FOLDS IN GNEISS BEYOND NORTH CAMPBELL AVENUE, TUCSON, ARIZONA

By

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INTRODUCTION

For the past several years the writer has taken classes in structural geology to study folds in gneiss in and near a cliff-walled ravine at the base of the Santa Catalina Mountains, about half a mile beyond the northern end of Campbell Avenue, Tucson. The locality is reached via a rough road that leads northward from the end of the pavement.

There are two reasons for publishing this paper. First, it seems wise, for the benefit of future students, to record and to attempt an interpretation of the features exposed at this easily accessible locality. Second, as a result of the structural survey, certain principles seem almost within grasp, which might be useful in a study of the overall structure of the Santa Catalina Mountains.

In order to present the structural features systematically to the classes, a rough structure plan was made of an area about 30 acres in extent, using a Brunton compass and pacing the distances. The data so obtained were used in constructing the maps (figs. 2 and 5). After this plan had been made, the class in Introduction to Geologic Surveying Methods, Department of Geology, University of Arizona, made an accurate topographic map of the area. The structure should be remapped, using the topographic plan as base and using a tape for additional horizontal control. Perhaps future classes in structural geology will accomplish this. Meanwhile, it is thought that with the aid of the foliation and lineation map (fig. 2), the fracture plan (fig. 5), the field sketches (figs. 1, 3, and 4), and the cross sections (fig. 6) a sufficient account of these structures can be given. It is hoped that in the future, students of structural geology will greatly extend the mapping.

THE ROCKS

Description

No petrographic study has yet been made at this locality, so the following is a field description only. The area should be a favorable one for petrographic and, perhaps, petrofabric study.

The principal rock is a medium- to coarse-grained cream- or ivory-colored granitic gneiss with rather sparse porphyroblasts(?) of potash(?)

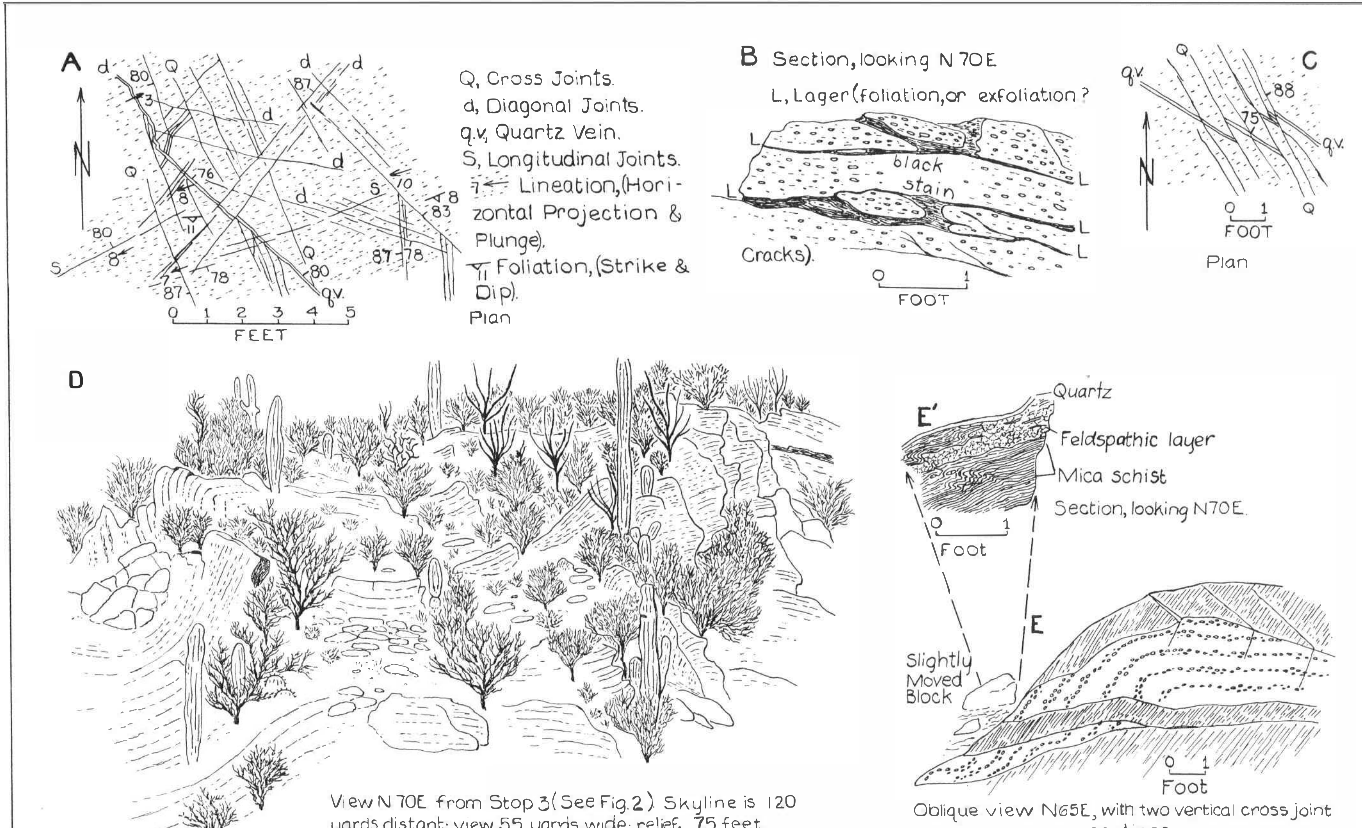

FIGURE 1.- FOLDS AND OTHER STUCTURE ELEMENTS.

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feldspar reaching half an inch in length. The other common and obvious minerals are quartz and muscovite. A dark mica, probably a member of the biotite group, is locally present, and it may in part be chloritized. Small yellowish-brown spots and local more extensive stains result from oxidation of some iron-bearing mineral.

The gneiss varies somewhat in appearance from place to place. Locally the color darkens because of the presence of dark mica, and at some places the grain of this dark phase is obviously finer than the average. There are also intercalated, very dark, greenish-brown layers of coarse-grained apparently biotite schist. This sombre rock, however, is decidedly minor in amount.

A few small pegmatitic layers or lenses, some with muscovite "books" as much as 2 inches across, and occasional narrow veins of white quartz complete the lithology.

Age and Possible Genesis

Apparent ages of the gneisses in the Santa Catalina and Rincon Mountains, obtained from muscovite and biotite by the K-Ar method, range from 24.8 m.y. to 29.5 m.y. and average 26.8 ± 1.7 (s.d.) according to Damon and others (1963, p. 116). This suggests that the gneisses first became cool enough that appreciable loss of argon ceased in Tertiary—upper Oligocene (Culp, 1961)—time. A radioactive age determination on zircon from the gneiss at the Hitchcock Memorial on the Mount Lemmon road, made by Edward Catanzaro (1963) using the isotopic lead method, yielded an age of 1,650 m.y., which suggests that a very ancient material has been reheated in Tertiary time. At present, the best guess seems to be that this ancient original material was the sequence of sedimentary and volcanic rocks first metamorphosed during the older Precambrian Mazatzal orogeny (Wilson, 1939) to form the Pinal Schist.

If the gneiss was formed from Pinal Schist, then three possible processes, or some combination of them, can be visualized: The schist may have been injected lit-par-lit by granitic magma; one may have to deal here with a rather extreme case of metamorphic differentiation; or perhaps the schist was metasomatized or migmatized. If the latter case applied, then the coarse-grained dark-mica schist may be remnants, perhaps enriched in iron and magnesium, of the original material—the paleosome (Wegmann, 1937, p. 307). The lighter colored gneisses then would include the added materials—the neosome. At present the writer is inclined toward this third interpretation, but it must be emphasized that any interpretation is speculative because the supporting data are far too few.

STRUCTURAL INVENTORY

South of the ravine, at the place indicated (fig. 2), a nearly horizontal, well-exposed, flat area of gneiss affords a good opportunity to see, within the limits of a few square yards, most of the smaller structure elements of the gneiss. At this place students are asked to measure and map these elements (fig. 1A) and to compile a structural inventory (table I).

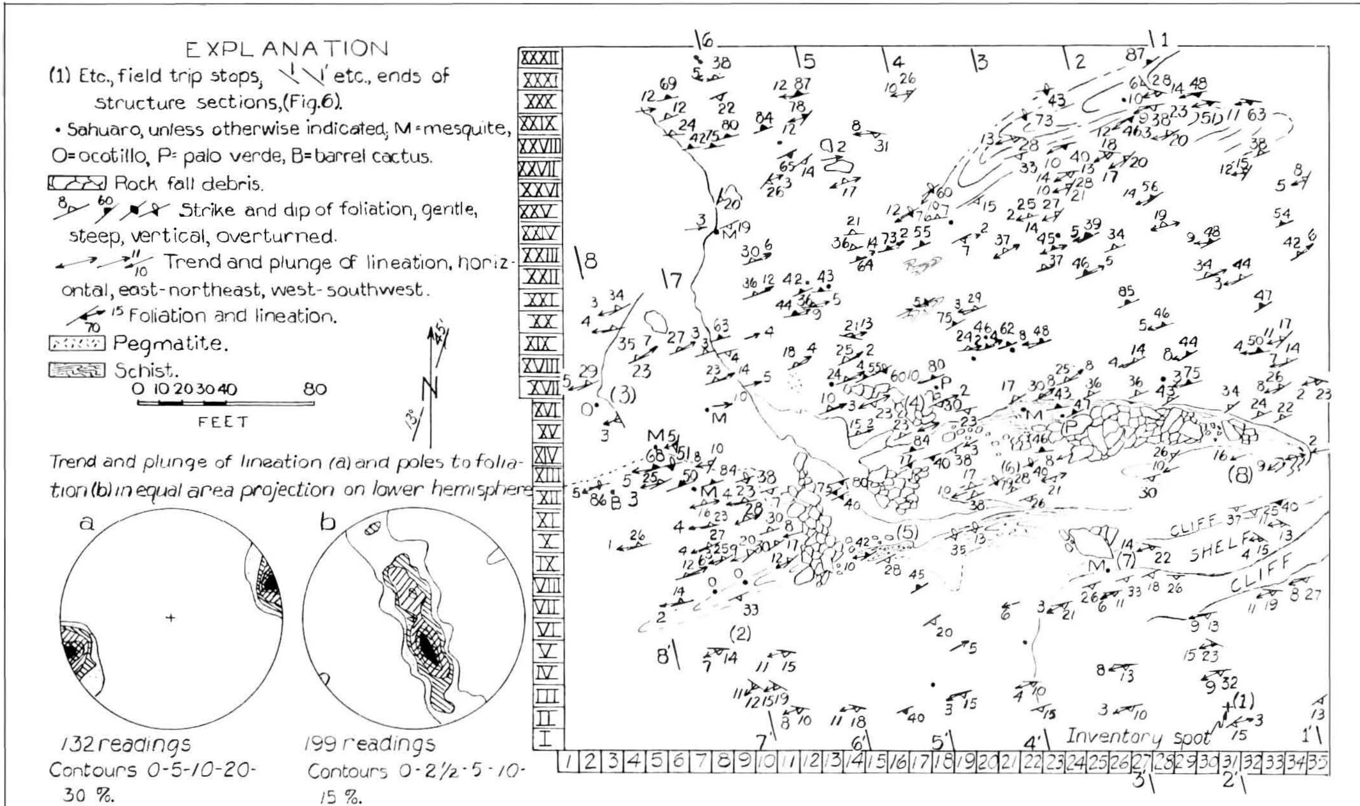

FIGURE 2 MAP AND FABRIC DIAGRAMS OF LINEATION AND FOLIATION IN FOLDS

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Arrangements and Minerals and Mineral Groupings

The oldest elements present are: (1) foliation, which here dips gently southward; and (2) lineation, which lies in the plane of foliation and plunges gently west-southwest or east-northeast.

The foliation is, at most places, not a definite layering; yet definite layers are locally present, giving a banded appearance to steep joint surfaces. Mica books, quartz, and the larger feldspars, which may average a third of an inch in length but rarely attain 2 inches or more, are oriented in planes. There is an observable tendency to develop quartz and feldspar augen, slightly flattened in the plane of mineral parallelism. The foliation, therefore, is in part at least a result of deformation, but the possibility is by no means precluded that this feature was overprinted on an original stratification. One aspect of the foliation is well exposed on a vertical cross-joint surface 25 feet east of the inventory spot (fig. 1B).

Locally, the foliation is accentuated by layers or lenses of pegmatite, 1/2 to 1 inch or more in thickness, that lie in the plane of mineral parallelism. Local lenses of quartz, as much as 3 inches thick, and extensive thin quartz sheets, some no thicker than a quarter of an inch, are also parallel to the foliation. The same is true of local thin or thick layers of dark coarse-grained mica schist. Finally, the foliation consists here and there of alternating layers or bands of relatively even-grained and porphyritic or porphyroblastic rock. Accordingly, the ease or difficulty of detecting this planar structure varies from place to place[1/].

A streaky linear parallelism of minerals and other features lies in the plane of foliation. Mica clusters, shaped like flattened spindles, reach a length of 3 inches, and there are local thin dark streaks of unknown composition as much as 6 inches long. Small pegmatitic or feldspar-rich mineral clusters are elongated parallel to the general lineation, and the same is true of individual quartz and feldspar augen. The surfaces of certain thin quartz sheets, or plates, parallel to foliation, are grooved parallel to lineation. The results of a few measurements of foliation and lineation at the inventory spot are shown on the little sketch map (fig. 1A).

1/ From the above description it is obvious that the term foliation is used here for a planar parallelism of minerals, bands, lenses, or layers in a crystalline metamorphic rock. This seems to approximate the meaning inherent in British usage, defined by Harker (1932, p. 203) following Darwin (1846, p. 141) as "a more or less pronounced aggregation of particular constituent minerals of the metamorphosed rock into lenticles, streaks or inconstant bands, often very rich in some one mineral and contrasting with contiguous lenticles or streaks rich in other minerals." The American definition (Billings, 1954, p. 336), based on Mead's proposal (1940, p. 1009) to regard "foliate structures" as "the textural or structural properties of certain rocks which permit them to be cleaved or split along approximately parallel surfaces or lines," is much broader than the concept employed here.

Fractures

Apparently later than foliation and lineation, but in part probably very little later or even overlapping in time the lineation, are several related fracture sets: "Lager" (bedding or foliation) joints, possibly in part opened by erosional unloading (exfoliation); two systems, or four sets, of diagonal joints; longitudinal joints with strike parallel, or nearly so, to the trend of lineation; and cross joints, with strike normal to lineation.

Many of the "lager" surfaces are rough irregular cracks (fig. 1B) parallel to foliation. They give the impression of having opened in response to erosional unloading, i. e., of being exfoliation features. But if this is the case, then there must be two generations of foliation fractures, for obviously some of these fractures opened early, as evidenced by the presence on them of sheets and lenses of pegmatite and quartz. Also, where foliation is not parallel to the present topographic surface, the foliation is still followed conformably, not by irregular cracks, but by well-defined joints. At one place (XIV-15-16, fig. 5) where both foliation and "lager" are nearly vertical, quartz veins were emplaced along the fractures. It seems, then, that just as the early deep-seated "lager" joints coincided with the foliation, so they now coincide locally with exfoliation cracks of late and shallow origin.

One of the two systems of diagonal joints encloses northwest- and southeast-facing angles of about 110°. These angles are not quite precisely bisected by the cross joints. One set of this system strikes N. 68°-70° W., dips 78° SW.; the other set strikes about N. 40° E., dips almost vertically, or 87° NW. Joints of the northeast-trending set are offset by adjustments on the northwest-trending set.

Of the other diagonal joint system, one set strikes N. 40°-50° W., dips 75°-83° NE. The other set is weakly developed here but is represented by a few short parallel cracks that strike north-south, or a few degrees west of north, and dip 87° W. Some members of the northwest-trending set of this system are occupied by white quartz veins an inch or less in thickness. At the inventory spot one of these quartz veins has been disrupted by adjustments on the northeast diagonals; and yet, a few feet away, the northeast diagonals are cut across by the quartz vein (fig. 1A).

The longitudinal joints strike approximately parallel to the trend (horizontal projection) of the lineation and dip very steeply toward north or south. These fractures are weakly developed, and no single one of them can be traced far. For this reason, perhaps, longitudinal joints were not observed to be disrupted by any other fractures or to displace other fractures.

The cross joints strike at right angles to the trend of lineation, but the dip of these joints is not perpendicular to the plunge of lineation at the inventory spot. The measured cross fractures dip 80° or steeper in the direction of plunge (fig. 1A). The cross joints were observed to displace some northeast-striking diagonal joints, but at nearby places the northeast diagonals have disrupted the cross joints. On a flat surface about 30 feet east of the inventory spot cross joints were observed to have displaced repeatedly a northwest-trending quartz vein (fig. 1C).

An attempt was made, based on the observed displacements, to establish a time sequence or order of formation of the several sets. The result was not satisfying because of the contradictions mentioned above. Of course, the possibility cannot be precluded that adjustments have taken place on any given fracture at various times since it was formed.

There may be a better possibility of establishing fracture sequence from the presence, nature, or absence of fracture fillings. For example, pegmatite and quartz together have so far been observed only on the "lager" joints, and quartz alone appears only on the "lager" and on one of the northwest diagonal sets. The large, numerous, and well-formed cross joints seem not to be accompanied by any vein or dike material at all; therefore, these fractures should have opened at some time after the pegmatitic and quartz-bearing solutions had ceased to travel. The fact that no vein or dike material appears on the weakly developed longitudinal joints may be without significance.

The order in which the fracture sets were presented above is thought, on the basis of locally available evidence, to be approximately the order of their formation. Uncertainties remain, however, and because of these and because of the small size of the investigated area, this suggested order will be subject to change. Of course, the possibility exists that many of the fractures were merely incipient at depth and only opened in response to erosional unloading.

Tabular Summary

The above are not all the structure elements developed in the mapped area, but they are all that can be easily observed at the inventory spot. Their arrangements throughout the mapped area are shown on the maps (figs. 2 and 5) and are summarized on the accompanying statistical diagrams. The list of the elements discussed so far is given in table I.

THE GENERATING MOVEMENT—A TRIAL HYPOTHESIS

The structure elements and their mutual arrangements furnish a clear, if not quite complete, picture of the geometry of the gneiss. From such a picture it seems to be customary to proceed at once to a discussion of the generating movements, and from this to consideration of the causative forces.

Accordingly, one might assume, after mapping the elements at the inventory spot, that the rocks had been compressed either from south-southeast or north-northwest, or perhaps from both directions. The lineation, then, indicates an extension at right angles to compression during a highly viscous stage of the materials. The cross joints record the reaction of brittle materials to the same compression, the diagonal joints are the corresponding shear fractures, and the longitudinal joints may be release fractures.

If the above concept of force and resulting adjustment is correct, then the gently southward-dipping foliation at the inventory spot must lie on the southern flank of an anticline. It would be important to know whether this anticline is symmetrical or asymmetrical, and if the latter, which side is the steep flank.

Fortunately, it is easy to answer these questions. A few paces

TABLE I
INVENTORY OF THE STRUCTURE ELEMENTS

Name of element	Notation according to Cloos (1921, p. 9-24; 1922, p. 9)	Notation according to Sander (1930, p. 21-32, 92)
7. Cross joints	Q	ac
6. Longitudinal joints	S	bc
5. Diagonal joints (WNW. and NE.)	d	hko
4. Diagonal joints (NW. and N.-S.)	d	hko
3. Lager (bedding) joints	L	hol
2. Lineation	F	b
1. Foliation	l	s

northward puts one on the southern brink of a ravine, which has been eroded into the core of an anticlinal fold. From this position the eye follows the gently southward-dipping layers up to a crest and then steeply downward in the cliffs on the northern wall. The element so followed is the lager, which is more clearly followed at a distance than is the foliation itself. The existence and northward asymmetry of a fold are thus proven. Apparently, the deforming pressure was applied from the south-southeast, and the materials were pushed before it toward the north-northwest.

The ability to map the pattern of the structure elements, and from this to derive a motion picture of the development of a structure, furnishes a sense of elation. At this stage the student seems to have acquired a certain mastery over nature. But nature can be a wily opponent.

TEST OF HYPOTHESIS THROUGH ACCUMULATING OBSERVATIONS

The Crest of the Fold

The classes in structural geology go from the edge of the ravine to stop 2 (fig. 2, VI-9). From this location one can look eastward almost directly along the axis of the structure. Should any doubt have remained concerning the asymmetry of the anticline, that doubt is easily dispelled here.

A few paces northwest of locality 2 the gentle southerly dip of foliation and lager changes to a northerly dip, indicating that the fold crest has been crossed. It is not possible to locate this crest exactly, but its position can be determined within a few feet. Standing as nearly as possible on this crest and looking eastward along it one can measure approximately the dip of the crestal plane. This dip is about 70° southward, thus confirming the asymmetry of structure.

The Northern Flank of the Fold

About 70 or 80 feet northwest of locality 2 the northerly dips of foliation steepen and closely approach the vertical. Apparently the asymmetry of the fold is even more marked than the previous observations suggested. At locality 3 (fig. 2, XVII-3-4) there is a good view eastward across the ravine, which has turned northward to cut through the northern flank of the anticline (fig. 1D).

The structures revealed in this view are astonishing. The crest of the anticline appears in the upper right-hand corner of the sketch, and under this crest are the cliffs of the northern wall of the upper part of the ravine. On these cliffs is exposed the northward-dipping foliation, locally very steep, and even overturned, as can be seen just to the right of the saguaro in the lower right corner.

North of this steep to overturned flank there appears to be a relatively broad gentle syncline, beyond which is a second narrow overturned anticline. That the syncline is not the gentle structure that it appears to be in this view can be realized from the structure sections (fig. 6). In the upper left corner (fig. 1D) the axial plane of the second anticline dips gently southward. It then rapidly steepens and descends to the floor of the ravine at a point almost directly beneath locality 3, where it again flattens (fig. 1E). In cross section, therefore, the trace of this plane must resemble an integration sign, reversed and tilted slightly northward (fig. 6, sections 4, 5, and 6). As this trace is followed downward, it can be seen that sharpness and amplitude of the second anticline decrease and that the axial plane of the second anticline approaches more closely the northern flank of the main anticline. That is, the two structures seem to be crowded more closely together at depth. The overall impression gained from this view is as though the northern flank of the main (southern) anticline had collapsed, had flowed northward, and had pushed up the second overturned anticline.

From stop 3 the students descend directly to the floor of the ravine. Here, extensive exposures reveal the subdued form of the second (northern) anticline, and a few cross-joint faces expose its internal structure (fig. 1E). As seen on these faces, the gneiss is distinctly layered; layers of coarse-grained feldspar alternate with finer grained bands. This foliation reveals the asymmetry of the fold and again creates the impression that the material moved northward, perhaps down a gentle gradient.

The lineation (parallel, slanting lines, fig. 1E) is parallel, or nearly so, to the fold axis. This linear structure is especially well shown on flat surfaces at this locality, where measurements prove that it plunges east-northeast. This is the reverse of the general plunge in the inventory area. Reversals of plunge are plainly revealed in the fabric diagram of lineation (fig. 2A). Where thin sheets of quartz coat these flat exposures the lineation appears as parallel shallow grooves in the quartz.

In the eastern wall of the ravine, on the northern flank of the fold, there are revealed a number of minor crumples in a sequence consisting of mica schist, feldspathic layers, and one thin quartz vein (fig. 1E'). All these little folds are overturned, and some of them are recumbent, toward the north-northwest. Again it looks as though the material had flowed northward, this time off the steep flank of the larger fold.

Another notable feature (fig. 1E') is the relation of the coarse feldspathic material to the finer grained mica schist. Remnants of the schist appear in the coarse-grained material, which seems to have been "frozen in the act" of devouring the schist. Obviously these structural features have a chemical as well as a mechanical history.

Twenty-five feet upstream from the exposure just discussed and on the eastern side of the ravine the smooth gently sloping exposures reveal a vaguely defined flat lens of quartz-feldspar-mica pegmatite, about 12 feet wide, parallel to the cross joints, and some 18 to 24 inches in thickness. This lens may be elongated parallel to lineation, but the exposure is not extensive enough to allow proof of this.

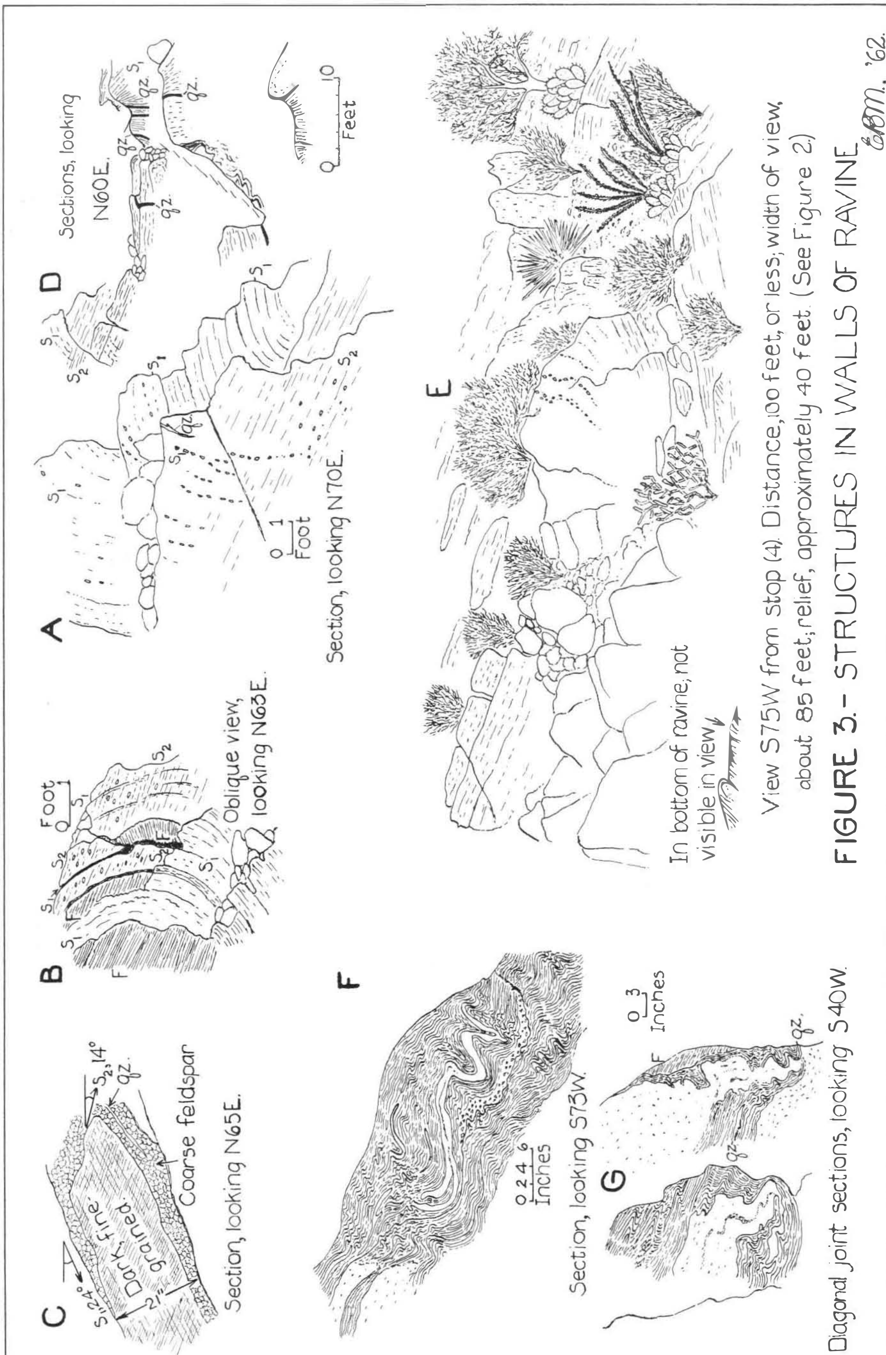
The bottom of the pegmatite lens is almost horizontal, but the upper surface is gently arched. Did the pegmatite form as space was made beneath the arch, which developed under horizontal compression? Or was the arch forced upward by the crystallizing pegmatite? Or were both of these processes somehow combined to form the structure? The stony geometry furnishes no answer; it only suggests possibilities.

From the pegmatite lens it is only some 50 feet to stop 4 (fig. 2, XVI-17), from which it is easy to examine closely the structure seen near the saguaro (fig. 1D, lower right corner). The steep to overturned foliation is exposed on a cross-joint face some 6 feet or more high (fig. 3A). Careful inspection reveals that the steep foliation, shown as thin bands containing large feldspar crystals, dies out downward where its place is taken by a second vague planar structure, which dips gently southward. A number of the large feldspars appear to have been rotated into, or to have grown along, this second gently dipping planar structure, which obviously is a new element not listed in table I.

Because it seems to destroy the foliation s, the new element must be the younger, and it is itself a kind of foliation, which may be designated s_2. The first described foliation, then, can be redesignated s_1 as indicated (fig. 3A, B, C, and D).

At this exposure (fig. 3A) no syncline is visible below the steep feldspathic bands; possibly a pre-existing syncline of foliation s_1 has been erased locally by movement and recrystallization on s_2. However this may be, a few feet northwest of this exposure the expected syncline is revealed (fig. 3B).

That this structure actually is a recumbent syncline must follow if the southern flank of the main anticline, as exposed south of the ravine, represents a normal uninverted sequence. To assume that this is so is simpler and more reasonable than to make the contrary assumption. The sketch (fig. 3B) shows the sweeping curve of foliation s_1, the lineation F, parallel to the fold axis, and the second foliation s_2, in the upper limb of the fold. Here again, some large feldspars are oriented to s_2, but s_1 still persists. The complete structure here, including the northern flank of the main southern anticline and this recumbent syncline (fig. 3A, B), resembles a capital S with some of the upper central part erased as shown (fig. 3A).



View S75W from stop (4). Distance, 100 feet, or less; width of view, about 85 feet; relief, approximately 40 feet. (See Figure 2.)

FIGURE 3.- STRUCTURES IN WALLS OF RAVINE

In the lower limb of the recumbent syncline (fig. 3C), both s_1 and s_2 are revealed in a dark fine-grained layer. Foliation s_1 dips 24° northward; s_2, which here has the aspect of flow cleavage (Leith, 1923, p. 113), dips 14° southward. Here again it looks as though coarse feldspathic material had been frozen in the act of consuming the finer grained darker band.

Some 20 feet south of stop 4, and therefore closer to the core of the main anticline, is a sharp nearly east-west ridge, perhaps 12 feet high and 20 feet across at the base, of light-colored granitic gneiss. This "rib" rises abruptly from the floor of the ravine and is overlain by debris at both the eastern and western ends. It resembles the prostrate trunk of an enormous tree. In the hope of revealing its internal structure, two sections were measured across the rib, and a third section was measured in the bottom of the ravine just beyond the western end of the rib (fig. 3D).

In the lowest section, on the floor of the ravine, a small northwardly overturned anticline of granitic gneiss overlies finer grained micaceous gneiss or schist with steeply dipping foliation. The next two sections and a fourth partial section show the development of this structure as it is followed eastward along the rib. The second and third sections through the rib show what appears to be a steep-flanked anticline, asymmetrical to the north, while the fourth partial section suggests that as elevation is gained in this structure the little anticline tends to become recumbent.

At first it was thought that the recumbent fold shown in the uppermost section (fig. 3D) must plunge westward to become the overturned structure shown in the lowermost section. However, lineation here is parallel to the fold axis, and the lineation at this place does not plunge steeply enough to permit the correlation suggested above. The structures shown in these sections are all parts of the same fold, but not corresponding parts. Accordingly, the axial plane of this little anticline must dip rather gently southward in the bottom of the ravine, rise very steeply through the rib, and flatten again at the top. This repeats in miniature the behavior of the axial plane of the second or northern anticline, as seen from stop 3 (fig. 1D, E).

The upper longest section (fig. 3D) shows the relation of the little "rib" anticline to the northern flank of the main southern fold. The second foliation, s_2, seems to appear just where needed to accommodate the northward transfer of material from the recumbent top and steep northern flank of the rib. Perhaps this very transfer bulged out and locally overturned the northern flank of the main fold. It seems significant that nothing like s_2 was found south of the rib in this part of the ravine.

If the above-derived concept of the northward travel of materials is correct, it should find confirmation in the exposures on the western wall of the ravine. A sketch of these exposures (fig. 3E) was made from a point near stop 4.

The crest of the main anticline, crossed between stops 2 and 3, is a few tens of feet to the left of the upper left-hand corner of the sketch. North of this crest the foliation at first dips gently northward, as shown; then the dip suddenly increases to vertical and even overturns, as indicated under the large bush in the center of the sketch. Gently south-dipping planar structure under this steep foliation may be s_2. Somewhat more steeply dipping layers among the flat ones, seen at a few places, are possibly remnants of s_1. The lower left part of the structure is concealed beneath a jumble of huge blocks, but the exposure in the bottom of the ravine has been shown, although it is not actually visible from the view point. This is the same exposure as that indicated in the lowermost section (fig. 3D), seen from the opposite direction.

On the right side (fig. 3E) a gentle anticline is visible. This is the western continuation of the second northern anticline, previously sketched (fig. 1D, E). Craggy outcrops with vertical foliation (fig. 3E) attain almost the very crest of the second anticline.

From these observations it appears that on the western side of the ravine the northern flank of the main anticline has sagged northward as a recumbent fold. The second northern anticline on this side seems to have been almost completely overwhelmed by the advance of this "miniature nappe." No convincing evidence is exposed of an underlying syncline, and if such a syncline was ever formed it may have been destroyed by recrystallization and by translations on s_2. In any case, the northward travel of material is more than amply confirmed by the exposures in the western wall of the ravine.

On the way to stop 5, situated where the ravine bends eastward, it can be seen that a thick mass of coarse dark mica schist is poorly exposed in the right western wall. This dark mass appears to be some 15 feet thick, and it may be thicker. The rock is very thinly foliated, and it is situated below and immediately to the north of the crest of the main anticline. With its many glide planes this schist should have facilitated, and could have caused, the northward flow of overlying materials to form the "miniature nappe."

At stop 5 (fig. 2, X-XI, 16-17) the southern wall of the ravine represents approximately the surface along which the dark schist mass was "peeled" from the core of the main fold. As revealed here (fig. 3F), the northward-dipping schist is thrown into many minute crumples, or puckers. Two especially favored glide planes appear in this little exposure. On one of these, just below the contorted white band, the schist, perhaps somewhat silicified, has been microbrecciated. The second glide surface lies some 3 to 6 or 7 inches below the breccia-bearing one. As would be expected, the little folds above a glide surface show some disharmony with the folds below. The folds above a gliding surface also tend to die out downward toward the surface. This tendency is locally obscured where the surface itself is folded. The thickness of any layer above a glide surface appears to lessen updip and to increase downdip, as though the updip portions had been places of efflux from which material had flowed downward to places of accumulation (Beloussov, 1959, p. 1). In the updip portions, also, curved prongs or shelflike extensions of granitic gneiss are inserted parallel to the foliation of the schist. In the absence of convincing evidence that the gneiss has forced the schist aside and in the presence of vague contacts at the termini of the prongs, it appears that the gneiss has either impregnated or replaced the schist or that both processes have operated. As the schist moved away, it seems that the devouring gneiss was on its heels.

A few steps east of stop 5 some prominent diagonal joint surfaces offer informative sections (fig. 3G) into the southern wall of the ravine. At this place the dark schist has been more completely removed from the gneissic core of the main fold than was the case at stop 5; yet remnants still remain as microfold cascades with cores of gneiss. From this structure it could be concluded that the gneiss did indeed force aside the schist, and to some extent this may have been the case. And yet, here again local vague contacts and the presence within the gneiss of wispy remnants of schist, apparently in several stages of incorporation, suggest that the gneiss core "consumed" part of the schist.

The southern wall of the ravine trends approximately parallel to lineation, some of which presents here the appearance mentioned before. In addition, there are on this wall dark streaks, yards in length, which represent the tightly appressed troughs of little synclines of schist, such as those shown (fig. 3G). Between these dark streaks small gneiss anticlines form lighter colored subdued ridges. Gneiss ridges and schist furroughs together form the feature called "fold mullions" by Wilson (1961, p. 512). A few of these fold mullions were sketched (fig. 4A, right-hand part).

Some 20 feet southeast of stop 5, at the place indicated on figure 2 by the lineation arrow showing a west-southwest plunge of 10°, is the western end of a second nearly east-west-trending rib (fig. 4A). This "rib" number 2 lies southeast of and en echelon to the one described above. At the western end of rib number 2 cross joints have facilitated the erosional removal of large blocks, thus exposing a series of small nearly vertical cross sections. These natural structure sections are connected by several gently westward-inclined "steps" on which is exposed a strong lineation. As shown by these natural sections, the foliation at the top and within this rib is nearly horizontal or dips very gently southward; but on the northern (left) side the foliation suddenly steepens and turns down vertically. At the northern base of the rib a mica schist layer is actually overturned, but with a little care it can be seen to become upright below and to flatten gently northward. The rib, then, expresses topographically the flat top and steep northern flank of a minor asymmetrical to overturned anticline just north of the crest of the major structure. This little fold is analogous to the one previously described (fig. 3D). Therefore, in the core region within the northern flank of the main anticline there are two en echelon asymmetrical minor anticlines leading up stepwise to the crest of the main fold. This arrangement recalls Beloussov's (1959) block folding.

The impression gained from the exposure (fig. 4A) is that northward-flowing material has cascaded off the northern flank of this rib, number 2. This impression is strengthened by what can be seen under the coarse blocky talus at the eastern end of the ridge just off its northern flank (fig. 4B; fig. 2, XIV-XIII-21, stop 6). Here, a mass of dark mica schist at least 10 feet thick is very intensely foliated. This foliation is s_2, and at this place it is obviously flow cleavage. Embedded in the schist are thin, distorted and disrupted, fine-grained, light-colored layers—remnants of s_1. Some details of the deformation of s_1 are clearly visible (fig. 4B'). It seems that by flowage (slip) on s_2, s_1 was thrown into hundreds of microfolds, overturned toward the northward direction of flow and that these little folds were disrupted by the flowage so that their fragments became strewn along s_2.

A few yards north of these exposures, under the overhang on the northern wall of the ravine, is revealed the relation between these dark schists and the overlying gneiss (fig. 4C). The steep northern limb of the main fold, enclosing all the structures seen since leaving stop 5, has moved downward and northward in relation to the underlying schist. Because of this relative movement the schist has been deformed into a number of "reverse" drag folds.

Review of Hypothesis

So far, all observations have seemed to bear out the hypothesis adopted

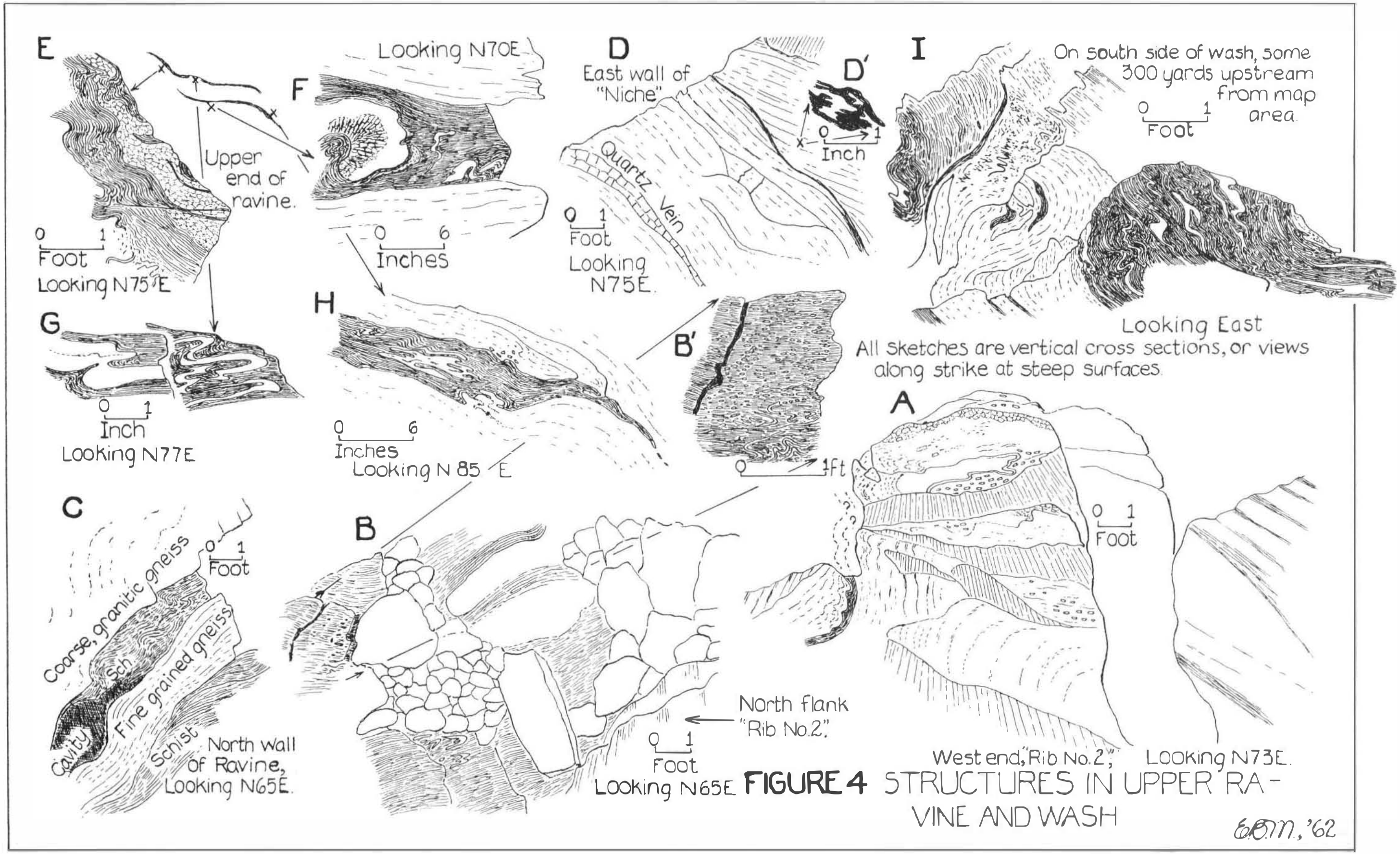


FIGURE 4 STRUCTURES IN UPPER RAVINE AND WASH

at the inventory spot. A lateral compressive force from south-southeast seems to have folded the gneiss-schist complex and to have driven it northward. In a sense, however, the agreement of evidence with hypothesis may be too good. Evidence of the northward flow of materials, as revealed in the exposures, far exceeds any expectations formed before leaving stop 2. Perhaps some observers will see in this apparent northward flow down a gradient the effect of gravity rather than of horizontal compression. Most students, however, and in fact some experienced geologists, will prefer to explain the observations on the basis of the original hypothesis. If their choice is correct, then the southern flank of the main anticline should display no comparable evidence of flowage, or if such evidence exists, again it should indicate a relative northward movement of the upper layers.

The students climb up the steep western end of the second southern rib and walk to stop 7 (fig. 2, IX-26). In gaining this position they cross the crest of the main fold. At this place a huge block has fallen from the south wall of the ravine, leaving a reentrant conveniently called "the niche." This niche allows one to look for a short distance into the southern flank of the main structure. In view of the statement made at the end of the last paragraph above, it is important to inspect the exposure in the eastern wall of this niche (fig. 4D).

The Southern Flank of the Main Anticline

The feature of this wall that first catches the eye is the relatively steep southward dip of the foliation in the left-hand lower part of the wall and the relatively gentle dip in the right-hand upper part. A shear surface (fault) separates the two parts, and the gently dipping foliation of the right-hand hanging wall appears to have been dragged upward on the fault. A small portion of the hanging-wall rock fabric (fig. 4D') revealed microfolds that clearly suggest a relatively downward and southward flow of the hanging-wall gneiss.

This evidence appears to be damaging to the assumption of deformation under compression from south-southeast; for here, south of the crest of the main fold, the higher rock layers seem to have moved southward against the compression. But perhaps the core of the fold, under a compression from the south-southeast, rose steeply, shearing across and dragging upward the more gently dipping foliation of its cover. Such an action could cause the observed appearance of a southward flow of the higher layers. It could be argued, also, that the exposure in the niche is very local and is not to be balanced against the much stronger evidence of northward flow.

Leaving the niche, the students walk to stop 8 (fig. 2, XIII-31, 32). Here, near the crest of the main structure, but still on its southern flank, are some schlierenlike remnants of coarse dark schist in granitic gneiss (fig. 4E, F, G, H). A detailed description seems unnecessary. Although, of course, the movement is relative, the higher gneiss layers appear to have cascaded or glided down the southern flank of the main anticline.

In order to remove the last doubt of the importance of this relative southward flow, a larger example was searched for. Such an example was found a few hundred yards upstream from the mapped area and on the southern side of the wash (fig. 4I). Here, interlayered, coarse, dark mica schist and light-colored granitic gneiss, on the southern flank of the main structure, show the pattern suggestive of flow southward down the flank. The illustration (fig. 4I) is a composite of several natural sections through the interlayered mass.

Although the observations made so far do not constitute proof, it now seems doubtful that there is any significant difference in the amount and importance of relative northward and southward flow. The direction of this relative motion depends directly upon the direction, and perhaps the steepness, of the dip of the flank of the main anticline. Apparently, the rocks flowed away to north and south from the crest of this structure. Perhaps it would be better to say that the core of the structure rose as a long narrow ridge, lifting its cover, dragging upward the layers on its flanks, and causing weak unstable portions to slump downdip.

FORMULATION OF A SECOND HYPOTHESIS

Preliminary Statement

It may be objected that the above interpretation, to which much of the evidence seems to drive us, does violence to the rest of the evidence. For example, how can the fracture pattern (fig. 5) and the uniformly trending lineation (fig. 2) be made to fit such an interpretation?

The Fracture Pattern

The essential features of the fracture pattern have already been discussed and illustrated (figs. 1A and 5). The fabric diagrams (fig. 5A, B) summarize the pattern. A troublesome feature is the presence of the diagonal joints, which probably originated as shear fractures. Experiments by Cloos (1931) on rising plastic masses appeared to indicate that diagonal (shear) joints formed only in those masses which, as they rose, were compressed laterally. That this result may not apply in all cases, however, was demonstrated by Ekkernkamp (1939) who generated diagonal fractures in rising experimental domes even when lateral compression was lacking. Accordingly, even if the diagonal joints formed relatively early in the history of the folds in gneiss, as is suggested by the presence of quartz veins in some of them (fig. 1A, C), their presence would not necessarily indicate that the rocks were at that time under lateral compression.

The cross and longitudinal joint relations (fig. 5) pose a more serious obstacle to the second interpretation. The longitudinal joints, as already stated, are weakly and locally developed; whereas, the cross joints are strongly developed everywhere. This clearly implies extension in east-northeast—west-southwest, with which it is usual to associate a south-southeast—north-northwest shortening. But how can this be if material was moving down the flanks of the folds and away from the crests? Even if it is assumed that the cores of the folds were the only active elements and that the layers on the flanks were merely tilted and dragged upward, still there should have been active tension at right angles to the fold axes, and longitudinal joints should have formed in perfection and abundance.

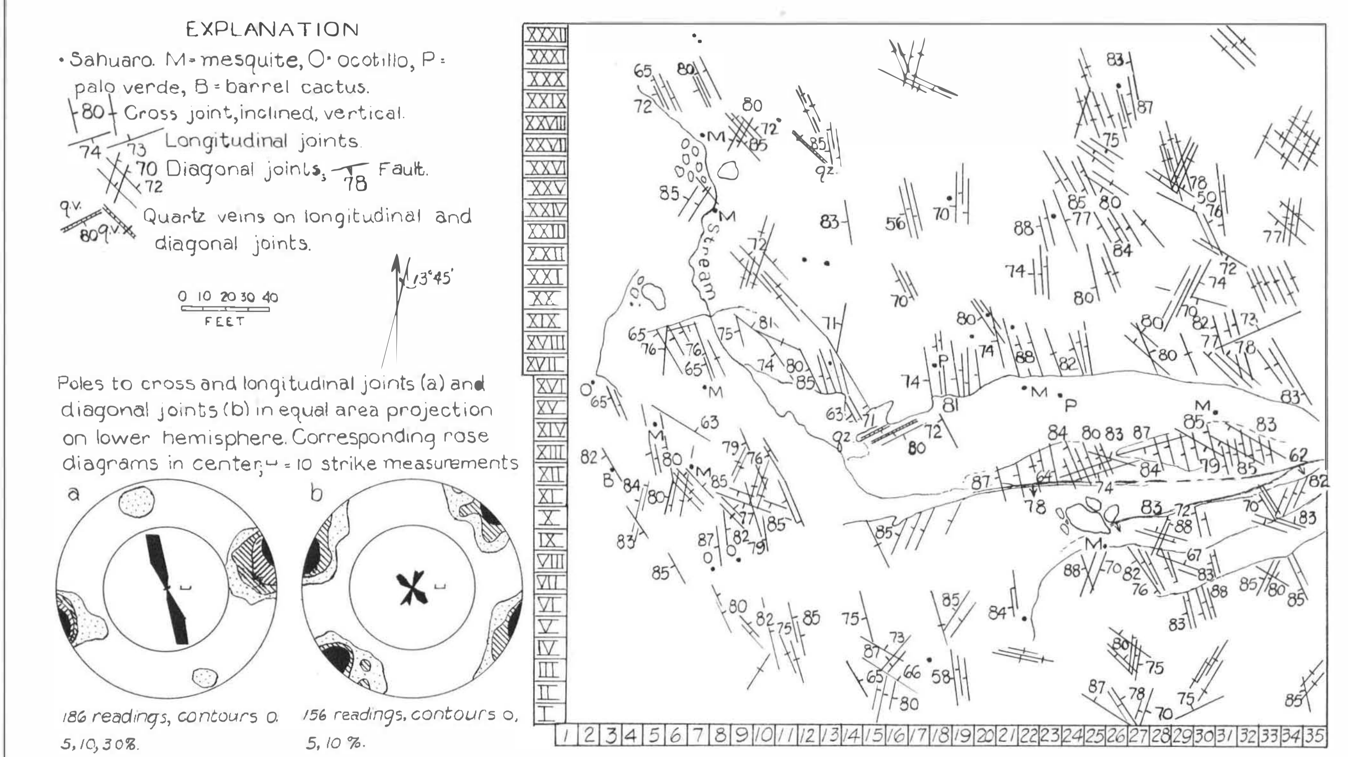


FIGURE 5 - MAP AND FABRIC DIAGRAMS OF FRACTURES IN N. CAMPBELL FOLDS

E.B.M. '63

Carey (1954, p. 99) has shown that in a deforming solid the formation of fractures is related, among other things, to the rate of deformation. Where "viscosity" is low, a high rate of deformation can be maintained without fracture, but if "viscosity" is high, the same deformation rate will lead to rupture. In the case of the gneiss, then, it could be that during the stage of plastic flowage either the "viscosity" or the rate of deformation, or both, were too low to allow fracturing. Perhaps the few weak longitudinal joints were formed at the very end of the plastic stage. From the view point of physics, such an assumption should be admissible.

The large number and strong development of the cross joints, however, are still not accounted for. The problem of the cross joints is so closely related to that of the uniformly trending lineation that these two features are best considered together.

Lineation

The very uniform trend of lineation, not only in the area being discussed but throughout the Catalina forerange, is difficult to explain. This difficulty is only enhanced if flowage from the crests of the anticlines is accepted. The lineation obviously indicates extension parallel to the crests of the folds, not across them. Of course, the many well-developed cross joints suggest a continuation of this lengthening into the brittle stage. But how can extension parallel to the fold axes ever be reconciled with the idea of the uplift of fold cores and flowage away from their crests, as developed from observations? At first, the evidence furnished by flowage folds, lineation, and cross joints seems hopelessly antagonistic.

The first noteworthy suggestion known to this writer as to the origin of the uniformly trending lineation was by a graduate student, Mr. E. F. Pashley, Jr., who suggested in conversation that the lineation was somehow inherited from the northeasterly Precambrian trend known at many places in the Pinal Schist of southern Arizona. This idea has appeal, for it appears to explain the constant trend. The relation of lineation to Precambrian grain must be indirect, however, for at no place known to me is there a constant northeasterly lineation in the Pinal Schist. As a link between the lineation and a possible Precambrian grain one group of structures is clearly indicated, the folds themselves. Their northeast or east-northeast trend is persistent throughout much of the Catalina forerange and in parts of the Rincon Mountains.

If certain strips have been activated parallel to an ancient east-northeast grain, perhaps by ingress of heat, the rise of the folds, their constant trend, and the adjustments by flow accompanying their rise could possibly be explained. But, again, why was the lineation formed parallel to the fold axes?

The writer thinks that a clue is offered by the previously mentioned reversals of plunge of the lineation. These reversals are recorded in the fabric diagram (fig. 2A). They indicate that along the fold crests there are culminations and depressions; in other words, that the fold crests are warped or cross folded in a manner that demands extension parallel to the axes. This cross-folded condition seems to be general in the Catalina forerange, and it recently has been revealed as a result of Peterson's (1963) study of the Sabino Canyon fold. It would be important to know at what stage of the structural history the cross warping and axial stretching took place.

The axes of all folds, including the largest and the smallest, constitute lineation. Therefore, lineation began to form and its trend became established during the plastic stage of deformation. At this early stage there may have been little extension parallel to trend, other than that occasioned by rotation around the axes of minor flowage folds.

Intensification of the lineation—i. e., stretching—by the crushing and streaking-out of minerals and by the formation of grooves must have taken place when the rocks had become essentially rigid. By this time plastic flowage must have terminated, or have very nearly terminated. It seems, then, that as the materials approached and attained the rigid state, the regular uniform uplift of the fold cores was replaced by cross warping and axial extension.

In order to test the above inference, a search was made for evidence of flowage parallel to the east-northeast-trending fold axes—that is, off the flanks of cross warps or down the plunge of lineation. For a time it seemed that such evidence was exposed in the southern wall of the ravine, but careful examination showed this impression to be an error caused by very oblique sections of little folds resulting from flow away from the major fold axis. There appears to be no evidence whatever of flowage down the flanks of cross warps. This observation coincides beautifully with the inferred late origin of the stretching and, therefore, of the cross warping. The great number and strong development of the cross joints now fit into place and time, as does the weak development of the longitudinal joints. The cross joints accommodated further the extension begun during intensification of the lineation. When the longitudinal joints started to form, extension across the east-northeast-trending fold axes had essentially ceased.

It seems, then, that the second hypothesis—that of vertical uplift along the east-northeast direction, with flowage away from the axes of uplift during the plastic stage, followed in the incipient solid and solid stages by cross warping—will satisfy all observations. Accordingly, the assumption of lateral compression that operated at this structural level to form the folds seems to be unnecessary. This, of course, does not preclude the possibility that lateral compression, acting at some deeper level, squeezed the anticlinal folds upward. Such a possibility, however, is not supported by the observations; whereas, the observed relations of light-colored gneiss and dark schist do suggest the rise of heat and of alkali and silica-bearing solutions into the core areas of the folds. Such action might have caused the folds to rise. An attempt to interpret the structural history of the folds, based on this possibility, is presented (fig. 6, left side). The assumption of an original flat layering in stage A is probably erroneous because it takes no account of possible earlier deformations. In fact, if a northward dip is assumed in stage A, it becomes easier to account for the northward asymmetry of the main anticline and for the apparently greater northward flow of materials as compared with southward flow. It should be obvious that the developmental stages A to E, as sketched, will be subject to revision, and perhaps to elimination, as information accumulates from adjacent areas.

SUGGESTIONS FOR FUTURE WORK

It would be of value to have the present small investigation followed and supplemented by petrographic, petrofabric, and geochemical studies. With a thoroughly investigated starting point, the mapping could then be

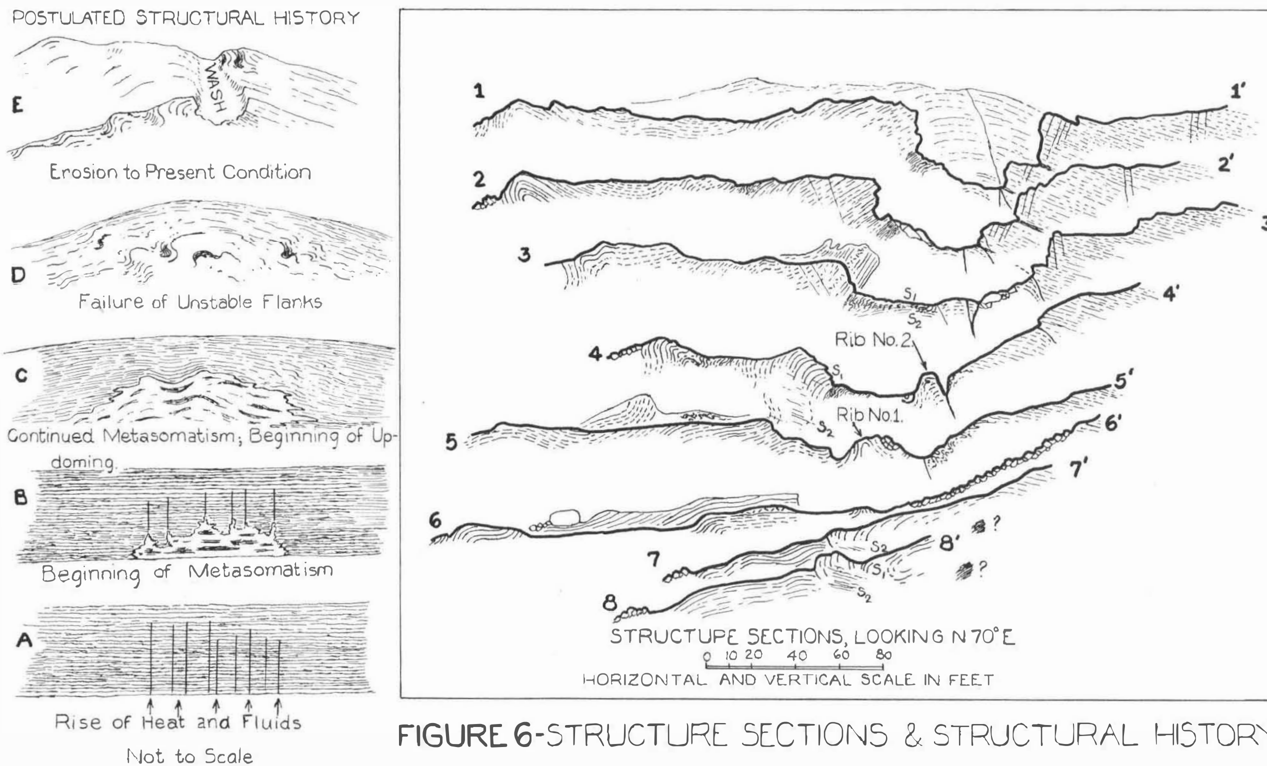


FIGURE 6-STRUCTURE SECTIONS & STRUCTURAL HISTORY

extended into increasingly larger areas, beginning with a scale of 100 feet to the inch and progressing by stages to 1,000 feet to the inch. In this way the entire Catalina forerange could eventually be mapped in detail, as Peterson (1963) has already mapped parts of Sabino and Bear Canyons.

Among the elements that should be recorded in the more extensive surveys are the flowage folds. A symbol can easily be devised to indicate the directions of flow revealed by these folds. If such symbols are plotted on maps with relation to major structural axes, the success or failure of the above-presented concept as a theory of the evolution of the Catalina forerange might become established.

ACKNOWLEDGMENTS

Information on the radioactive dates was kindly furnished by professor P. E. Damon, and the manuscript was carefully edited by professor E. J. McCullough, Jr. The writer is indebted to both colleagues, but he assumes full responsibility for the provisional conclusions.

SELECTED BIBLIOGRAPHY

Beloussov, V. V., 1959, Types of folding and their origin: Int. Geol. Review, v. 1, p. 1-21.

Billings, Marland, 1954, Structural geology: New York, Prentiss-Hall, p. 336.

Catanzaro, Edward, 1963, in Culp, J. L., Revision of interpretation of zircon discordance patterns observed in several Precambrian areas: Investigations in Isotopic Geochemistry, Ann. Progress Rept. no. 8, Appendix C, p. 25-26.

Cloos, E., 1946, Lineation: Geol. Soc. America Mem. 18, p. 23.

Cloos, H., 1921, Der Mechanismus tiefvulkanischer Vorgange: Braunschweig, Sammlung Vieweg, p. 9-24.

________ 1922, Der Gebirgsbau Schlesiens: Verlin, Gebruder Borntrager, p. 9.

________ 1931, Einige Versuche zur Granittektonik: Neues Jahrb, Min. Geol. Pal., Beil. Bd. 64-A, p. 829-836.

Culp, J. L., 1961, Geologic time scale: Science, v. 133, p. 1105-1114.

Damon, P. E., Erickson, R. E., and Livingston, D. E., 1963, K-Ar dating of Basin and Range uplift, Catalina Mountains, Arizona: Nuclear Geophysics, Nat. Research Council Pub. 1075, p. 113-121.

Darwin, Charles, 1846, Geological observations in South America: p. 141. (Cited by A. Harker.)

Ekkernkamp, M., 1939, Zum Problem der alteren Anlagen in Bruchgebieten: Geol. Rundsch., v. 30, p. 730-733.

Harker, A., 1932, Metamorphism: London, Methuen and Co., Ltd., p. 203.

Leith, C. K., 1923, Structural geology: New York, Henry Holt and Co., p. 113-118.

Mead, W. J., 1940, Folding, rock flowage, and foliate structures: Jour. Geology, v. 48, p. 1007-1021.

Peterson, R. C., 1963, Structural geology of the Sabino Canyon fold, Santa Catalina Mountains, Pima County, Arizona: unpublished master's thesis, Univ. Arizona, Tucson.

Sander, Bruno, 1930, Gefugekunde der Gesteine: Vienna, Julius Springer, p. 31-32, 92.

Wegmann, C. E., 1935, Zur Deutung der Migmatite: Geol. Rundsch., v. 26, p. 307. (Wegmann's terms for paleosome and neosome are Wirtgestein and Zufuhr.)

Wilson, E. D., 1939, Pre-Cambrian Mazatzal Revolution in central Arizona: Geol. Soc. America Bull., v. 50, p. 1113-1164.

Wilson, Gilbert, 1961, The tectonic significance of small scale structures and their importance to the geologist in the field: Ann. de la Soc. Geol. de Belgique, v. 84, p. 512.