southern California. The first of these has been subjected to intense regional metamorphism since intrusion; the others have not.

Port Deposit Complex

The Port Deposit granodiorite complex[3] intrudes older intrusive rocks as well as schists and metamorphosed extrusive rocks. The specimens from which orientation diagrams have been prepared were collected

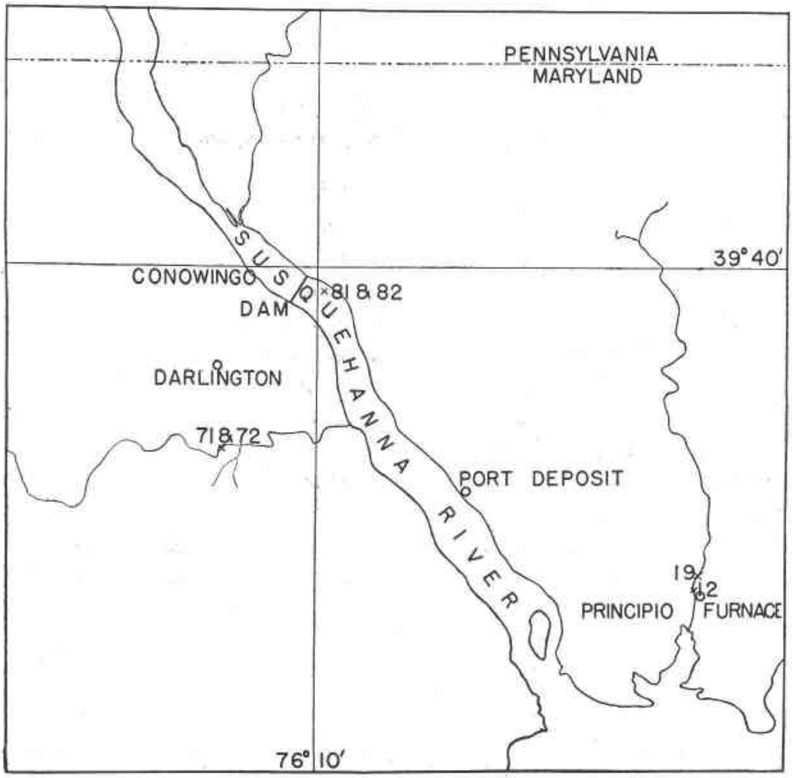


Fig. 1. Index map showing the locations of the specimens from the Port Deposit complex.

from three different localities in the area: (1) at Principio Furnace, near the contact with metadacite (12 and 19), (2) from a road cut on the south side of Deer Creek, 3 miles S 30°W from the dam (71 and 72), and (3) just below Conowingo Dam (81 and 82). See Fig. 1.

The intrusive at Principio Furnace is a light gray granitic rock. The texture is entirely metamorphic, but its intrusive nature is indicated by

[3] For a description of the rocks of the Port Deposit granodiorite complex, and a bibliography on the area, *see* Hershey, H. G., Structure and age of the Port Deposit granodiorite complex: *Maryland Geol. Survey*, **13**, 107–148 (1937).

the contacts with the country rock, and the presence of large numbers of inclusions. These inclusions are variable but in general contain essentially the same minerals as the granite. The fabrics of two inclusions from Principio Creek have been studied. No. 12 was collected just above the bridge on U. S. 40, and No. 19 from a cut bank a quarter of a mile up the creek.

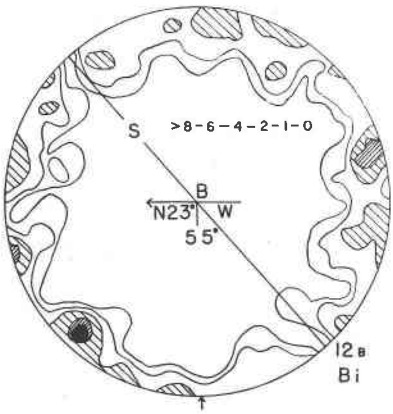


FIG. 2. Poles of 100 biotite flakes from the intrusive rock at Principio Furnace, Maryland.

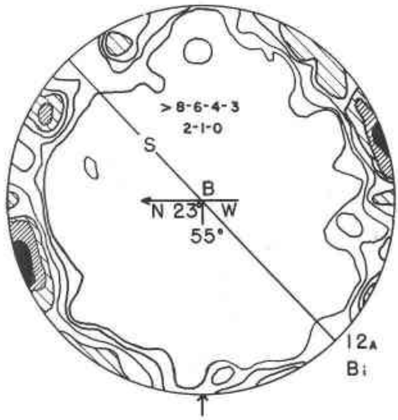


FIG. 3. Poles of 200 biotite flakes from an inclusion in the intrusive rock from which the diagram of Fig. 2 was prepared.

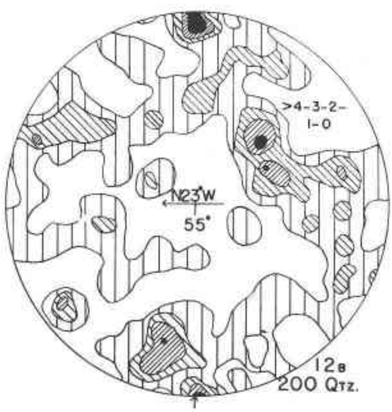


FIG. 4. 200 quartz axes from the intrusive at Principio Furnace.

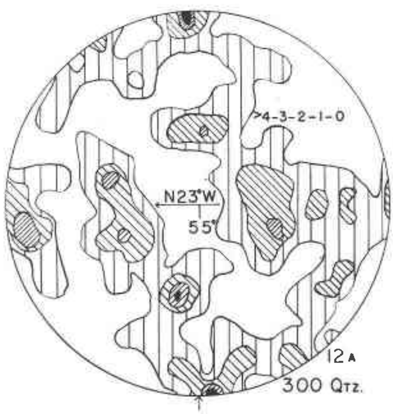


FIG. 5. 300 quartz axes from the inclusion of Fig. 3.

In No. 12 the inclusion differs from the host rock only in higher percentages of hornblende, biotite, and garnet. The foliation plane is common to host and inclusion, running across the contact with no deviation at all. The lineation in the foliation also appears to be the same in both rocks.

Biotite and quartz orientation diagrams were prepared from a thin section cut normal to the lineation (Figs. 2–5). The biotite diagram from

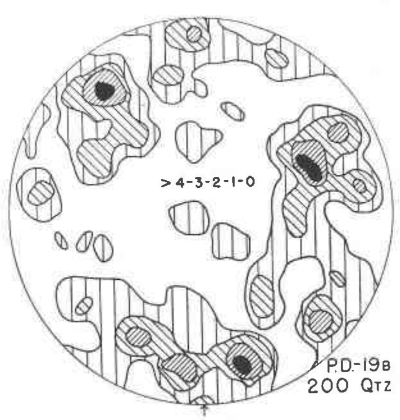


FIG. 6. 200 quartz axes from the intrusive rock up the creek from Principio Furnace, near the contact with metadacite.

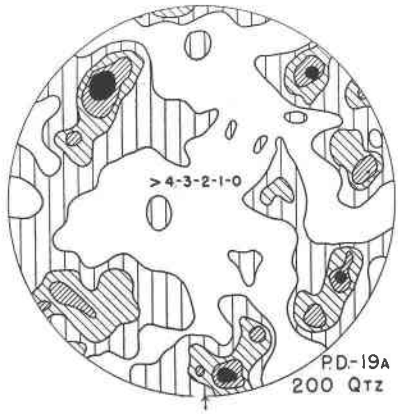


FIG. 7. 200 quartz axes from an inclusion in the intrusive rock of Fig. 6.

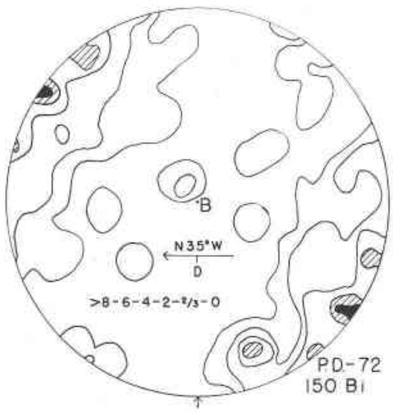


FIG. 8. Poles of 100 biotite flakes from the "pudding granite" on Deer Creek southeast of Darlington, Maryland.

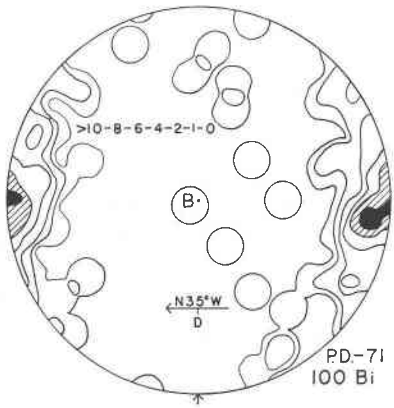


FIG. 9. Poles of 100 biotite flakes from an inclusion in the rock of Fig. 8.

the host rock, Fig. 2, shows a well developed girdle normal to the lineation. The principal maximum is normal to the *s*-plane, which is the arrangement that is to be expected. In the inclusion also the biotite forms a girdle normal to the lineation, but the principal maximum is not normal to the megascopic *s*-plane. This indicates that host and inclusion were subjected to the same metamorphic environment after intrusion was complete. The difference in the position of the maxima is probably due to the effect of an older set of *s*-planes in the inclusion, possibly the original foliation. There is no chance for difference in orientation of thin sections, because both diagrams were prepared from the same section.

The quartz fabric of the inclusion has been even more completely re-made. Both quartz diagrams, Figs. 4 and 5, have the principal maximum on the periphery near the orientation arrow, a decided minimum extending from the center to the periphery in the NE–SW quadrants, and almost identical sub-maxima.

The intrusive rock and inclusion of specimen No. 19 are much like those of No. 12, except that they have less quartz and more hornblende. The intrusive rock contains very little biotite and the inclusion has none at all. Inclusions from this part of the complex,—near the contact with volcanic rocks,—have been called metadacite. If this inclusion was originally dacite the plagioclase has been albitized. The texture is entirely metamorphic and it may just as well have been a sedimentary rock.

This specimen does not have as definite a foliation as does No. 12, but there is a marked lineation visible in the elongate hornblende crystals, and it is parallel in host and inclusion. A thin section cut normal to the lineation (strike of thin section, N 23°W; dip 55°SW; arrow points up dip, N 67°E) shows both cleavages in a majority of the hornblende grains, indicating that they are elongate parallel to the c-axis. No fabric diagram was prepared from hornblende.

An orientation diagram was prepared from the quartz in each part of the thin section, Figs. 6 and 7. In each case there is a girdle normal to the lineation, indicating that the relation is the same as for specimen 12.

The specimens from Deer Creek (71 and 72) are quite different from those taken on Principio Creek. The intrusive rock (72) is a dark gray "pudding granite," with white blebs of quartz and albite up to half a centimeter in diameter. It is difficult to classify most of these rocks, because not only texture, but also mineral composition have been changed since intrusion. The most obvious change is the development of albite porphyroblasts, but much of the quartz is either secondary, or has been recrystallized, and some of the mafites may be secondary. On the basis of the present mineral composition this intrusive rock is (after Johannsen) a sodaclase-granodiorite. If the albite has replaced more basic plagioclase the rock was originally a normal granodiorite; if it has replaced potassium feldspar the rock may have been a hornblende granite.

The inclusion (71) is a fine-grained, dark-gray rock that looks, in the hand specimen, much like the "groundmass" of 72. In thin section the mineral composition is seen to be much the same except that there is much more hornblende and somewhat less quartz and feldspar. These inclusions have been called "gabbro." They are not gabbro now but may have been originally, if all the quartz is secondary and if the original feldspar was labradorite.

It is not necessary, however, to decide what these rocks were, or even what names should be given them now, in order to accomplish the present purpose, which is merely to compare fabrics of host rocks and inclusions.

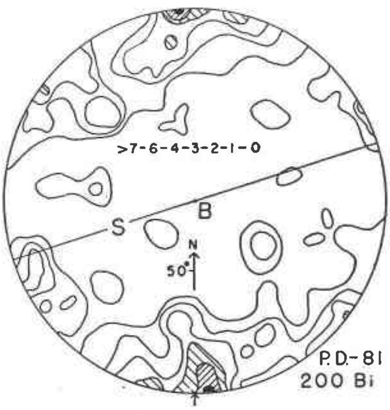


FIG. 10. Poles of 200 biotite flakes from the more acidic facies of the intrusive rock exposed below Conowingo Dam.

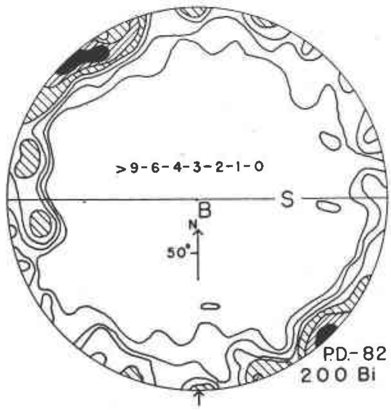


FIG. 11. Poles of 200 biotite flakes from an inclusion of quartzite in the intrusive rock of Fig. 10.

Specimens 71 and 72 appear almost structureless in the field, but there is a faint linear structure. Thin sections were cut normal to this lineation and Figs. 8 and 9 show biotite diagrams from intrusive and inclusion respectively. Each shows a partial girdle normal to the lineation, but the maxima do not coincide. This indicates, again, that the two have been affected by the same deformation after intrusion, but that response was along slightly different *s*-planes in the two rocks.

Immediately below Conowingo Dam the rocks are well exposed in the river bed at low water. Hershey[4] has prepared a detailed map of this area showing three different intrusive rocks, an older amphibolite and a series of sedimentary schists. An inclusion of the sedimentary rock (82) and a piece of the adjacent "granodiorite" (81) were collected for the purpose of comparing the fabric of an inclusion of known sedimentary origin with that of the enclosing rock.

[4] *Maryland Geol. Survey*, **13**, Pl. XI.

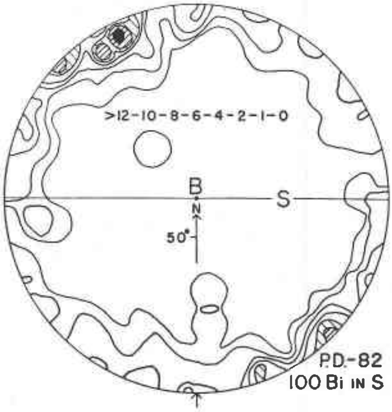


Fig. 12. Poles of 100 biotite flakes lying in the *s*-plane of the inclusion of Fig. 11. Figs. 12 and 13 are the partial diagrams that were added together to give Fig. 11.

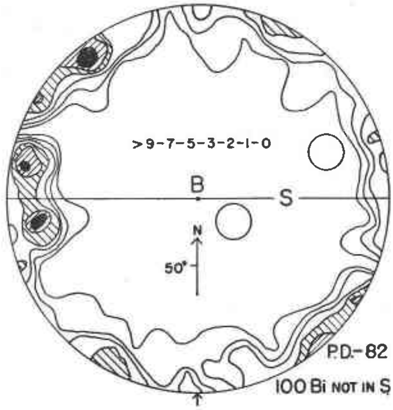


Fig. 13. Poles of 100 biotite flakes lying between the visible *s*-planes of the inclusion of Fig. 11.

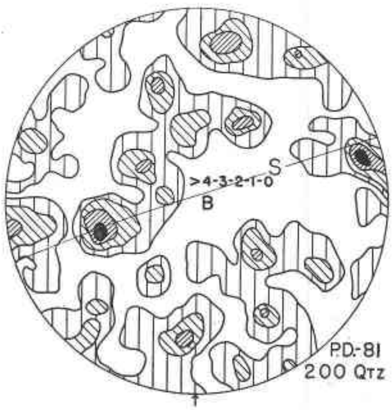


Fig. 14. 200 quartz axes from the intrusive rock below Conowingo Dam. Same thin section from which Fig. 10 was prepared.

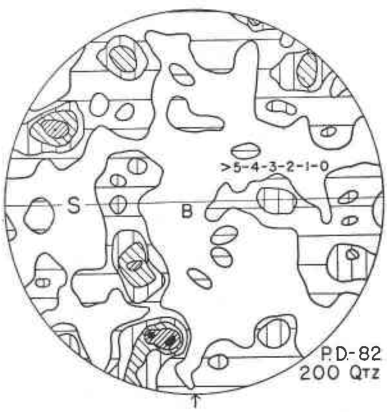


Fig. 15. 200 quartz axes from the inclusion from which the diagrams of Figs. 11 to 13 were prepared.

The inclusion is a quartzite with well-developed parting along closely spaced planes (2 to 3 mm.) containing mica. These planes may be the original bedding, but there is no independent evidence that they are. The intrusive rock is light creamy-gray and moderately fine-grained. It is high in quartz and has biotite as the dark mineral. It may well have been a granite before albitization took place. There is a rough megascopic foliation approximately parallel to one side of the inclusion. This is the s-plane indicated on the diagrams (Figs. 10 and 14) and it does not correspond with the position indicated by the micas.

Nor is the maximum in the biotite diagram from the inclusion, Fig. 11, normal to the megascopic s-plane. In this case it is easy to see in the thin section that the mica flakes lying in the s-plane are not parallel to it. This is clearly shown in Fig. 12, which is a selective diagram prepared from biotite flakes lying in the s-plane. Another selective diagram prepared from the biotite flakes lying between the s-planes, Fig. 13, shows a second (double) maximum almost normal to the megascopic s-plane. This appears to indicate the existence and activity of another set of s-planes. An s-plane, in the position of the one indicated by the secondary double maximum, is such that it could readily explain the asymmetry of the principal maximum of the non-selective diagram with respect to the megascopic s-plane.

This may also be the explanation for the asymmetry of the biotite diagram from the intrusive rock, Fig. 10, with respect to its foliation. At any rate, the mica fabrics in the two rocks are very similar, and they have a common B-axis.

The correspondence is less perfect between the quartz diagrams, Figs. 14 and 15. In each, however, there is a decided minimum around the B-axis (as determined by the mica) and there is a girdle roughly normal to this axis.

As is indicated above, this study is not intended to be a detailed study of any one region. Not enough field work has been done in either area to make feasible any attempt at comprehensive interpretations. In the case of the Port Deposit rocks, however, the few fabric diagrams that have been prepared all point in the same direction and it may be well to call attention briefly to this tentative interpretation. In each case studied, the fabric of the inclusion is essentially identical with that of the host.

This identity of fabric, together with the completely metamorphic texture of all the rocks, suggests that the primary structures in all the rocks have largely been obliterated and the foliations and lineations are now largely secondary metamorphic features. Where the original s-planes (foliation in igneous rocks and bedding in sedimentaries) were in the proper zones they may have been preserved and even emphasized by later motions. It is difficult to see, however, how the lineations common to host and inclusions can be other than secondary, superposed structures.

Uncle Sam Porphyry

It has been suggested that it is possible for an intrusive rock to impart its fabric to an inclusion by continued movement after incorporation of the inclusion, but before final solidification. In order to give full consideration to this possibility it was necessary to study an igneous intrusion, with inclusions, that had not been deformed after solidification.

Professor James Gilluly suggested that the Uncle Sam porphyry would be a compact unit for such a study. It intrudes rocks ranging in age from pre-Cambrian to Mesozoic, but in the Tombstone district it is in contact principally with quartzite and limestone of the Bisbee group. Figure 16 is a sketch map modified from Butler, Wilson, and Rasor[5] showing the general relationships. Tombstone lies just off the northeast corner of the map, half a mile to the east.

A preliminary field study indicated to Gilluly and Cannon that the porphyry might have been intruded along a thrust fault dipping some 30° to the west. They suggested that a statistical study of the orientations of platy inclusions and of their relations to the contacts might provide a definite answer. The actual contact is exposed in very few places and in these it dips 60–75° to the west, as do the nearby shear zones in the porphyry.

The orientations of all the inclusions measured could not be plotted on the map without using an impracticably large scale, but a spherical projection of the poles of the platy inclusions and of the contacts shows the relations clearly. In Fig. 17 the dots represent poles of the inclusions, and the small circles are poles of the contact surface at the various points where the orientation could be determined. (Some of these are from the area outside of the area shown on the map.) The circles are numbered and the numbered dots (with vertical lines) are poles of inclusions collected at, or near, corresponding contact exposures. The unnumbered dots with vertical lines represent poles of inclusions collected near contacts where the attitude could not be determined. A glance at the projection shows that there is no significant preferred orientation of the platy inclusions. Even near the contacts there is slight tendency for inclusions to lie parallel to the contact surfaces, there being only 5 out of 21 inclusions measured near contacts that are within 20° of parallel to the contact surfaces. Two of the inclusions stand almost normal to the contacts, and two others make angles of over 60°, the average being 40°.

[5] Butler, B. S., Wilson, E. D., and Rasor, C. A., Geology and ore deposits of the Tombstone District, Arizona: *Univ. of Ariz. Bull.*, **9**, No. 1, Plate III (1938).

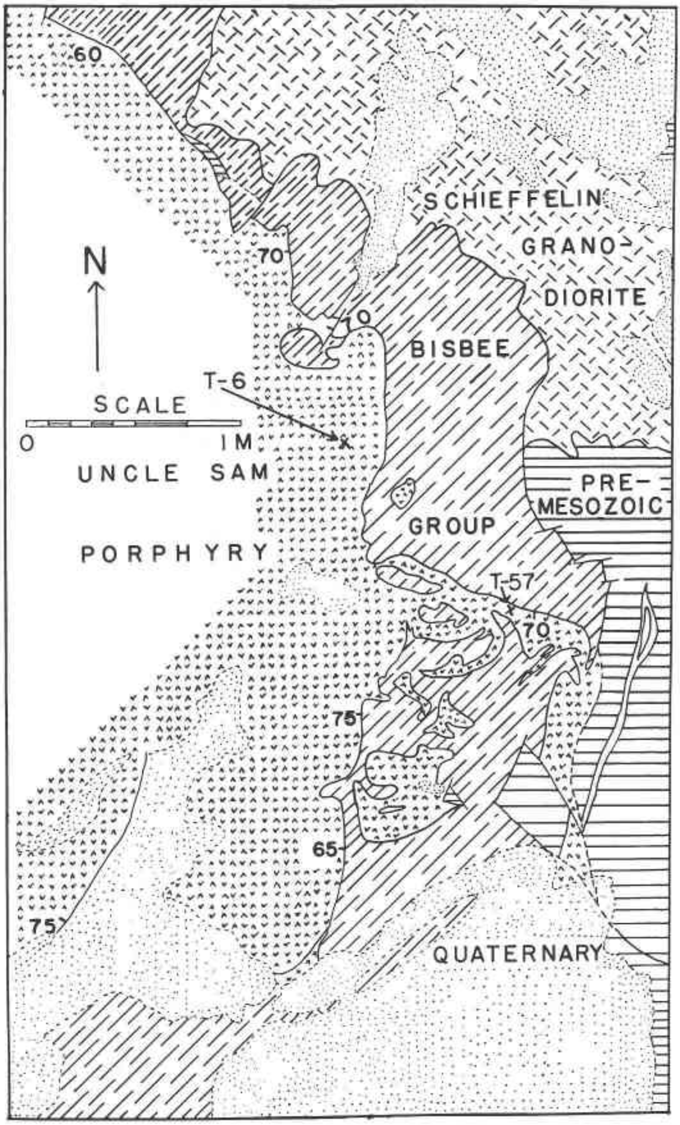
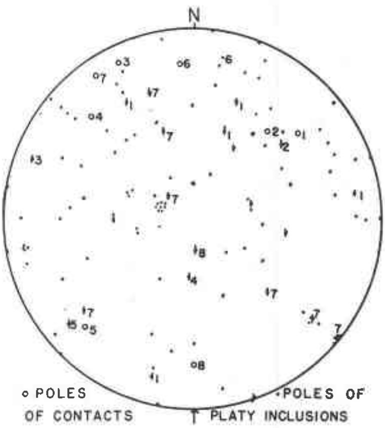


FIG. 16. Sketch map showing the eastern contact of the Uncle Sam porphyry in the Tombstone, Arizona, area. Modified after Butler, Wilson, and Rasor.

At each outcrop where inclusions were collected or measured the joint systems were measured. Prominent joint systems were also measured in other outcrops where inclusions were absent. It was thought that the attitude of the joints might possibly indicate something concerning the floor of the intrusion. The projection of the poles of the joints (Fig. 18), however, shows a more or less random distribution of the joints from vertical down to a dip of about 45°. Gilluly[6] points out that the flatter



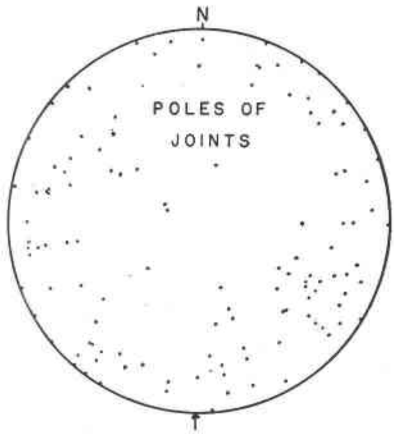


FIG. 17 (left). Equal area projection on a horizontal plane of the poles of the platy inclusions from the Uncle Sam porphyry. The poles of the contact surfaces that were measured are also shown. The numbered poles are of inclusions that lay near contacts having the same numbers. The poles through which lines have been drawn, but which are not numbered, are of inclusions that lay near contacts whose attitude could not be measured.

FIG. 18 (right). Equal area projection on a horizontal plane of the joints measured in the Uncle Sam porphyry.

joints are likely to form weathered surfaces and hence not be measured as joints. In the absence of quarries, or measurements in actual mine shafts, the steep joints are over-emphasized. Therefore, Fig. 18 does not give a true statistical picture for all the joints, but it does show the absence of well-defined systems of joints related to a shallow floor.

The detailed study of the inclusions and of the jointing does not confirm the presence of a thrust fault along which the porphyry was intruded.

The porphyry is a medium gray rock with abundant small phenocrysts (up to about 3 mm. in diameter) in a very fine groundmass. Neither foliation nor lineation is apparent. For this reason all the thin sections were cut in a horizontal plane and the orientation arrows on the diagrams point north.

[6] Oral discussion.

The inclusions in the Uncle Sam porphyry are principally shale, limestone, and quartzite. The quartzite inclusions are the only ones in which a direct comparison of mineral orientation with that in the porphyry is possible. Quartz diagrams were prepared from three of these quartzite inclusions and from the adjacent host rock.

There is no point to discussing the individual diagrams, because they bear no apparent relation either to structures in the intrusive rock or to the flat surfaces (=bedding?) of the inclusions. Figures 19 and 20 are quartz diagrams from an inclusion and the adjacent porphyry respectively. The diagrams are not at all similar; the principal maximum of the diagram from the porphyry coincides with the largest minimum in the other diagram.

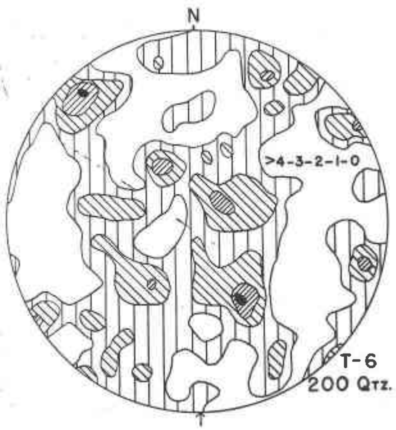


FIG. 19. 200 quartz axes from a quartzite inclusion in the Uncle Sam porphyry.

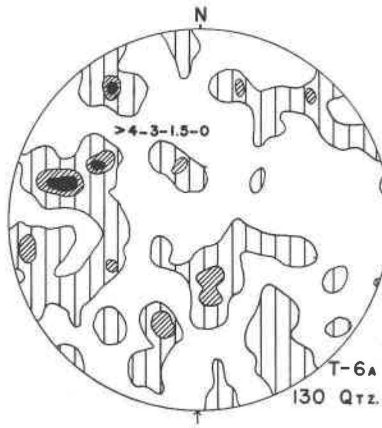


FIG. 20. 200 quartz axes from the porphyry adjacent to the inclusion of Fig. 19.

Figures 21 and 22 are from an inclusion and porphyry taken at another outcrop and show no better correspondence. The two inclusions from which the diagrams of Figs. 19 and 21 were prepared are comparatively large (3×4×6 cm. and 8×15×20 cm.); in one of the thin sections of porphyry (T-57*a*) there is a cross-section of a small quartzite inclusion, its greatest diameter being less than 4 mm. There has been enough reaction so that the boundary between the inclusion and porphyry is not sharp, being apparent only by the predominance and equigranularity of quartz in the inclusion, yet the quartz fabric (Fig. 23) has not been affected and shows no more correspondence to that of the porphyry than does that of the large inclusion.

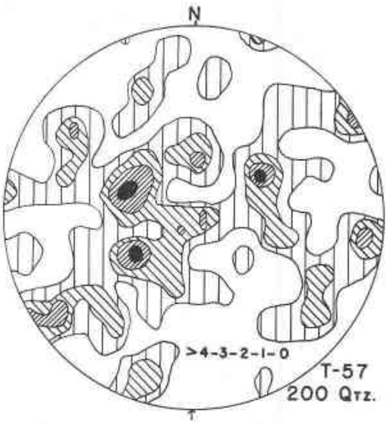


Fig. 21. 200 quartz axes from another quartzite inclusion in the Uncle Sam porphyry.

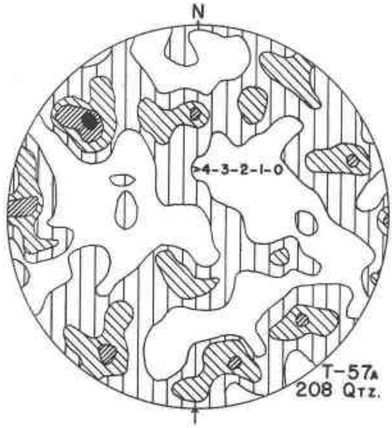


Fig. 22. 200 quartz axes from the porphyry adjacent to the inclusion of Fig. 21.

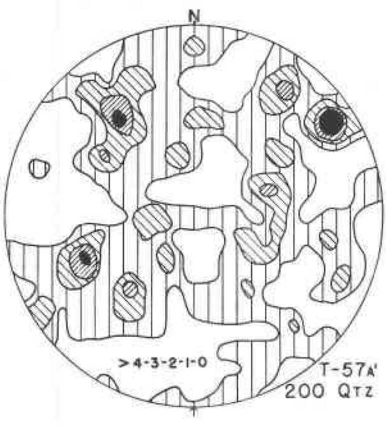


Fig. 23. 200 quartz axes from a small quartzite inclusion in the thin section from which the diagram of Fig. 22 was prepared.

For this intrusion, then, the fabric of the xenoliths is quite different from that of the intrusive rock. This must not be taken as a general rule for unmetamorphosed intrusions, however, until other examples have been studied. Inclusions incorporated in deeper-seated intrusions would have a much better chance to be heated to the temperature of the magma before its final consolidation. The higher temperature, together with continued motion of the crystallizing magma, might change the fabric of inclusions and could conceivably make it almost identical with that of the host.

VAL VERDE TONALITE

The tonalite intrusions studied by Hurlbut[7] and Osborn[8] may be examples of the action of such deep-seated intrusions on included material. However, the depth of intrusion of these bodies is not known, and it is by no means certain that the inclusions are xenoliths.

Hurlbut bases his interpretation of the inclusions as xenoliths on mineralogical and chemical similarities between the inclusions and an older gabbro in contact with the tonalite, and differences between these

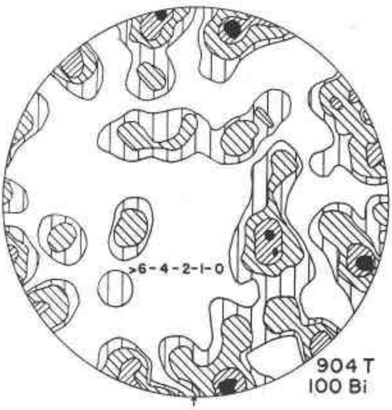


FIG. 24. Poles of 100 biotite flakes from the Val Verde tonalite. The diagrams of Figs. 24–29 were all prepared from parallel thin sections cut from a single hand specimen showing both inclusion and host.

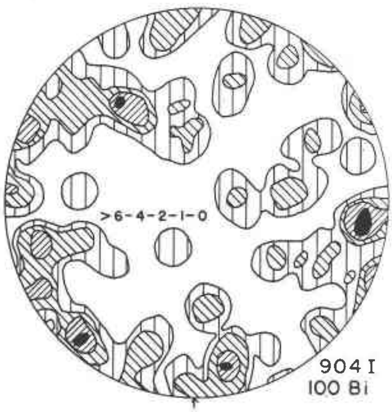


FIG. 25. Poles of 100 biotite flakes from an inclusion in the hand specimen from which the diagram of Fig. 24 was prepared.

rocks and the tonalite. However, these differences are such as would be expected if the inclusions are early segregations, i.e. "autoliths." Moreover, he points out that the mineral orientation is the same in inclusions and tonalite, but shows a *greater* preferred orientation in the inclusions than in the host. This relation might be expected in an autolith. In a xenolith the degree of preferred orientation might approach that of the host, but it is difficult to imagine its going beyond that of the host.

[7] Hurlbut, C. S., Jr., Dark inclusions in a tonalite of Southern California: *Am. Mineral.*, **20**, 609–630 (1935).

[8] Osborn, E. F., Structural petrology of the Val Verde tonalite, Southern California: *Bull. Geol. Soc. Am.*, **50**, 921–950 (1939).

Osborn found similar orientations of quartz and biotite in inclusions and host, but did not make a comparison between a given inclusion and the adjacent intrusive rock.

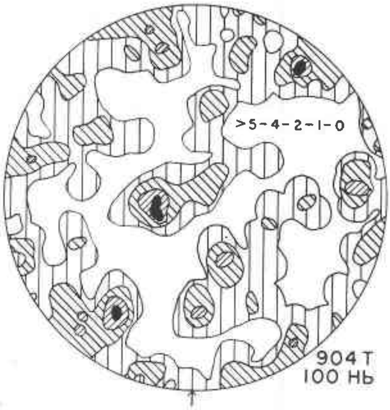


FIG 26. 100 hornblende c-axes from the Val Verde tonalite.

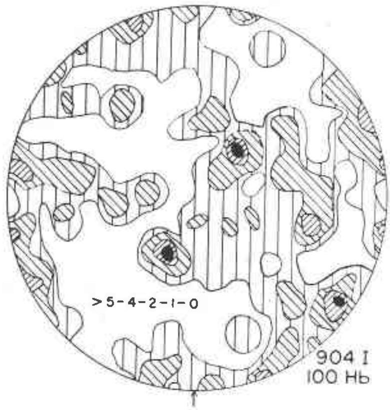


FIG. 27. 100 hornblende c-axes from an inclusion in the Val Verde tonalite.

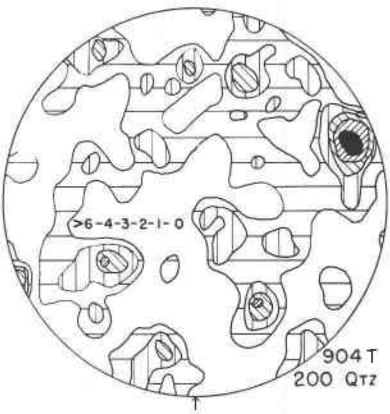


FIG. 28. 200 quartz axes from the Val Verde tonalite.

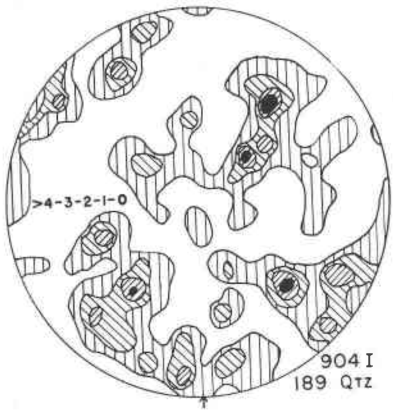


FIG. 29. 189 quartz axes from an inclusion in the Val Verde tonalite.

He was kind enough to lend some of his specimens for the present study, in which inclusion and host occur in a single hand specimen. In these specimens the foliation and lineation are but poorly developed and the same degree of preferred orientation is not to be expected as in more highly foliated specimens. Thin sections were cut normal to the rough lineation, and biotite, hornblende, and quartz diagrams were prepared from inclusion and host. The biotite diagrams, Figs. 24 and 25, are in good correspondence, each showing a girdle about the lineation. The hornblende diagrams, Figs. 26 and 27, are not entirely dissimilar, but are by no means identical. Perhaps measuring more grains would give a better picture, but the coarseness of the tonalite necessitated using two parallel sections in order to measure 100 hornblende crystals and it was not feasible to continue the measurements. It is possible, though unlikely, that the hornblende has two different crystal habits[9] in the rock, which would explain the maximum away from the lineation.

The quartz diagrams, Figs. 28 and 29, show even less correspondence, which is perhaps logical in view of the fact that the quartz is late and may have crystallized mostly after motion in the magma had ceased. Osborn, however, found the quartz fabric of inclusions and tonalite to be quite similar.

These diagrams do not give conclusive evidence either concerning the nature of the inclusions or as to the similarity of their grain fabric with that of the host. Nevertheless, it is considered worthwhile to put them on record as perhaps being more typical of the intrusions as a whole than are other published diagrams, because both Hurlbut and Osborn selected the most highly foliated specimens which certainly show an abnormal degree of preferred orientation.

Moreover, some of these diagrams may not give a true statistical result. For example, Hurlbut[10] gives a diagram of a-axes of plagioclase prepared from grains in which both cleavages are visible. A non-selective diagram of the plagioclase a-axes from the same section would give quite a different result. Dr. Hurlbut was kind enough to let me have the specimen from which the diagram was prepared. There is a large percentage of the grains in which both cleavages cannot be measured; out of 25 grains studied both cleavages could be measured in only 12 of them.

It is evident, therefore, that more work needs to be done, not only on these tonalite intrusions and their inclusions, but also on other intrusions concerning whose depths and conditions of intrusion more definite information is available, and concerning the nature of whose inclusions there is better agreement.

Conclusions

Of the following conclusions the first two are definite and fairly well established by the examples described; the third is tentative and

[9] See Larsson, W., Der Nygård Pluton: *Bull. Geol. Inst. Upsala*, **25**, 13–134 (1935), for an example of plagioclase and pyroxene in the same rock, each with two crystal habits.

[10] *Op. cit.*, p. 622 and Fig. 7, C.

must be established or modified by further studies of clearer examples:

(1) Xenoliths in an intrusion that has not been subjected to regional metamorphism retain their original fabric, which is in general quite different from that of the host. (Further studies may make it necessary to confine this conclusion to intrusions that were intruded high in the earth's crust and hence cooled rapidly, restricting magma movement after incorporation of the inclusions.)

(2) The fabric of inclusions in an intrusion that has been subjected to regional metamorphism conforms in type to that of the host, but shows minor differences dependent upon the original fabric of the inclusions.

(3) Autoliths tend to have the same fabric as the main part of the intrusive rock. The degree of correspondence is variable, however, and depends upon how strong a preferred orientation has been developed at a given point while the magma is "plastic."