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STRUCTURE OF THE LARGE PHENOCRYST PORPHYRY NEAR ARIZONA-SONORA DESERT MUSEUM

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INTRODUCTION

Through field work by Robert E. Colby (1958) the writer became acquainted with a number of small intrusions into Cretaceous(?) sediments near the Arizona-Sonora Desert Museum. Of these, two small masses with aphanitic matrix and large plagioclase phenocrysts (1, Fig. 1) form the subject of this paper.

Because of unusually good exposures, a handsome rock which lends itself to structural study, and the ready accessibility and proximity to the museum, it was considered worth while to investigate these intrusions and their surroundings in some detail. The 1959 class in Introduction to Geologic Surveying Methods, of the Geology Department, University of Arizona, made a topographic map, at 50 feet to the inch, of the locality; classes in Granite Tectonics have made some 1,200 measurements of crystal orientations in the porphyry and to this total the writer has added 100 more. Much of the writer's spare time for the past three years has gone into the detailed mapping. No petrographic or chemical work has been done, and the following is a report of progress only.

The intrusions may be reached downstream via the wash that leads westward from the Juan Santa Cruz picnic area, south of the museum. The wash is followed fairly directly for perhaps 1,200 feet, crossing brightly-colored exposures of gently- to moderately-dipping, coarse- to fine-grained clastic rocks—the Cretaceous Recreation red beds and volcanic rocks of Brown (1939). At this distance the wash turns abruptly south-southeast. Rounding the turn, one sees ahead pinkish gray sandstones with very steep dips and brick red to almost blood red siltstones and mudstones with steeply dipping bedding and cleavage. The steep cleavage appears to explain the sudden turn of the wash which continues as a small gorge along the strike. The large phenocryst porphyry has intruded the pinkish gray sandstones in the western wall of the gorge (Fig. 1).

THE INTRUSIONS

Besides the large phenocryst porphyry (1, Fig. 1) there seem to be at least three other intrusive masses in this little area. The rock in the small, irregular body just west of the northern end of the larger of the two lenses of coarse porphyry, consists of small, or medium-sized feldspar phenocrysts in a dense, light gray matrix with some small, dark, femic grains. This rock somewhat resembles the coarser porphyry, and may be only a finer-grained phase of it. The same may be true of the larger, elongated mass south of the coarse porphyry. The largest, poorly exposed intrusion along the western side of the area is a dark, rather highly crystalline rock of basaltic appearance.

It is thought that one or more strips of porphyry may separate the sedimentary outcrops in the southeastern part of the area, but although very limited exposures of intrusive contacts were observed at two places, the existence of the inferred porphyry strips is still questionable.

A nearly east-west dike of dark, fine grained, cleaved, probably igneous rock joins the westernmost intrusion to the southernmost and extends an unknown distance eastward (Fig. 1).

THE LARGE PHENOCRYST PORPHYRY

Appearance

The two masses of coarse porphyry are distinguished from other igneous rocks in the area by the presence of large (0.1 to 1.0 inch) plagioclase phenocrysts in a dense matrix that is brown or brownish gray when fresh. The packing, or spacing, of the feldspar crystals seems reasonably uniform. A count made on 12 square inches of surfaces near the eastern contact of the larger coarse porphyry lens (Fig. 2, Sketches 1a and 1b) yielded an average between 20 and 21 crystals per square inch. This average can be expected to vary somewhat from place to place, but unless visual estimate is in error, the variation is slight. Small, dark, femic mineral grains are also present.

Shapes and Sizes of the Intrusions

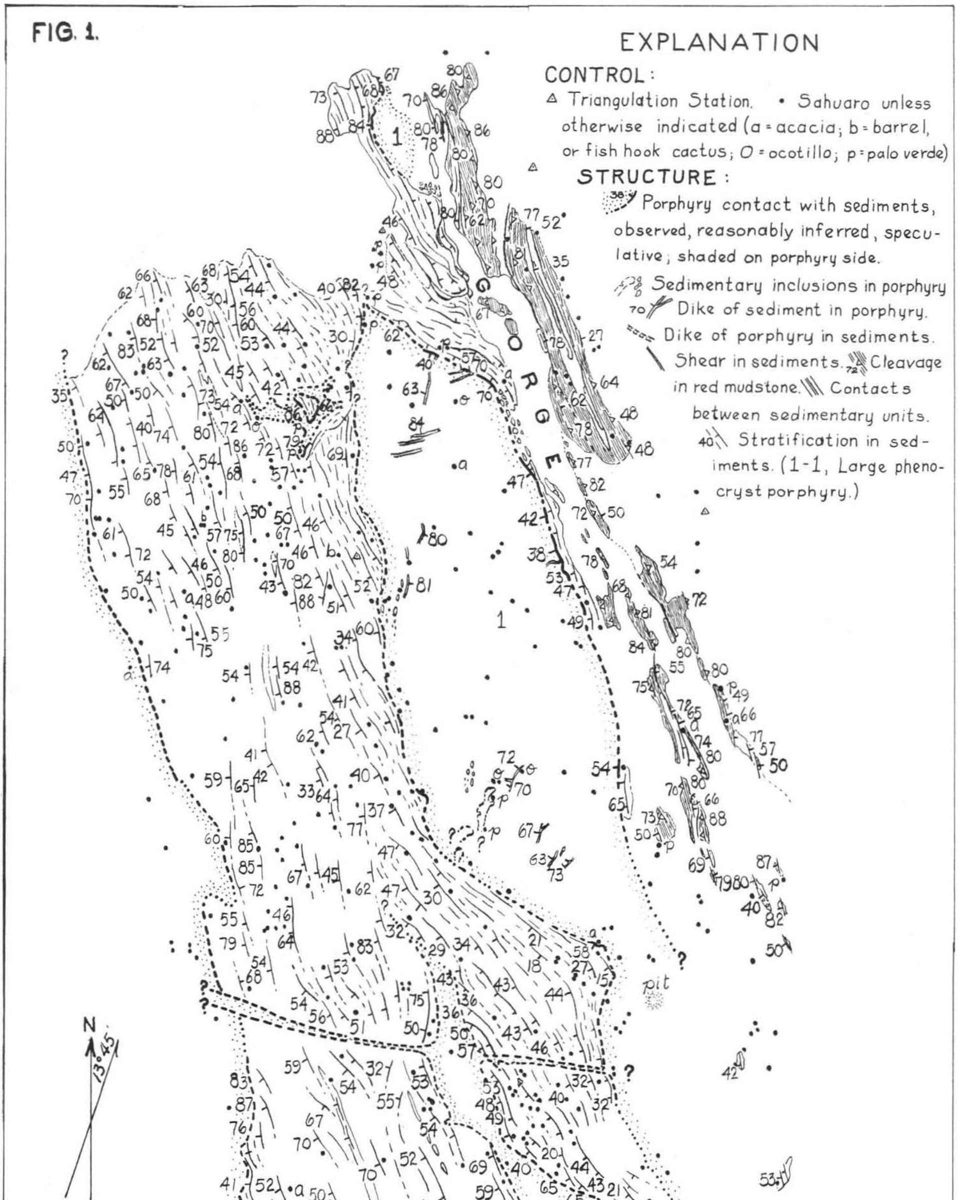
The smaller large-phenocryst body, in the northern part of the area appears to be lens-shaped, some 55 to 60 feet long and 20 or 25 feet wide. Because most of the contacts are concealed, the dimensions cannot be given more precisely and the northward extent could be much greater than supposed. The much larger mass to the south is at least 400 feet long and up to 125 feet wide. In shape, this body is also lens-like, or like a rhomb with short northeast and southwest sides. The southern end of this porphyry is not exposed, so the over-all length may be considerably greater than stated.

Contacts

Contacts of the intrusions with the sedimentary rocks are obviously discordant in detail, yet there is a definite over-all concordance (Fig. 1). Even in the case of the small northern mass it seems as though the sedimentary strata have been spread apart somewhat by the porphyry. In the case of the larger coarse porphyry lens this impression is very strong, yet the western contact sharply transects bedding at several places. The other intrusions also seem to have mostly concordant contacts. All of these boundaries seem to be sharp.

Two measurements show that the western contact of the small

FIG. 1.


EXPLANATION
CONTROL:
△ Triangulation Station. • Sahuaro unless otherwise indicated (a = acacia; b = barrel, or fish hook cactus; O = ocotillo; p = palo verde)
STRUCTURE:
Porphyry contact with sediments, observed, reasonably inferred, speculative; shaded on porphyry side.
Sedimentary inclusions in porphyry
Dike of sediment in porphyry.
Dike of porphyry in sediments.
Shear in sediments.
Cleavage in red mudstone.
Contacts between sedimentary units.
Stratification in sediments. (1-1, Large phenocryst porphyry.)
GORGE
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northern porphyry dips 68 and 84 degrees westward. All of the measurements that could be obtained on the dips of contacts of the large central porphyry lens are indicated (Fig. 1). Both eastern and western boundaries incline westward, and dips vary from 38 to 70 degrees. At most places the contact can be located within an interval of 3 feet, but at very few places can it actually be seen.

Locally, along the eastern contact of the larger porphyry lens, a schistose border, some 6 to 18 inches thick, composed of fine-grained porphyry with small, wafer-like sedimentary inclusions (Fig. 2, Sketches 2 and 3) separates the "normal" porphyry from its sedimentary wall rock. At one place (Fig. 2, Sketch 3) this schistose, porphyry-sediment mixture seems to have broken across the sedimentary bedding, guided perhaps by transverse fractures. In the only exposure seen of the western contact, this surface is irregular, knife-sharp, and dips 58 degrees to the southwest. The porphyry has no schistose border. It appears as though the rise of this large porphyry mass had intensely foliated a thin layer along the lower boundary or floor, whereas no comparable phenomenon was developed along the upper surface.

A surprising observation was made along the southeast contact of the irregularly-shaped little intrusion just west of the northern end of the big central lens. Approaching from the south, the northwest trending stratification of the sandstone is observed to be abruptly cut off a few feet from the intrusive contact by what appear to be faint sedimentary laminae that parallel the intrusion (Fig. 2, Sketch 4). The sandstone contains a few small, round cavities that seem to have resulted from the weathering out of soft, round sandy inclusions.

At first these structural relations seem mechanically impossible; especially so since the two directions of structure in the sedimentary rock are separated by an ill-defined contact, with no sign of brecciation. They appear more rational, however, if the sediment along the intrusive contact, perhaps water rich and expanded by steam, rose along the edge of the porphyry and therefore across its own stratification. In other words, perhaps a shell of wet sediments, heated by contact with the intrusion, was fluidized to the entrainment stage (Reynolds, 1954). If so, the apparent sedimentary laminae parallel to the intrusive contact would actually be flow laminae, and perhaps the soft, round inclusions are residuals of the original sandstone.

Another example of the same phenomenon was found at the northeast end of the same irregular intrusion (Fig. 2, Sketch 5). Just beyond the porphyry contact a jagged little shatter belt extends about N. 65 E. across the sedimentary bedding. Within the shatter belt and nearest the porphyry, the sandstone is faintly laminated E.-NE., and one irregular little area of intensely laminated, yellowish gray rock with many small, angular inclusions, as well as numerous cavities, is developed. This seems to represent a spot more intensely mobilized, with possibly some constituents derived from the porphyry. A petrographic study of this material might be very revealing. One cannot but wonder if the intrusion rose along a fracture or shatter zone, and if a certain amount of space were provided by the upward streaming of fluidized sediment.

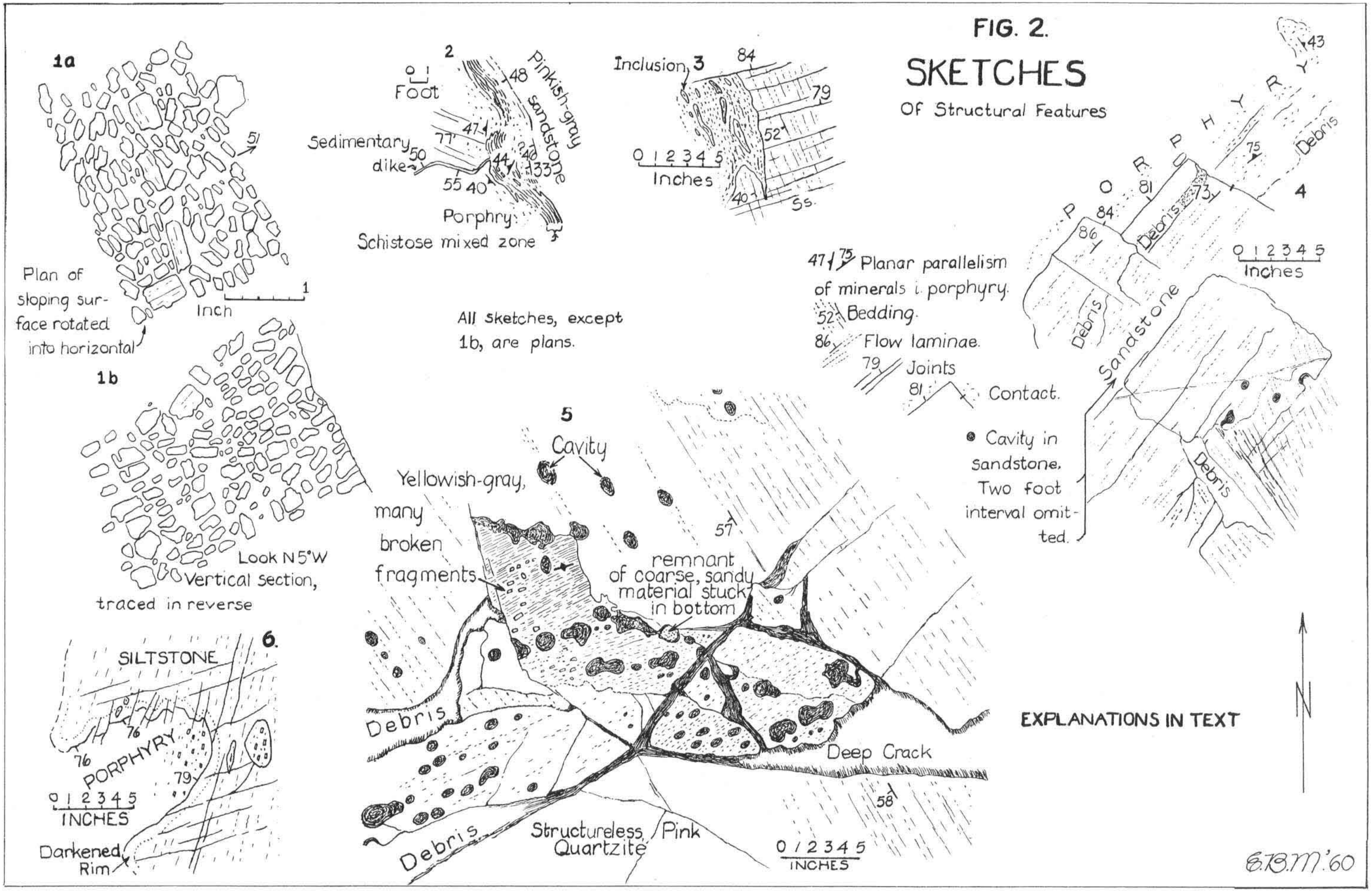


FIG. 2.

SKETCHES

Of Structural Features

Sedimentary Inclusions or Roof Pendants

The sedimentary inclusions in the porphyry (in some cases roof pendants?) are indicated where large enough to map (Fig. 1). Some of the larger sedimentary masses are thoroughly shattered and resemble piles of loose rubble, a condition which made the mapping somewhat uncertain. Some inclusions, therefore, may have been overlooked, but it is thought that the ones mapped are truly inclusions, or roof pendants, and not mere surface rubble. These features vary in size from perhaps 30 feet in length to mere crumbs.

The contacts between these little sedimentary masses and the enclosing porphyry were not well exposed, but many broken pieces that must have come from such contacts showed finely pitted surfaces, some with adhering porphyry. Some specimens show little pipe-like or pocket-like extensions of porphyry into the sediment. A large specimen in the writer's office consists of mottled, reddish sandstone with one fresh porphyry apophysis or inclusion, many small altered porphyry inclusions in several stages of break up and strew and fragments of feldspar crystals. Some of the finer of this debris is arranged in planar schlieren. Obviously, the sediment was once highly mobile, and it seems that solid (solidifying?) projections of porphyry have become detached, entrained, altered, disintegrated and their components strewn along the flow layers of the sediment.

At one place (Fig. 2, Sketch 6) a contact between porphyry and sedimentary remnant is well exposed. A narrow tongue of porphyry, perhaps guided by fractures, projects into the sediment. The contact is very steep and sharp, and is bordered on the sedimentary side by a narrow band that is slightly darker than the rest of the sediment, and lacks any trace of bedding. This narrow rim may be baked sediment, or it may represent a mobilized shell. Two inches beyond the end of the porphyry extension is a small, somewhat elongated oval patch of porphyry in the sediment. Perhaps this is a horizontal section of a nearly vertical pipe.

From the study of contacts and inclusions or roof pendants one gains the impression that the porphyry rose in some measure as a host of little pipes, tongues, and variously-shaped projections into the mobilized sediments. Many of these projections acted mechanically as solids and were incorporated into the fluidized wall or roof. This impression has to be added to the previous one that space for the porphyry was made by spreading apart the sedimentary strata.

Sedimentary Dikes

Dikes of red siltstone and of pinkish gray sandstone in porphyry were mapped wherever seen (Fig. 1). Most of these dikes strike north of northeast, or east of northeast, and the dips at most places are very steep. The widths vary from a quarter of the inch to perhaps 18 inches; widths of an inch or two are common (Fig. 2, Sketch 2). Most of the dikes narrow irregularly or abruptly, and very few can be traced for more than 10 feet. Some of them have been partially replaced by quartz and epidote.

The dike contacts are usually very sharp and they can also be highly irregular. The porphyry walls are strongly altered, with development of much epidote, for an inch or more from the dikes. No trace of bedding was seen in the sedimentary rock of the dikes, but the sediment may be very faintly laminated near and parallel to the walls.

When these dikes were first found, several theories of origin suggested themselves; but after the evidence of mobilization of the sediments was recognized, most of these theories no longer seemed reasonable. The presently favored theories of origin are as follows: As the porphyry fractured under stress, the mobilized sediment was flushed up into the cracks from below, or from the sides; or, as seems most probable, as vapor tension fell the overlying fluid mud sank into the opening fissures. Because the porphyry was still hot at the time, it became altered by reaction with the wet mud.

The irregularities in the dike walls are of some interest. Variously sized and shaped projections of porphyry seem to have pushed into the sediment. At some places this process has gone so far that a sedimentary dike appears to have been pinched in two, or only an irregular sedimentary film now remains of a former dike. It could be that the rigidity of the porphyry walls was locally reduced by absorption of water carried in (probably down) by the wet sediment. As a result, the dike walls may have flowed inward, and some of the sediment may have been forced upward again. This action appears to explain why the dikes do not persist along strike.

"Red Schlieren" in Porphyry

Near its contacts with red siltstone beds in the pinkish gray sandstones, the phenocrysts of the porphyry become somewhat smaller, and the matrix changes color from the usual brown to brick red. Further, at a few such places well-formed, unbroken feldspar crystals were noted in the red sediment adjacent to the intrusive contact. During a recent field trip of the class in Granite Tectonics it was noticed that, near the western contact of the big porphyry lens, some steeply westward dipping layers with brick red matrices were present in the porphyry. These red layers contained abundant large feldspar crystals. It seems reasonable to conclude that the red layers represent tabular red siltstone inclusions that were incompletely assimilated into the porphyry. In addition to the mechanical means of gaining space there appear to have been chemical processes that worked to convert sediment into porphyry.

Preferred Orientations of Plagioclase Crystals

The appearance of the plagioclase phenocrysts in the coarse porphyry is shown in plan and vertical section (Fig. 2, Sketches 1a and 1b) from near the eastern contact of the big lens. To a structural geologist accustomed to dealing with igneous rocks the evidence of a planar preferred orientation of the phenocrysts seems unmistakable, but to a beginner the structure is not obvious. For this reason it was decided to investigate the statistical basis of the visual impression of preferred orientation.

In 1958 and 1959 the class in Granite Tectonics was divided into parties of two students each, and each party was assigned a place to measure on a fairly plane surface the orientations of the longest dimensional axes of 100 plagioclase crystals. The surfaces were usually nearly horizontal, and yielded an analyses of strike; but in two places they were nearly vertical and gave information on dip. To avoid measuring the same crystal twice, each crystal was marked with a red dot as the attitude was taken. To avoid selection among the various orientations, the measurements were begun at a selected center and every plagioclase crystal was recorded, progressing outward from this center until 100 crystals had been measured. The area occupied by these crystals was therefore roughly circular, and the students were asked to record the diameter of this area, and to report the average length of the crystals. This information was checked against the average phenocryst packing in order to detect possible selection among the orientations. In one case questions confirmed a selection so revealed and the data were discarded.

The measured strikes, or dips, obtained at each locality, were plotted on rose diagrams in the manner described many years ago by Robert Balk (1932). Two of these diagrams confirmed the westward dip shown in Figure 2, Sketch 1b. Nine much-reduced diagrams, representing data from flat surfaces, are shown on Figure 3-I. There is statistically a preferred orientation of the longest dimensions of the plagioclase which trends generally north-northwest to northwest (Fig. 2, Sketch 1a) approximately parallel to the porphyry contact. Along the northeastern margin of the big porphyry lens, this preferred orientation swings to west-northwest, parallel to the contact.

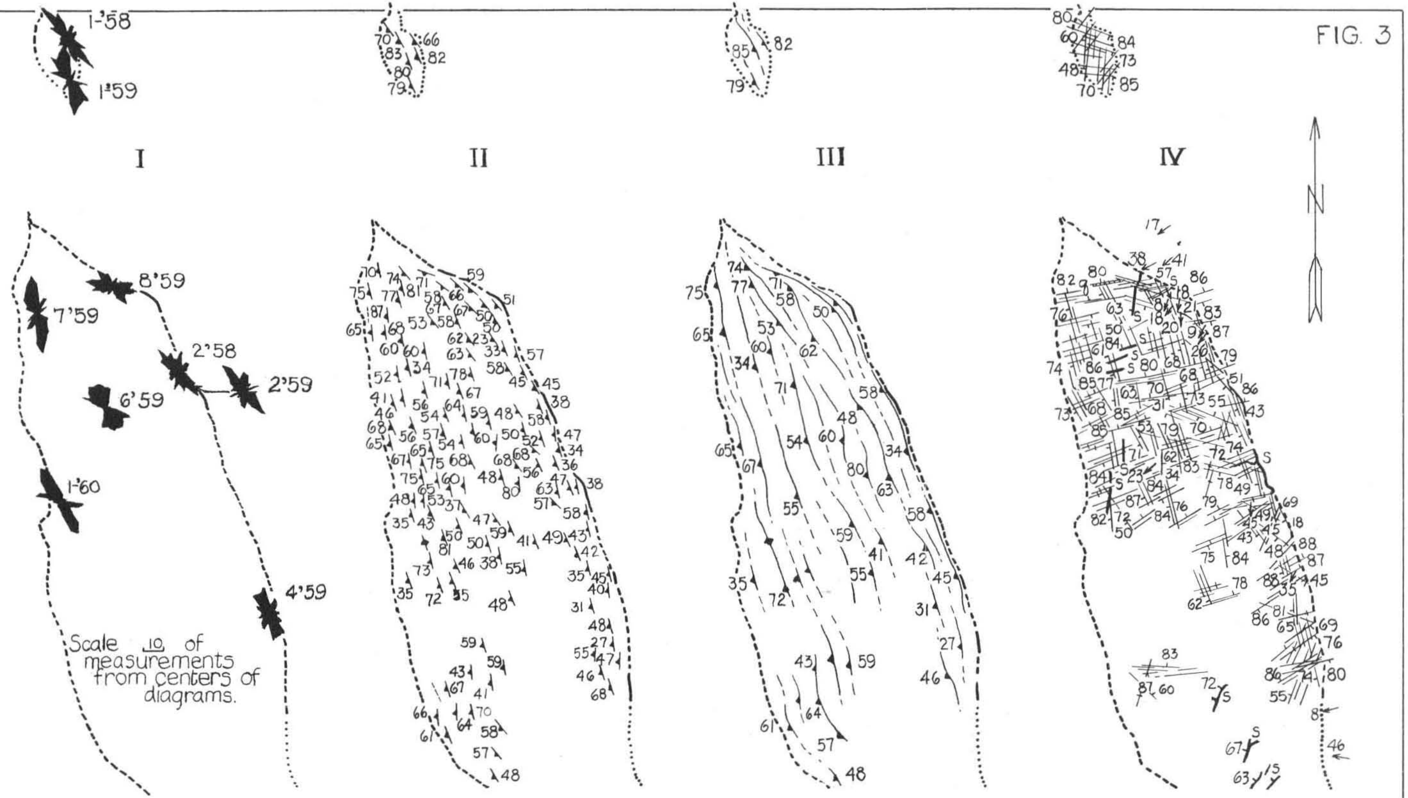
Two of the field parties that worked on the big porphyry lens obtained an apparently anomalous result: The rose diagrams indicated the strongest maxima oriented east-northeast. One of these parties appeared to have exercised every precaution against selection, therefore there may be locally a planar orientation of phenocrysts across the usual northwesterly one. This "anomaly" is not shown on Figure 3-I, but it may be significant that several of the plotted diagrams show a small east-northeast sub-maximum. It should be noted also that in every case several larger sub-maxima are present. The possible significance of these features will be discussed later.

The measurements based on visual impression of strike and dip have been plotted (Fig. 3-II) and they seem to be in reasonably good agreement with most of the statistical data. The reality of the planar structure, therefore, seems to be firmly established. So far, no linear (as distinguished from planar) arrangement of the phenocrysts has been detected. The strike and dip readings are also shown in generalized form (Fig. 3-III). They appear to support the earlier suggestion that the porphyry gained space by forcing aside the sedimentary walls.

The Fractures

Figure 3-IV represents an attempt to portray the pattern of steeper fractures in the porphyry. The breaks shown appear to be the most systematic ones. Many joints with variable strike, and many gently dipping joints, were not recorded. There may be doubt as to the primary nature of some of the illustrated fractures; that is, were all of them formed during or at the end of the act of intrusion, or were some formed long afterward?

FIG. 3



MAPS OF THE COARSE PHENOCRYST PORPHYRY

I Rose diagrams of measured crystal orientations **II** Measurements of preferred orientation **III** Flow pattern, generalized from the measurements **IV** Joints, 50 Quartz veins q, sedimentary dikes, 72 and striations (horizontal projection and plunge), 26.

SCALE 0 10 20 30 40 50 75 100 FEET

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In the big porphyry lens a fracture set that strikes east-northeast, and one that strikes north-northeast carry nearly all of the recognized sedimentary dikes, therefore must constitute a primary system. Much of the alteration in the porphyry is associated with this system. In the little, detached northern body of coarse phenocryst porphyry, only one set of this system, the north-northeast one, is present. Here these joints are tight; they contain no dikes and no alteration except thin red films.

A west-northwest joint set is common to both bodies of coarse phenocryst porphyry. Near the northeastern contact of the big lens, joints of this set displace, by several fractions of an inch, a sedimentary dike of the north-northeast set. The displacements, of course, are later than the dike, but the north-northwest fractures may be little or no younger than the dikes. They could, of course, be much younger than the dikes.

A northwest joint set, or possibly two sets enclosing a very small angle, seems to be restricted to the big porphyry lens. These fractures are approximately parallel in strike to the planar arrangement of the feldspar phenocrysts, but the fractures as a rule dip much more steeply. Further, the steep fractures may dip either to east or west. Expressing the lack of any downwardly concave arch of the planar orientation of the phenocrysts, the dips of the northwest, longitudinal joints do not form an upward-opening fan. Such arching, and such a fan of longitudinal joints, were expected, but they do not exist at the exposed level.

Northeast-trending joints appear in the lesser porphyry body and along the southeastern contact of the larger one.

Striations (Fig. 3-IV) were found on some of the joint surfaces, both in the porphyry and in the adjacent sediment. These striations plunge everywhere into the intrusion and appear to indicate either an upward and outward expansion of the intrusive core or an inward and downward shrinkage. At one place (Fig. 3-IV, near the southeast contact of the big lens at the west-northwest-plunging arrow with the plunge value of 46 degrees) it is possible to see features that may decide this alternative in favor of expansion. In an old prospect pit about 20 feet east of the porphyry contact, steeply eastward-dipping beds of red siltstone and light gray sandstone are displaced by several parallel, approximately 50 degree westward-dipping fractures. At least four of these fractures, which are little thrust faults with striated surfaces, are exposed in the south wall of the pit. The largest displacement measured was about 2 inches. Apparently, inward-dipping plates of sediment have been pushed outward from the intrusion along fracture surfaces. Similar features were looked for on the western side of the intrusion, with no success. Because the striations were found on west-northwest and northwest joints, it seems that the fractures in these directions are also primary.

DISCUSSION

Origin of the Preferred Orientation of the Phenocrysts

The two classic examples of phenocryst orientation in intrusive rocks are in the granite of the Riesengebirge in Silesia (Cloos, H., 1925) and in the sanidine trachyte of the Drachenfels (H. Cloos and E. Cloos, 1927) in the Siebengebirge on the Rhein. These examples were interpreted in the field as results of crystal orientation by the laminar flow of a viscous liquid held back along its borders by friction with the solid rock walls. The flow patterns developed were arches, or domes, in vertical section; round or elongated cylinders in plan.

The field interpretation was tested by W. Riedel (1929) who presented a mathematical theory of this orienting mechanism and performed a series of confirmatory experiments. The deformation of the flowing liquid was analyzed in two dimensions and was visualized in terms of an imaginary circle of which the originally equal radii lengthen and shorten. The deformation at any given time was represented by the ratio of the length of the longest radius to that of the shortest radius of the resulting ellipse. Solid inclusions, such as crystals, were assumed to have had originally random orientation. As the deformation progressed, an increasing number of these inclusions would rotate toward parallelism with the longest radius of the deformation ellipse. As a result of calculations Riedel presented a graph showing the relative number of originally random solid particles that would be parallel, or nearly parallel, to the longest radius at various stages of the deformation. Smooth curves rise from the minimum parallel to the shortest radius to the maximum parallel to the longest radius. As deformation increases, and as the ratio of the lengths of the longest and shortest radii grows, the curves progressively steepen toward the longest radius and flatten toward the shortest one. The experiments confirmed the results of the calculations and also reproduced the over-all flow patterns of the natural examples.

When the 900 best measurements of strikes of the longest dimensions of plagioclase crystals in the porphyry are plotted as a curve on Riedel's graph, this curve fits surprisingly well into the series of curves drawn by Riedel. According to the curve based on the orientations of the plagioclase phenocrysts, the porphyry has in plan so deformed that an imaginary circle has become an ellipse with longest radius, parallel to strike, slightly less than two and one half times the shortest. This is an astonishingly small deformation. When the 200 measurements of dimensional orientation made on nearly vertical surfaces are treated in the same manner, the resulting curve is irregular but it seems to indicate that in vertical section nearly at right angles to the strike of planar parallelism an imaginary circle in the porphyry has become an ellipse with longest radius, parallel to dip, somewhat more than two and one half times the shortest radius. In other words, an imaginary sphere of porphyry has been flattened into a "biscuit" in the plane of preferred orientation. The "biscuit" seems to have been very slightly elongated parallel to the dip, but in view of the relatively few supporting data this elongation, slight at best, may not exist at all. This condition, flattening with little or no elongation in any one direction, seems to explain the failure to detect any linear arrangement of the phenocrysts.

Deformation entirely, or almost entirely, by flattening is a strange result if the porphyry rose as a viscous liquid into the sediments and was retarded by friction with the walls. The lack of domes, or arches, in the arrangement of planar structure has been mentioned. The presence in or on the porphyry of masses of sediment that may be remnants of a former roof suggests that the porphyry never extended far above the presently exposed level; therefore it is not likely that the present exposures are situated too deeply in the conduit to reveal the arching structure. The small northern mass, which must be very near the level of its former roof, has about the same structure as the big lens.

If, in spite of this evidence, it is supposed that erosion has removed the upper, dome-like portion of the porphyry structure, and that the material did flow upward as a viscous melt, the present exposures should reveal a pattern of planar parallelism resembling a series of nested, flattened cylinders. It will be recalled that orientation measurements by two of the field parties did reveal a northeasterly maximum. At a few places it was thought that a faint northeasterly parallelism could be detected by eye and successive attempts were made to trace this elusive parallelism into the stronger northwest structure, thereby revealing the expected cylindrical pattern, but every attempt failed. The most obvious pattern of preferred orientation is as shown (Fig. 3-III). No flattened cylinders were ever formed unless at the places where the cylinder walls bent most sharply the feldspars have been reoriented. Further, the theory of crystal orientation by the planar flow of a liquid does not account for the rather prominent sub-maxima in the rose diagrams (Fig. 3-I).

Two papers by Oertel (1955a and b) appear to throw much light on the origin of the planar preferred orientation of the porphyry. Field observations on a Scottish granitic intrusion revealed at some places a single direction of planar parallelism, at others two such directions that crossed one another at angles ranging from 90 degrees to very small. Experiments showed that in the deformation of a solid by compression two sets of shear planes formed which enclosed angles of 10 to 15 degrees if the solid was highly plastic. The bisectrix of this acute angle was perpendicular to compression, or to tension in tension experiments. As such a plastic solid continued to deform with the further development of these earliest shear planes, its physical properties changed so that new sets of shears were formed having the same symmetry relation to the deforming stress, but enclosing acute angles ranging toward 90 degrees. When a solid with lower plasticity and higher elasticity was chosen in the first place the angle between the first formed sets of shear planes was large. Applying these results to the structures observed in the Scottish granites, Oertel concluded that the planar orientation of crystals in the granites was brought about by the crystallization of minerals along the shear planes of a solid that displayed varying degrees of plasticity from the highly plastic to the almost perfectly elastic. Observations that would lend some support to this conclusion were made many years ago by H. Phillipp (1936).

In the case of the coarse phenocryst porphyry it will be noted (Fig. 3-II) that the field measurements, based on visual impression, vary slightly to one side or the other of a mean direction, the bisectrix of the small angle between readings. This condition was generalized (Fig. 3-III) as small warps in the average strike of planar parallelism, but it could as well mean two nearly parallel directions of preferred orientation. According to Oertel (1955, p. 23) if two planes of preferred orientation lie within 25 degrees of each other it is almost impossible to distinguish them by eye alone and the impression is gained of one plane only. If these considerations apply to the coarse phenocryst porphyry, this rock acquired most of its preferred orientation of crystals while under compression (or tension, which does not seem probable) at right angles to the over-all strike and dip. Further, if the porphyry at the time of emplacement was a hot plastic body (glass with suspended crystals) as cooling progressed it would become less plastic and would gain elasticity, therefore new shear planes should develop which would enclose larger angles, but fewer crystals than formerly would grow along these later shears. In this way perhaps the sub-maxima of the rose diagrams can be explained.

Origin of the Fractures

A comparison (Fig. 3-I and IV) shows obvious similarities between the orientations of sub-maxima in the rose diagrams and trends of the fracture sets. Some of the students have mentioned that while making orientation measurements they observed many crystals oriented to some of the directions of jointing. The northwest-trending fractures, which may be two nearly parallel sets, seem to occupy some of the first formed shears to develop in the plastic stage of the porphyry. Because of the steepness of the fractures, however, the stress at the time the joints were formed must have been essentially horizontal. The west-northwest and northeast joint sets, which enclose a larger angle, may be along somewhat later shears that formed at a less plastic, more elastic stage. The north-northeast fractures may represent a system of shears of which only one set developed. In any case these joints were to be opened by tension because they now contain some of the sedimentary dikes.

The east-northeast set very nearly bisects the northeast and southwest angles of the other systems mentioned. It is thought, therefore, that the east-northeast fractures lie in the direction of greatest principal stress and are tension fissures. The fact that they contain some of the sedimentary dikes and are associated with most of the alteration would seem to favor an origin by tension.

There is an important element of uncertainty in this discussion of the origin of the fractures. This uncertainty relates to the possibility that some of the fracture directions are regional and that the fractures parallel to them were present before emplacement of the porphyry. In this case these joints would be "inherited" by the porphyry during or after emplacement. Too little is known about the structure of the surroundings to allow an evaluation of this factor, but observations suggest that fractures following the east-northeast direction were already present in the sediments before the porphyry was emplaced (Fig. 2, Sketches 3 and 6) and west-northwest fractures seem to have controlled to some extent the shape of the big porphyry lens. They surely controlled emplacement of the dike in the southern part of the area (Fig. 1). In any case, crystals could grow along these directions as shears parallel to them worked into the hot, plastic porphyry from the walls.

Emplacement of the Porphyry

If the above arguments are not greatly in error the large phenocryst porphyry was squeezed into place as a hot, plastic solid. The structure of the surrounding sediments is an anticline, asymmetrical and locally overturned to the east. The porphyry is the core of the anticline. This core may have been for a time the most plastic part of the fold; certainly it was the hottest part. Heat from this core, in conjunction with moisture in the sediments, seems to have caused the phenomenon of fluidization, and the small scale intrusive relations described above. It is thought that the amount of space gained by the porphyry in this way, and by the assimilation of the sediments as indicated by the "red schlieren" was relatively small, but no reliable measurement of the space so gained is available.

That the porphyry did rise, and was not formed essentially in place is strongly suggested by the position of this rock in the asymmetrical fold and by the apparent great thinning and relatively gentle dip of the pinkish gray sandstone along the eastern, overturned flank. This is where a thin, schistose border was developed in the porphyry along the contact (Fig. 2, Sketches 2 and 3). It seems that the core did actively rise and shear over the sandstone of the overturned limb. Friction along the contacts was not recorded in the internal structure because the porphyry core had already become a plastic solid, therefore could not yield as a viscous liquid.

The porphyry may have been squeezed upward from a much larger, cooling mass below, or possibly from a sill that intruded the sediments before they started to fold. The hot rock completed its cooling history in the core of the fold under stress from west-southwest. Here it developed several generations of shear systems as the elasticity increased. Fluidization and assimilation of the sediments were minor processes because the supply of heat was limited.

CONCLUSION AND ACKNOWLEDGMENTS

Whether or not the above sketch of a hot, solid igneous mass forced into place by tectonic stress will endure must depend upon the results of future studies. Mr. Charles Bock, a graduate student at the University of Arizona, is presently beginning a petrographic investigation of the intrusion. Much more could probably be learned about the structure of the porphyry by more precise macroscopic methods (Clark and McIntyre, 1951) or by the method of Sander (1930, 1948, 1950). The internal structures of the other intrusions in the area are as yet unknown; they may contain patterns that would be interesting for comparison with that of the coarse phenocryst porphyry. There is still much to be learned about the surrounding sediments.

It is hoped that small areas such as this one may become places for detailed structural and petrologic studies by graduate students. Through such studies we might gain new insight into some of our local geological problems. In any case, the well studied local areas make good localities for class field trips.

Sincere appreciation is expressed to Mr. R. E. Colby, who first reported these intrusions, to Mr. Edgar J. McCullough who supervised the preparation of the base map, and to those University of Arizona students who did the surveying and who made many hundreds of orientation measurements.

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POSTSCRIPT

During the time since the manuscript of this paper was submitted, Mr. Carol Halva, working in Professor Damon's laboratory at the University of Arizona, made some chemical studies of the coarse phenocryst porphyry. As a result of these tests, Mr. Halva informed me that the coarse phenocryst porphyry appeared to be identical with the "Turkeytrack" porphyry, which is distributed over a large area in southeastern Arizona.