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ORIGIN OF THE RED HILLS—PIEDMONTITE HILLS UPLIFT [1]

by

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Abstract

The Red and Piedmontite Hills comprise possibly 3,000 feet (914 m) of pre-Cretaceous, clastic volcanics, flanked and overlain on the northeast and southwest by more than 2,000 feet (609 m) of Cretaceous Amole Arkose. Structures in the pre-Cretaceous volcanic core suggest two times of disturbance—late Middle Jurassic and Laramide. The clastic volcanic rocks were invaded by magmas at both times.

At approximately 150 m.y. ago, the older Mesozoic volcanic rocks were uplifted to form a north-northwest-trending, doubly plunging dome. During the Laramide, on the site of the Jurassic dome, the pre-Cretaceous core rose and stretched as a response to the emplacement of igneous intrusions and the accompanying effects of heat and fluids. As a result, the Amole Arkose appears, in part, to have sagged, or slipped, off the core and, in part, to have been shouldered aside. Where the amount of core uplift appears to have been greatest, deformation of the adjacent arkose is the most severe.

No convincing evidence has been found of intense regional compression. On the contrary, at presently exposed levels, the area appears to have been in a tensional stress field for many millions of years. Moderate compression may have prevailed at a deeper level during the Laramide, and local compression was generated by the demand for space to accommodate magmas and certain pre-Cretaceous rocks rising from depth. Apparently, compression can exist and operate even in an overall tensional stress field.

Introduction

Throughout most of the present century various workers have postulated the transport of vast thrust sheets over parts of southeastern Arizona. With regard to the Tucson Mountains (Fig. 1), Brown (1939) suggested that during the Laramide orogeny a "great Tucson Mountain overthrust" had placed older rocks on younger. This overthrust concept was challenged by Kinnison (1959) and Mayo (1963), but the overthrust is still shown on the latest geologic map of Arizona (Wilson, Moore, and Cooper, 1969). Detailed field work in these mountains during the past 18 years has failed to disclose evidence of an extensive overthrust.

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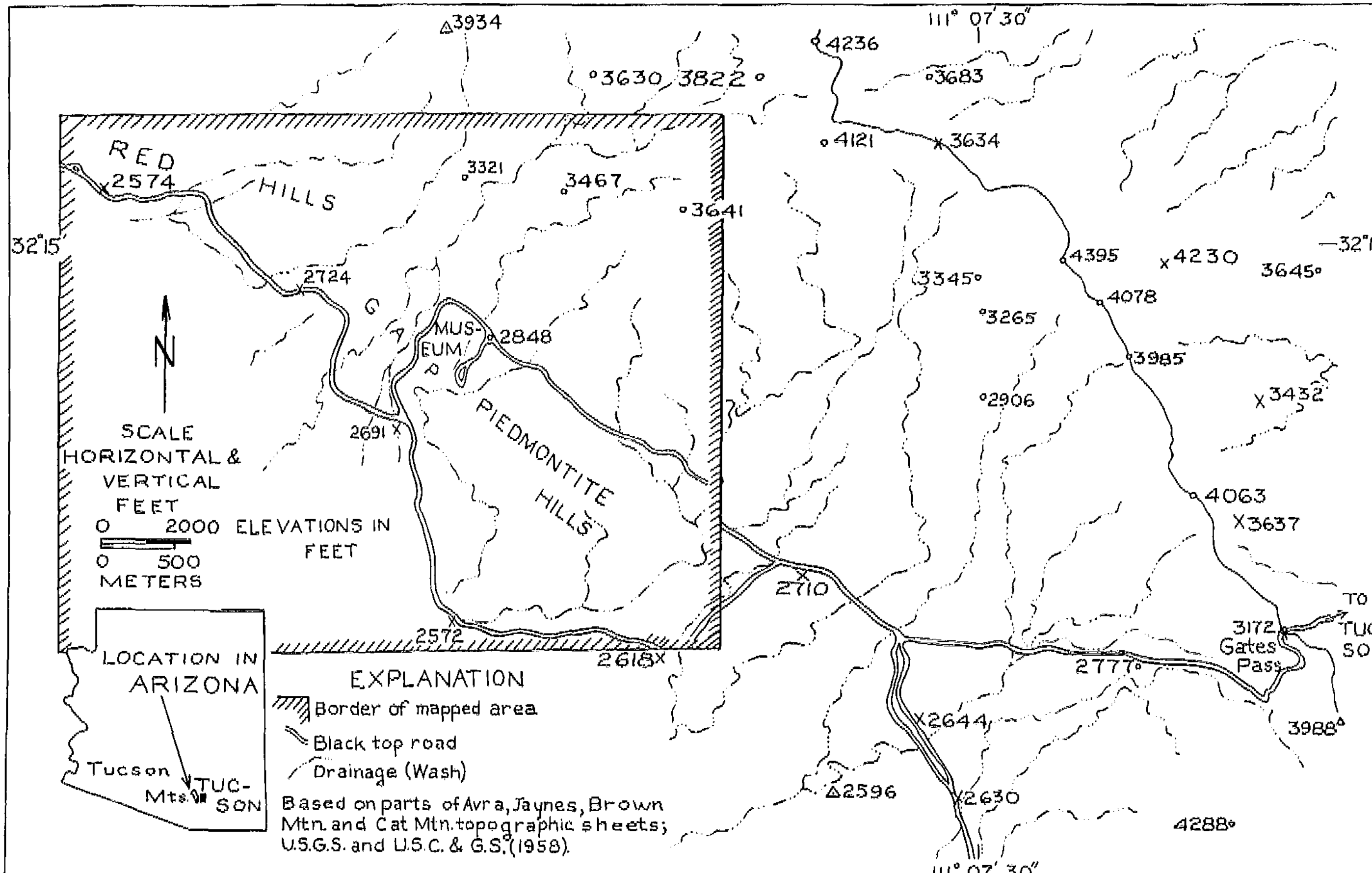

Figure 1. Location map.

Probably, few local geologists accept the notion of such an overthrust today.

According to Brown's tectonic model, the area of this study (Fig. 1) would constitute part of the autochthonous block. Furthermore, the area contains, in the Red Hills, the Gap, and the Piedmontite Hills, the best exposures of pre-Cretaceous Mesozoic rocks in the Tucson Mountains. In this paper we attempt to evaluate the relative roles of compressional crustal shortening and primary vertical tectonics with gravitational response in this structurally low, but topographically high part of the supposed autochthon.

The Piedmontite Hills (also known as Brown Mountain) and the Red Hills (Fig. 1) are at the southwest edge of the Tucson Mountains, some 12-18 miles (19-30 km) west-northwest of Tucson, Arizona. The geography of these hills and of some of the adjacent country is represented on the topographic map (Fig. 2). The hills form two groups on a roughly northwest-trending axis, separated by a relatively low gap in which is the widely known Arizona-Sonora Desert Museum.

Maximum relief in the Piedmontite Hills is nearly 600 feet (183 m); in the Red Hills some 560 feet (174 m); and in the northeastern part of the map area (Fig. 2) about 770 feet (325 m). Along some of the usually dry stream courses (washes), on ridge crests and on steep slopes, exposures are usually good, but on the gentler slopes, which are veneered with the debris of disintegration in a hot, semiarid climate, exposures may be poor or lacking. In general, the outcrops permit structural interpretation with reasonable confidence.

Rock Sequence

With the exception of small inclusions in certain intrusive masses, no pre-Mesozoic rocks crop out in this area. Nor are there any Cenozoic rocks if alluvium and Pliocene(?) gravels are ignored. All other exposed units appear to be of Mesozoic age.

Brown (1939) regarded all of the Mesozoic strata as Cretaceous. He divided these rocks into three formations: Cretaceous volcanic rocks (the oldest), Recreation Redbeds (next higher in the succession), and Amole Arkose (youngest). The Cretaceous volcanic rocks comprise most of the Piedmontite Hills, the Recreation Redbeds most of the Red Hills. The Amole Arkose is extensively exposed on the northeastern side of these hills, and limited exposures of the arkose are present on the southwestern side also (Fig. 3). Colby (1958) recognized that the two older Mesozoic formations are interlayered and suggested that they be combined into one unit, the Recreation Redbeds. In this report we follow his suggestion and infer further that volcanic rocks and red beds are facies of one large depositional unit (see Fig. 8).

Damon (1967) published an apparent age of 150 $\pm$ 5 m.y. obtained by the K-Ar method from an andesite porphyry intrusion into the Recreation Redbeds at N,0-17, 18 (Fig. 3). Apparently, the Recreation Redbeds are pre-Cretaceous, possibly Triassic, in age. As will be shown, these pre-Cretaceous rocks have been disturbed during at least two intrusive episodes widely separated in time.

Recreation Redbeds

The Triassic(?) fragmental volcanic rocks, best displayed in the Piedmontite Hills, consist essentially of a sequence of volcanic pebble,

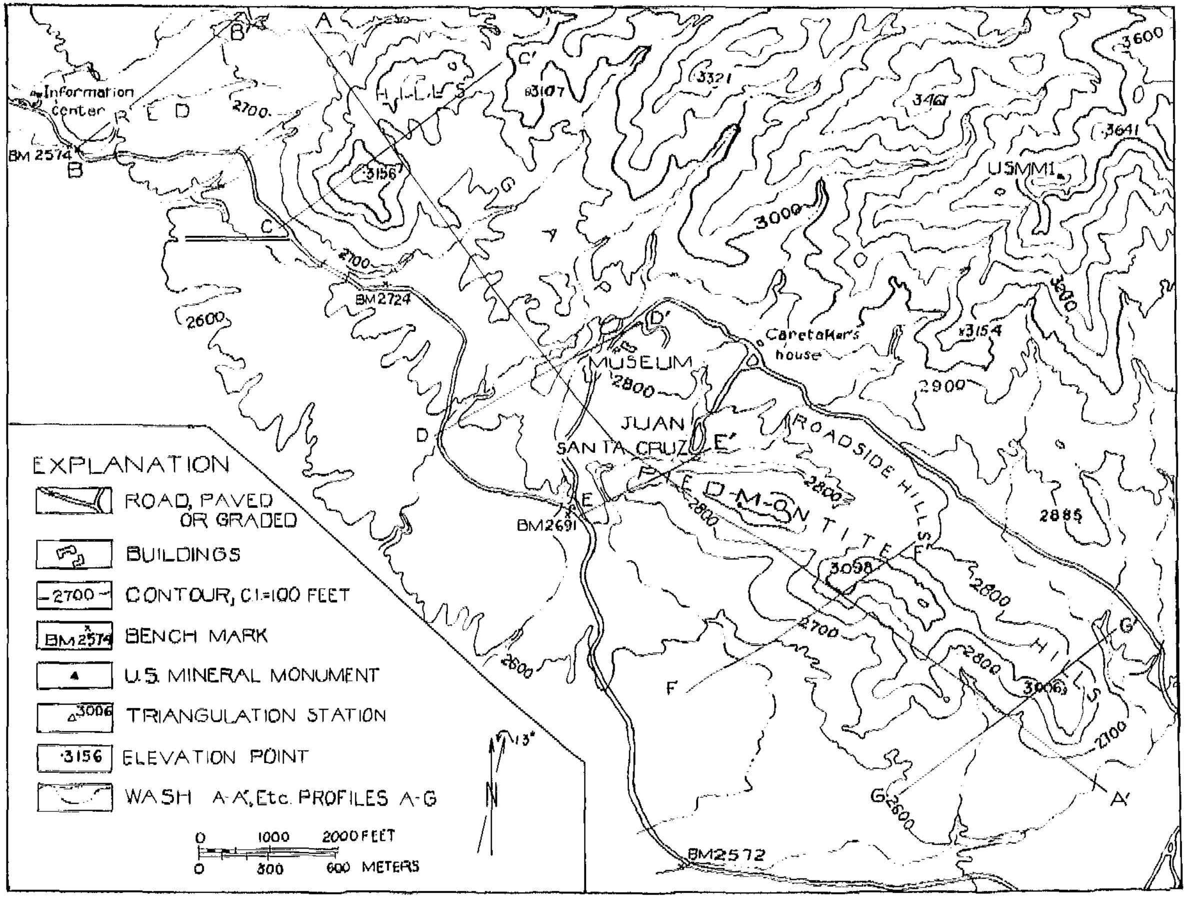

Figure 2. Topographic map of Red Hills—Piedmontite Hills and vicinity.

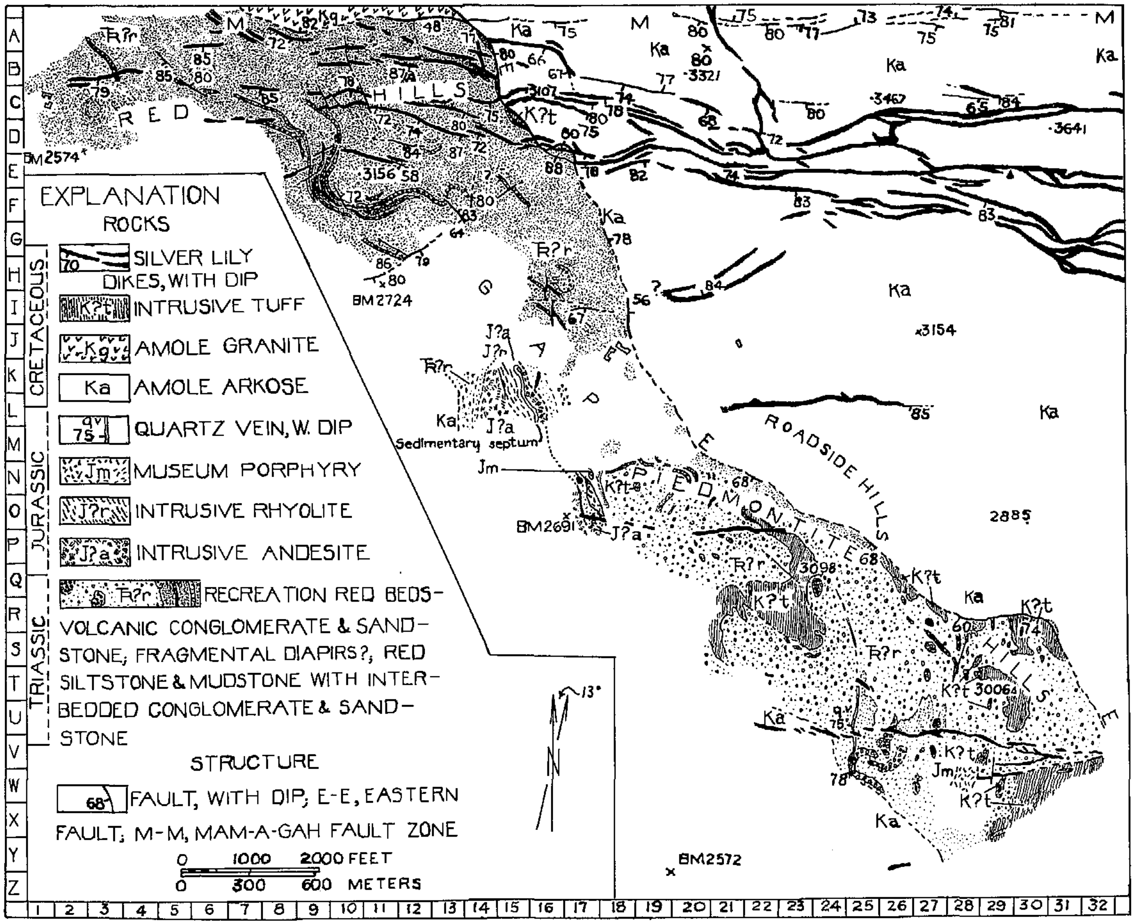

Figure 3. Geologic map.

cobble, and boulder conglomerates and tuff breccias. Each is several meters thick, and many grade abruptly upward into coarse-grained, light-gray, laminated volcanic sandstones 1 to 10 or more decimeters thick. These layers may represent lahars that came to rest under water, with the sandstones in each case the last-deposited "tail" of the subaqueous flow.

In the southwestern part of the Piedmontite Hills, light-gray, pinkish-brown, and smoke-gray sandstones crop out among strata of the Recreation Redbeds of Colby (1958). Northward in these hills, thin beds and isolated blocks of red mudstone, siltstone, and fine-grained sandstone become increasingly conspicuous. A band of these red rocks extends southeastward from Juan Santa Cruz Picnic Area parallel to the Eastern fault (Fig. 3, N-20 to P-25). Followed southeastward, this red band is seen to break up into isolated blocks embedded in the coarser clastics (Fig. 3, R-26). The red blocks have been interpreted as remnants of a formerly more extensive band that was disrupted and largely dispersed by the more permeable, fluidized, coarse-grained clastics (Mayo, 1963). Several small apophyses of intrusive tuff are exposed where the red band breaks up. Heat from these intrusions, acting on pore water, might have been responsible for fluidization and activation of the coarser grained clastics.

The principal rocks of the Red Hills are the red mudstones, siltstones, and fine-grained sandstones which are sparingly present in the Piedmontite Hills and more abundantly so in the intervening Gap. These fine-grained red rocks exist as beds that may reach as much as 4 to 6 meters in thickness. The beds are usually devoid of internal stratification, except at the tops where the grain size coarsens somewhat and laminae, or even cross laminae, are present. The origin of these thick, mostly "massive" red beds is as yet an unsolved problem.

Reddish-gray or gray sandstone beds as much as 8 m thick are not rare in the Red Hills, and several beds of pebble conglomerate or breccia, 3 to 4 m thick, are known (Fig. 3). These coarse-grained clastic units appear to have been deposited in very broad, shallow channels eroded on extensive red mud flats. Two deeper, steep-walled, filled channels are exposed on the topmost peaks near the eastern end of the Red Hills (Fig. 3, B, C-11, 12, and B-13-14), and what appears to be a third large filled channel is on a hilltop in the Gap (Fig. 3, H-16).

The andesite porphyry (Museum porphyry), reported by Damon (1963) to be about 150 m.y. of age, intrudes the Recreation Redbeds and is part of an intrusive complex (Fig. 3, J, P-14, 18) which includes apparent basaltic andesite and intrusive rhyolite. Because of the close association of these igneous rock types, we have assumed all members of this complex to be Jurassic in age.

The Recreation Redbeds are also intruded by several large and small bodies of rhyolitic tuff (Fig. 3), a few of which have already been mentioned. At R, S-30, 31 (Fig. 3), this tuff intrudes Amole Arkose. The tuff may be correlative with the Cat Mountain Rhyolite (Brown, 1939), shown by Damon (1963) to have been emplaced in earliest Maestrichtian or latest Campanian time.

Apparently related to emplacement of the intrusive tuff are relatively small masses of volcanic conglomerate or breccia (fragmental diapirs, Mayo, 1969) that seem to have risen through and disrupted overlying layers of the Recreation Redbeds. Most carefully studied of these mobilized masses is at Q-23, 24 (Fig. 3) in the central part of the Piedmontite Hills. The energy for this reaction might have been supplied by heat, and perhaps fluids, from the intrusive tuff. This appears to be the same as the action by which the coarser clastics attacked and partially destroyed the red band southeast of Juan Santa Cruz Picnic Area.

Because of limited exposures and disturbances resulting from at least two intrusive episodes, there is at present no satisfactory estimmate of the thickness of the Recreation Redbeds sensu Colby and there may never be. Brown (1939) measured 1,265 (386 m) of red beds in Mine Gulch in the northern part of the map area. Colby (1958) measured 2,290 feet (699 m) of the same rocks in the Red Hills and 2,635 feet (803 m) of fragmental volcanics in the Piedmontite Hills. In no case were both top and bottom of the formation exposed, so the measurements are minima. Colby thought the Red Hills rocks to be older than the coarser clastics of the Piedmontite Hills, but unless our longitudinal section (see Fig. 6) is in error, the two units may, as previously suggested, be facies of one volcanic formation. Accordingly, we suggest that 3,000 feet of volcanic debris may have accumulated on the Paleozoic floor many millions of years before the onset of deposition of Amole Arkose.

Amole Arkose

Apparently, no local geologist questions the Cretaceous age of the Amole Arkose, and the consensus of opinion at present seems to be that this formation is Early Cretaceous. The evidence, however, is not as definite or as complete as could be desired.

The Amole Arkose consists of at least 2,275 feet (690 m) (Brown, 1939), p. 718) of coarse, medium, and fine-grained arkose, sandstone, siltstone, and shale, with a few thin beds of conglomerate and argillaceous limestone. The usual absence of volcanic debris and the drab-gray, black, green-gray, and buff colors serve to distinguish this formation from the more brilliantly colored, volcanically-derived Recreation Redbeds.

The two formations, Recreation Redbeds and Amole Arkose, record strongly contrasting environments of deposition--the red beds record extensive channeled mud flats, perhaps frequently inundated, that received drainage and occasional hot (?) avalanches from an adjacent volcanic highland; the arkose records an alluvial flood plain that received sediments largely from granitic sources and had many local ponds and marshes in which limy muds and black muds accumulated.

Silver Lily Dikes

The distribution of the Silver Lily dikes of Brown (1939) in the map area is shown on the formation map (Fig. 3). The dike material was tentatively identified by Brown as quartz latite porphyry. The porphyry appears to have filled irregular fissures. Most of the fissures opened immediately south of the Mam-a-gah fault zone, yet the dikes do not occupy the zone itself. As shown many years ago by Hans Cloos (1939), shears usually make poor channels for viscous fluids.

East of the map area, the Silver Lily dikes transect at least part of the Campanian-Maestrichtian Cat Mountain Rhyolite. We consider the dikes to be Maestrichtian, but in the absence of radiometric dates a Paleocene, or even a mid-Tertiary, age cannot be precluded.

Structural Geology

Structural Setting

The major structural elements of the map area (Fig. 3) are: (1) the volcanically derived core of Recreation Redbeds and various intrusions in the Red Hills, Gap, and Piedmontite Hills, (2) the pre-Cretaceous erosion surface formed by removal of the upper part of this core and a portion of which is now the Eastern fault, (3) the thick mantle of Amole Arkose which was deposited on the erosion surface and now lies on either side of the uplifted core, (4) the east-trending Mam-a-gah fault zone which separates an intruded and greatly upheaved terrain on the north from downfaulted Amole Arkose on the south, and (5) the Silver Lily dike swarm immediately south of and parallel to the Mam-a-gah zone.

Within the volcanic core and the Amole mantle, the fabric elements that we have measured are stratification and planar flow layers, cleavage, mostly gently dipping, striated surfaces, and faults.

Stratification and Flow Layers in the Volcanic Core

Measurements of the attitudes of stratification and planar flow structure are plotted (Fig. 4), and the poles to strata in the pre-Cretaceous core are shown on stereonets (Fig. 5). Modal bedding orientations for the Piedmontite Hills, Gap, and Red Hills are N 20° E, 20° SE; N 42° W, 22° NE; and N 58° W, 22° NE, respectively. Figures 4 and 5, together with section A-A' (Fig. 6) and the profiles (Fig. 7) give the impression of a north-northwest-trending, doubly plunging anticline, or dome, in the pre-Cretaceous rocks. For example, the stereographic plot of poles to bedding for the Piedmontite Hills reveals a great-circle distribution corresponding to folding about an axis plunging 27° S 32° E. The culmination of the inferred dome (Fig. 6) is in the Gap immediately beyond the northern end of the intrusive complex.

The fact that Recreation Redbeds strata locally appear as though molded to the form of the intrusive complex (Fig. 4, J, P-14, 17) suggests that the intrusions might have forced aside the strata and that therefore at least part of the core structure might be of Jurassic age. Moreover, at numerous places where Recreation strata meet the Recreation–Amole contact at a large angle (Fig. 4), the core structure is obviously pre-Amole. Apparently, emplacement of the intrusive complex and initial deformation of the Recreation Redbeds could well have been Jurassic events.

The post-Amole intrusive tuff must have encountered a structure created long before and have been emplaced without destroying the old arrangement. The northernmost large mass of tuff in the Piedmontite Hills (Fig. 3, O, R-20, 23) is a sill-like or laccolithlike intrusion, generally conformable with the bedding of the fragmental volcanics, but locally crosscutting. The same appears to be true of the other sizable mass of tuff in these hills (Fig. 3, T, U-28, 30) and the one in the big wash to the southeast (Fig. 3, V, Y-29, 32). A few tuff dikes and other steep-sided apophyses seem to be examples of the feeders of the larger, mostly concordant intrusions.

Although the tuff insertions along stratification of the volcanic rocks obviously did not cause the overall structure of the Piedmontite Hills, they must have modified it. Emplacement of the tuff, of which we may now see only a portion, surely thickened the stratigraphic section. Indeed, Guild (1935) considered the emplacement of this rock, which he called felsite, to be the cause of the uplift of these hills.

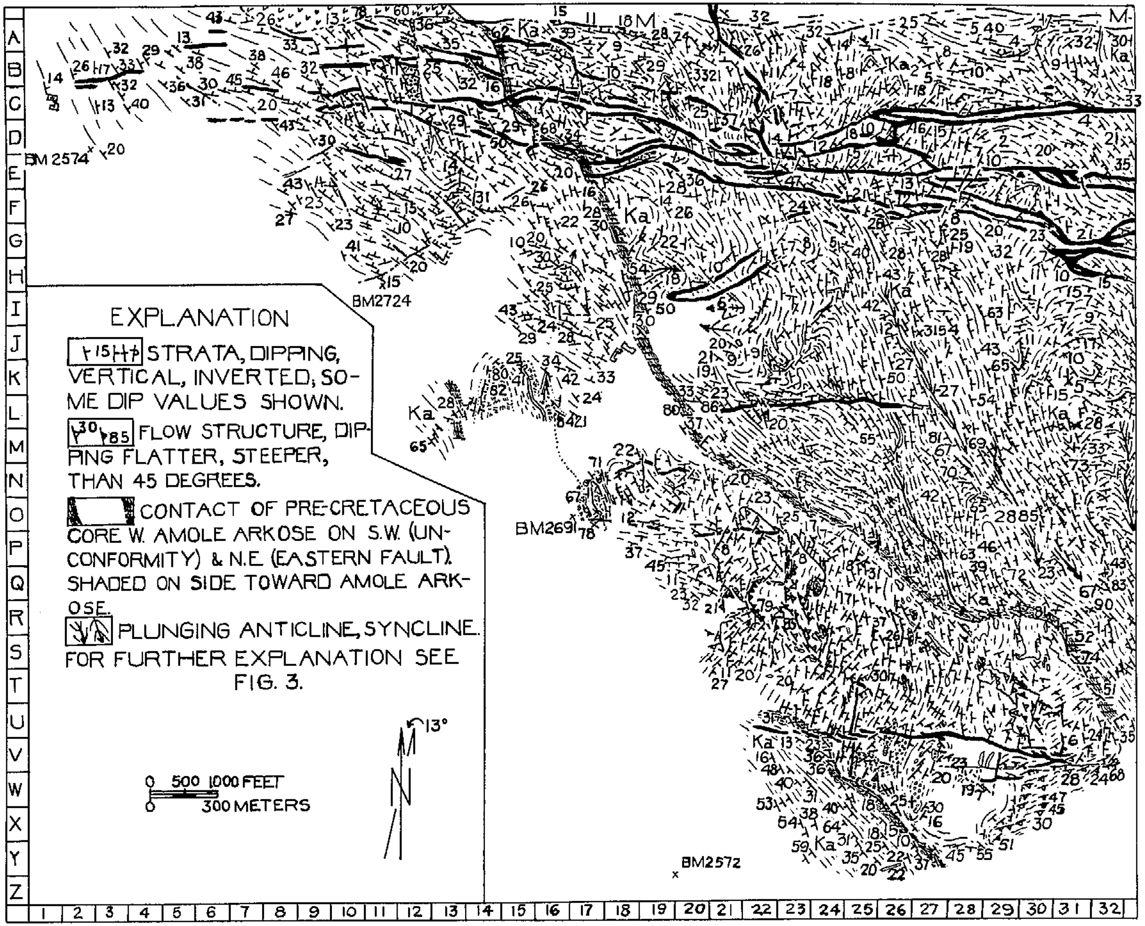

Figure 4. Measurements on strata and flow structures.

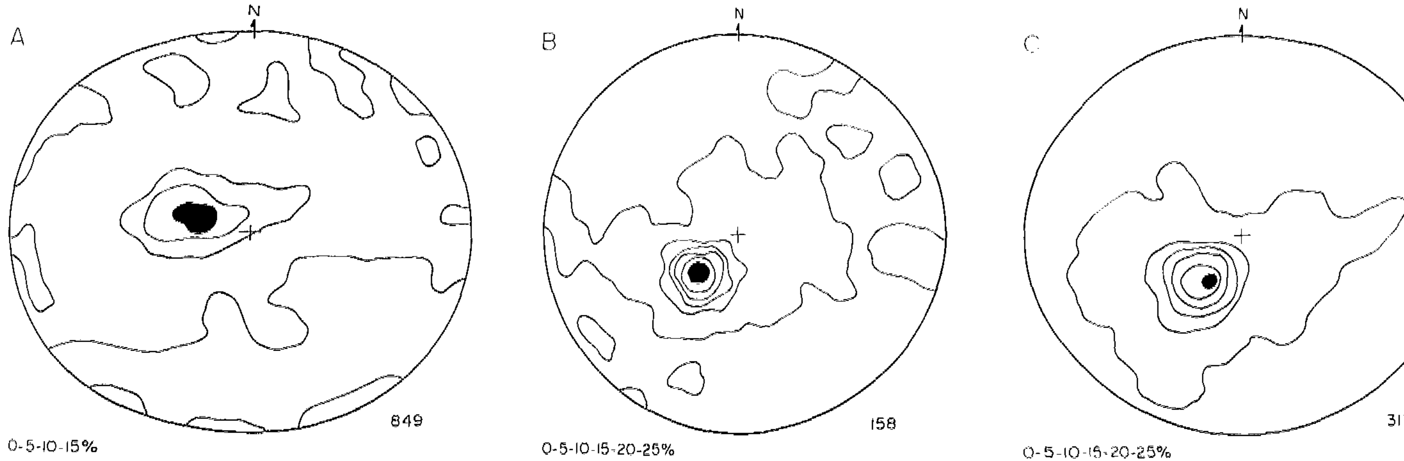

Figure 5. Lower hemisphere equal-area projections of poles to strata in (A) the Piedmontite Hills, (B) the Gap, and (C) the Red Hills.

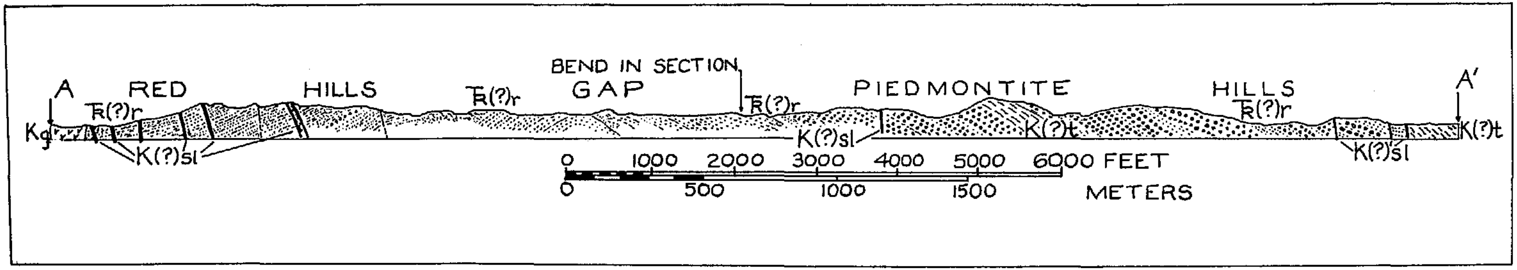

Figure 6. Longitudinal profile through Red Hills, Gap, and Piedmontite Hills.

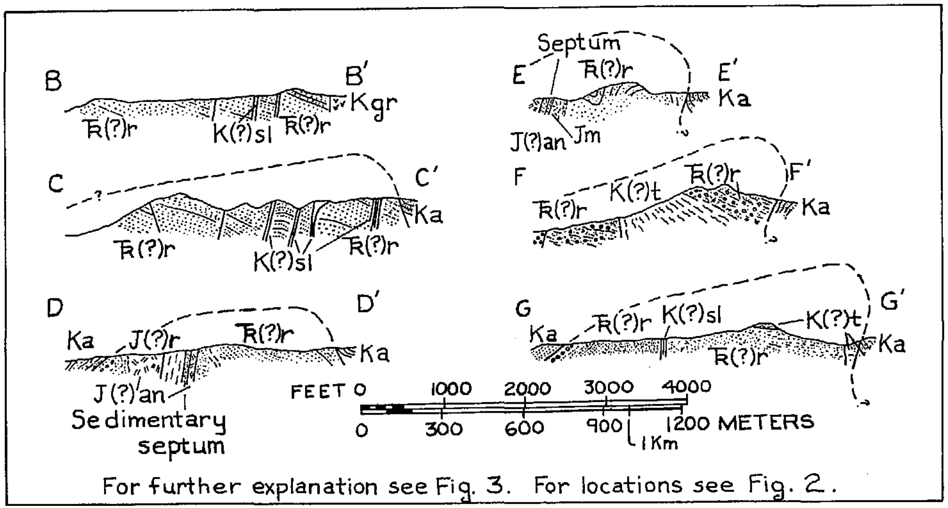

Figure 7. Six profiles across the volcanic core.

Contact between Recreation Redbeds and Amole Arkose

At no place in this area is the base of the Recreation Redbeds exposed, but the contact between red beds and arkose can be studied in the map area. Perhaps the best exposures of this surface are in the walls of a wash at Y-27 (Fig. 3). There the contact appears to be a disconformity, or at most an angular unconformity with very slight angular discordance. Moreover, a red layer, perhaps two meters thick, is interbedded with the arkose at this place.

Because of the above relations, it was once assumed the redbeds deposition progressed with no great time lapse into Amole sedimentation. However, in view of the considerable age difference—Triassic(?) and Early(?) Cretaceous—of the two formations, the above interpretation is not tenable. Apparently, at the onset of Amole deposition, some parts of the Recreation Redbeds were eroded and the resulting red debris was deposited on the basal Amole stratum.

Confirmation of this revised interpretation is present at U, V-22, 23 (Figs. 3, 4) where the base of the Amole Arkose is seen to turn westward, truncating Recreation strata at large angles. Apparently the Amole was deposited on a surface with considerable relief, superimposed on previously disturbed red beds. Erosion of pre-Amole hills could have readily supplied the red debris interbedded with the basal Amole strata.

On the northeast side of the Piedmontite Hills, the unconformity between the Recreation Redbeds and the Amole Arkose is additionally a movement surface, named by Colby (1958) the Eastern fault. That this is indeed a fault seems abundantly attested by the intense shearing and alteration along it; yet this boundary is a surprising feature. In the northern part of its trace the Eastern fault is reasonably straight, steep, normal, east side down, but at D, E-16, 17 (Fig. 3) this trace becomes very strongly curved. Farther south the fault trace is locally strongly curvilinear, and the fault becomes a steep upthrust (Fig. 3, E-9, F, G).

Such irregularity of the trace of this steep structure is enigmatic, but it can be understood if, as already noticed, the pre-Amole erosion surface had considerable relief. If such an irregular surface were tilted steeply eastward, the hills or ridges on the old erosion surface should now be expressed in plan as eastwardly convex "bulges" in the trace of the Eastern fault. The pre-Cretaceous valleys, on the contrary, should appear as eastwardly concave "saddles" between the bulges. This accords with observations.

If the above is not idle speculation, then the moderately tilted unconformity on the southwest side of the Piedmontite Hills and the steep, or even overturned, Eastern fault on the northeast side are one and the same. Accordingly, in profile, the form of the Recreation–Amole contact would be an irregular arch, strongly asymmetrical and locally overturned toward the northeast (Fig. 7). The Eastern fault should flatten northeastward at depth.

Deformation of Strata in the Amole Arkose

The structure of the Cretaceous mantle of the volcanic core is surprisingly complicated (Fig. 4). True, the Amole cover to the southwest, so far as it is exposed, is simple, as it should be if the arkose was deposited on an erosion surface that has since been only moderately tilted. Quite to the contrary, the Amole Arkose northeast of the core is complexly deformed. In the southeast, the general trend of Amole strata is about north-northwest, roughly parallel to the trace of the Eastern fault; but this trend becomes increasingly deflected if followed northward toward the Mam-a-gah fault zone. So followed, the strata are seen to bend westward to parallel the zone (Fig. 4, A, D-15, 18). This observation has suggested to some that movement on the Mam-a-gah was mostly left-lateral strike-slip. However, a study of the Mam-a-gah fault zone disclosed only one left-lateral offset which amounted to as much as 18 inches, and even that was not demonstrably a result of strike-slip movement.

With approach from the south to a large, east-trending normal fault, which dips southward, there are four possibilities for changing the trend of strata in the hanging wall. Assume that the pre-faulting trend of the strata was north-northwest and the dip of the strata was eastward. If the hanging wall tilts or slumps toward the fault plane, the strata with approach to the fault should turn westward. West-dipping strata, on the contrary, should turn eastward (Fig. 4, A, B-29, 31).

If, instead of tilting or slumping toward the fault plane, the hanging-wall strata are dragged upward along the fault, the opposite of the above will happen, i.e., east-dipping beds will turn eastward, west-dipping ones westward. Study of Figure 4 seems to suggest that tilting of the hanging wall toward the Mam-a-gah zone was more important than "normal" drag on the faults. A further complication is the presence, south of the Mam-a-gah zone, of at least one broad, south-plunging syncline (Fig. 4, D, Q-26, 32) with minor anticlines and synclines within it. Some changes of trend merely express the trough of this syncline.

In view of the above and of the apparent lack of evidence for appreciable strike-slip displacement in the Mam-a-gah fault zone, generation of the structure in the northern part of the Amole mostly by normal faulting under tension appears to be an attractive possibility. The presence of the fissure-filling Silver Lily dike swarm appears to strengthen the case for tension.

A peculiar feature of Amole structure northeast of the volcanic core is the presence, opposite the Gap with its Jurassic(?) culmination, of a broad area of Amole Arkose with gentle dips, confused strikes, and open folds, which plunge in several directions (Fig. 4, E, L-17, 23). There, perhaps, a broad, irregular cross warp or ridge in the hidden Triassic(?) floor extends eastward beneath the Amole cover. If so, the confused but mild structure may be largely the result of differential compaction above an uneven floor.

Southeast of the Gap, beginning at the "picnic area dike" (Fig. 4, L-20, 25), the Amole trend becomes more uniform and rather tight anticlines and synclines appear. In this area also, the Eastern fault changes trend from S 30° E to S 60° E, whereas the Amole Arkose undergoes no corresponding change of trend. Instead, the arkose appears to have been lifted and forced aside to make room for the transgressing core (see Fig. 14, profiles 5, 6, 7). Southeast of the second abrupt turn in the trace of the Eastern fault (Fig. 4, Q, R-27, 31; Fig. 14, profile 8), the Amole strata are intensely squeezed and sheared and fold hinges are difficult to locate. Apparently, as the core transgresses ever more eastward, the Amole Arkose becomes the more strongly compressed. As these changes take place, the Eastern fault changes from a steep normal fault to a steep upthrust. Furthermore, in this southeastern area, the volcanic core contains the largest and most abundant insertions of intrusive tuff and has presumably been dilated the most. Guild's (1935) suggestion that emplacement of the tuff caused the uplift appears to have merit.

Cleavage

A steep cleavage is present almost everywhere in the pre-Cretaceous core, including even the Upper Cretaceous(?) intrusive tuff and, as expected, at some places in the Amole Arkose (Fig. 8). In the coarser grained fragmental volcanics, this structure element has the appearance of fracture cleavage, but in the finer grained siltstones and mudstones it exhibits some of the characteristics of flow cleavage. At H-12 (Fig. 8) and at many nearby places, small calcareous concretions in red siltstones are somewhat flattened in the plane of cleavage and slightly elongated parallel to the dip, which is almost vertical. This suggests that when the cleavage formed the rocks were shortening perpendicular to the cleavage plane and elongating nearly vertically. The amount of horizontal shortening and vertical elongation, however, seems to have been modest. The fine-grained rocks are by no means slates, and the cleavage barely approaches the perfection of slaty cleavage.

Bonney (1884) was probably first to point out structures in laminated slates that definitely suggest that fluids and mineral grains streamed upward as flow cleavage formed. The cleavage planes were flow planes. Hills (1963, Fig. X-16, p. 300) illustrated some of these structures, which he termed "festooned bedding." Nothing of the sort has yet been found in the Red Hills or Piedmontite Hills, probably because most of the fine-grained red rocks are not laminated. Further evidence of upward flow of fluids and mineral grains at the time of formation of flow cleavage was presented by Braddock (1970) and by Maxwell (1962). These authors emphasized that flow cleavage is a record of upward laminar flow.

An almost identical viewpoint was taken by Kirillova (1965), who suggested that compression at right angles to cleavage might result from rehydration of clay minerals, especially montmorillonite, by fluids driven up from depth by increasing temperature and resulting metamorphism. The direction of compression would be determined by the presence and the attitudes of "constraints," such as resistant beds. An important point favored by some Russian geologists (Beloussov, 1962) is that compression is not applied to a sediment-filled trough from the outside but is generated within the trough itself.

The observation that cleavage is present not only in the pre-Cretaceous volcanic core but also in the Lower(?) Cretaceous Amole Arkose as well as in the Upper Cretaceous(?) intrusive tuff points to a Laramide, or possibly mid-Tertiary, age of the cleavage. At present, assignment to the Laramide seems reasonable.

The cleavage trend averages about north-northwest in complete disregard of most attitudes of stratification in the core (Fig. 8; compare Figs. 5A, 9A). The average orientation of the cleavage in rocks in the Piedmontite Hills is N 20° W, 80° NE (Fig. 9A). In the Red Hills, the cleavage strikes N 44° W and dips 85° NE (Fig. 9B). The cleavage appears to be approximately parallel to the axis of the Jurassic(?) doubly plunging anticline (Figs. 4, 8). An exception is in the northwest corner of the map (Fig. 8) where the cleavage is seen to turn westward, then northward around the Laramide (Damon, 1967) granite as though forced aside or as though molded by compression to the form of the granite. South of the southernmost Silver Lily dike (Fig. 8, V, W-22, 32; Fig. 4, V, W-22, 32), the cleavage continues with direction unchanged across strongly disturbed strata. The disturbances seem older than the cleavage and might be Jurassic in age.

Apparently, the cleavage expresses a Laramide (or mid-Tertiary ?) reactivation of the Jurassic(?) north-northwest-trending anticline.

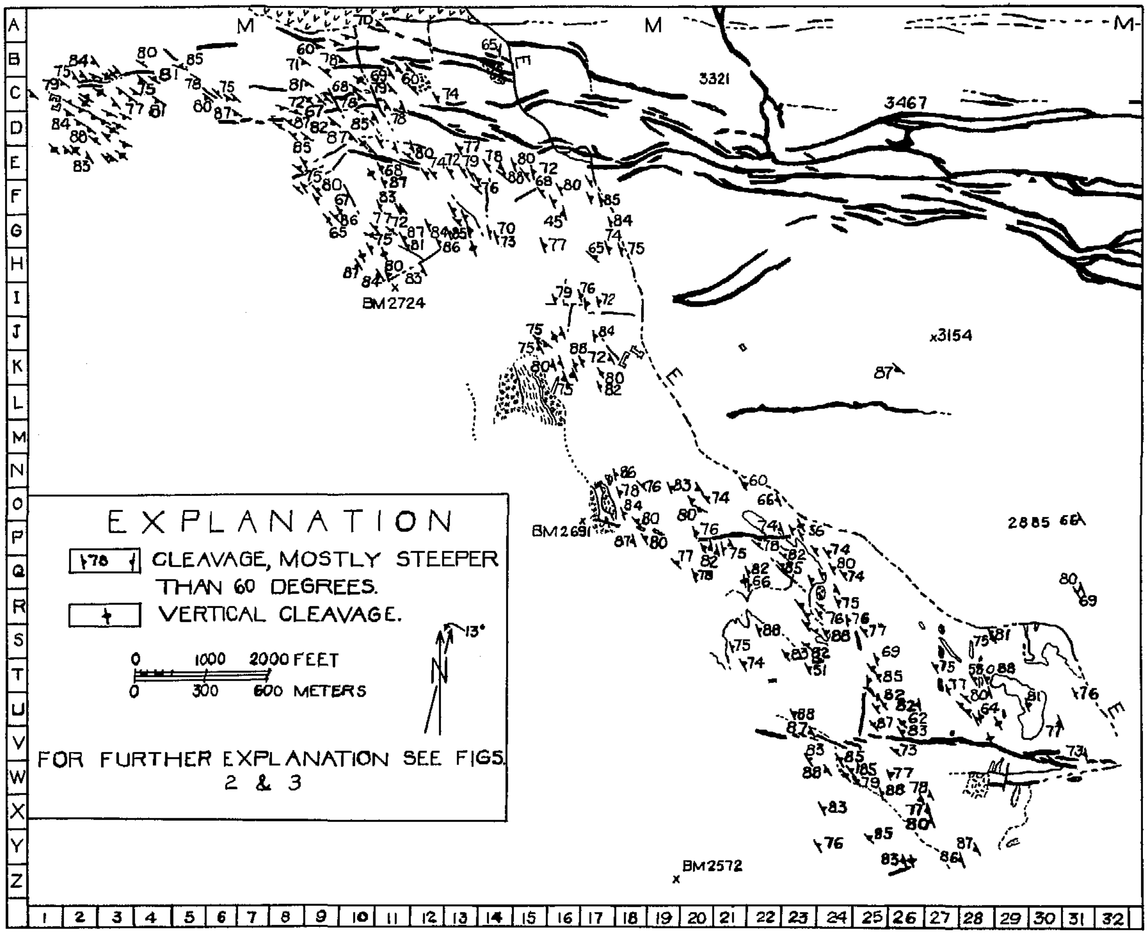

Figure 8. Measurements on cleavage.

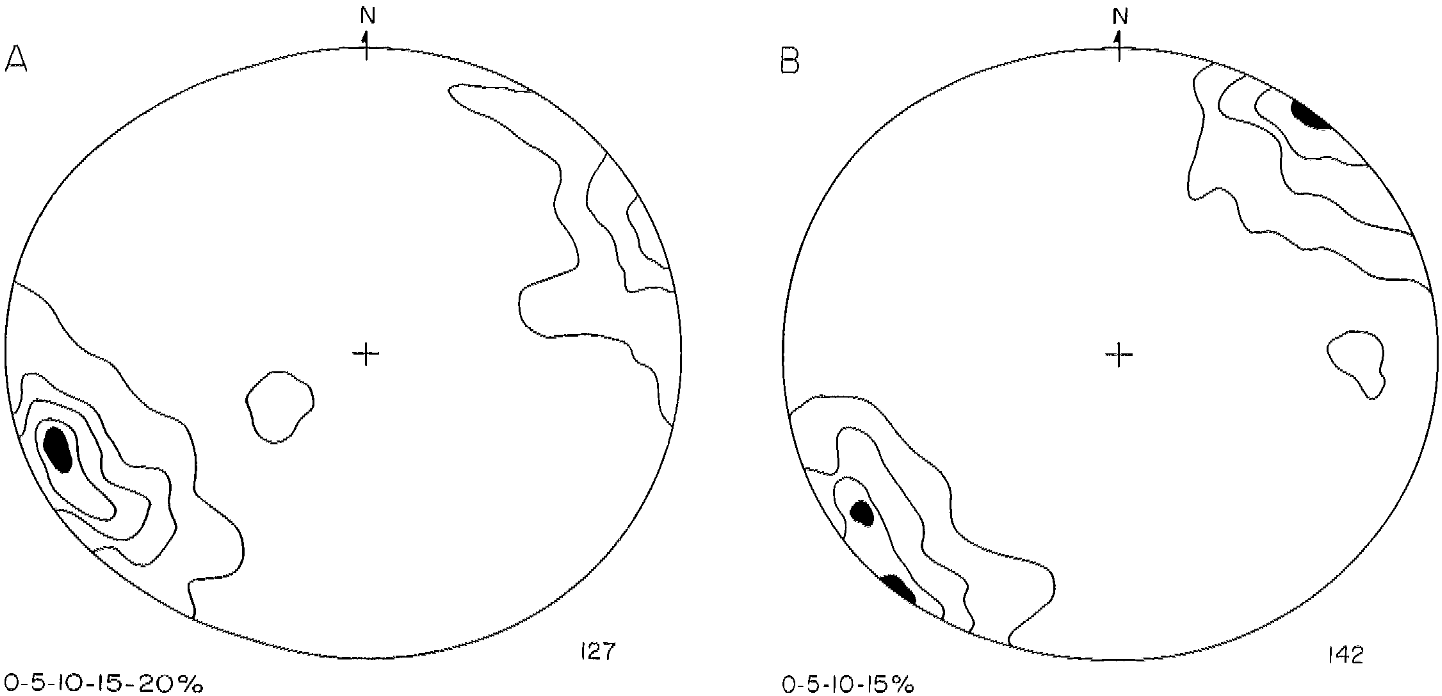

Figure 9. Lower hemisphere equal-area projections of poles to cleavage in (A) the Piedmontite Hills and (B) the Red Hills.

Striated Surfaces

Flat to moderately dipping fractures, slickensided and engraved with striae (Fig. 10), are extremely abundant in the Piedmontite Hills, more sparingly developed in the Red Hills, and even more so in the Gap and the Amole Arkose (Fig. 11). The surfaces strike and dip in a variety of directions. Frequently, but by no means always, they coincide with stratification. In marked contrast to strikes and dips, the trends of striae are remarkably uniform and the striae plunge mostly northeast but also southwest (Fig. 12). These elements are present even in the intrusive tuff, so that a Laramide age is again suggested.

Similar surfaces, present along the intrusive contact of the Museum andesite porphyry, are known (Mayo, 1961) to be small thrusts that might have helped to provide space for the porphyry. Displacements on these little thrusts range from a fraction of an inch to perhaps as much as 3 inches. Throughout the mapped area in general, however, exposures that reveal direction and amount of movement on the slickensides are very rare. The few that we have been able to find suggest that these displacements are all flat to moderately dipping normal faults with slips measurable in inches.

Several possible theories bear on the origin of the surfaces.

1. Perhaps the Laramide (or mid-Tertiary ?) uplift of the volcanic core was accomplished by flexural slip folding. The observation that many slickensided surfaces are parallel to bedding would seem to support this idea. The surfaces functioned to transport higher strata over lower ones in the direction of the crest of the doubly plunging anticline. The rather uniform northeast and southwest plunges of the striae negate this theory. No striae plunge either northwest or southeast off the ends of the structure. Also, according to this idea, all slickensided surfaces should be thrusts, which seems not to be the case.

2. If there still are geologists who accept the concept of a great "Tucson Mountain overthrust" that traveled across these mountains from southwest to northeast, they might suggest that the slickensides formed as a drag, or frictional effect, beneath the overthrust as it moved across the autochthon. In this case, the surfaces should be most abundant and most strongly developed in the upper part of the Amole Arkose which was closest to the overriding thrust sheet. As a matter of observation the surfaces are most numerous deep in the pre-Cretaceous part of the autochthon. Moreover, if the surfaces were engendered as suggested above, all southwest-dipping ones should be small thrusts, northeast-dipping ones should be normal faults. This does not accord with our observations.

3. Perhaps, as the pre-Cretaceous core rose, its Cretaceous mantle slid off to the northeast and southwest. The striated surfaces might then be shears resulting from frictional drag along the Recreation–Amole contact. In this case, all of the slickensides should occur on normal faults—just as our data suggest. But this hypothesis cannot be accepted either because, if true, the striated surfaces should be mostly restricted to the immediate vicinity of the Eastern fault and of the unconformity on the southwest side of the core (Fig. 11). The mapping did not reveal such a distribution. Furthermore, one might in this case expect the striae near the Eastern fault to plunge more steeply than any that we have measured. Apparently, the striated surfaces were not engendered by sliding of the Amole cover off the rising core.

4. Similar surfaces, although probably more extensive than these, were first reported from the granite massif of Striegau-Zobten in Silesia by Hans Cloos (1922), who explained them as results of stretching in the

Figure 10. Photograph of striated surfaces.

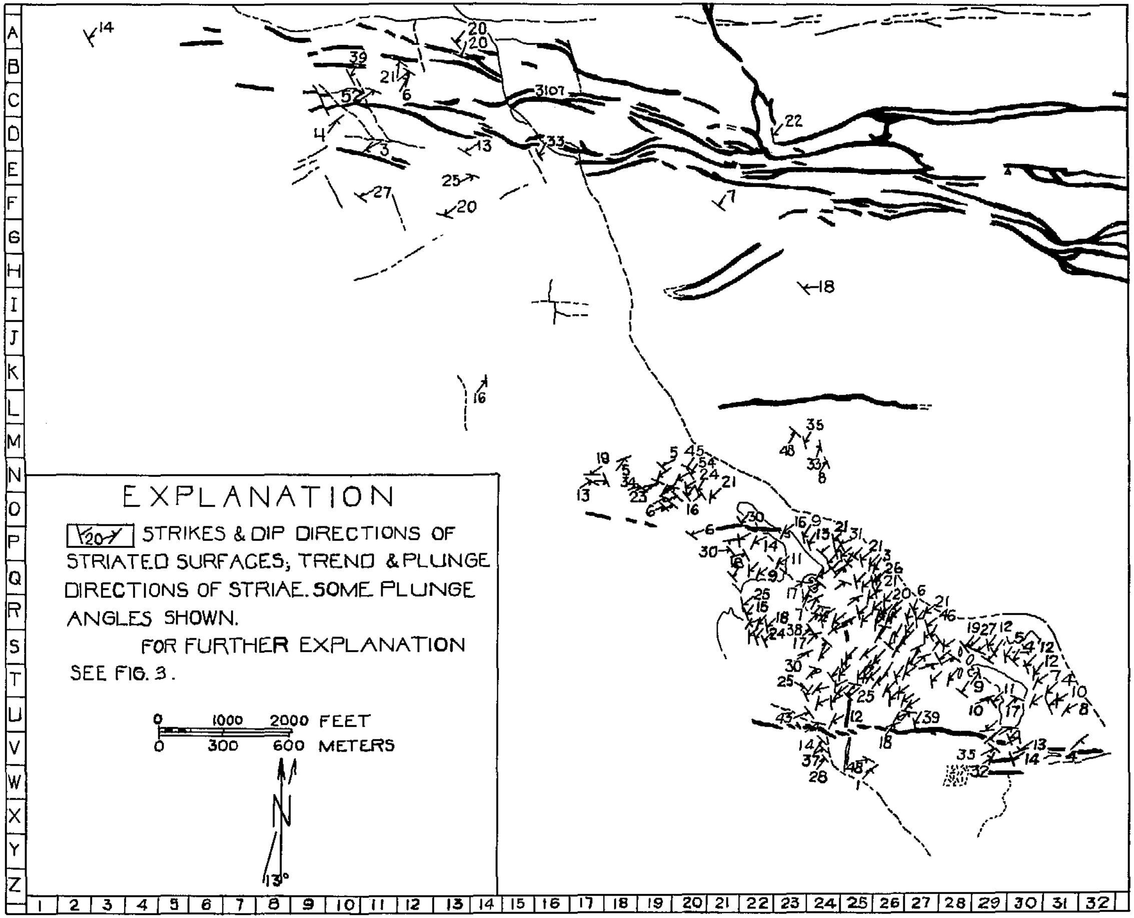

Figure 11. Measurements on striated surfaces.

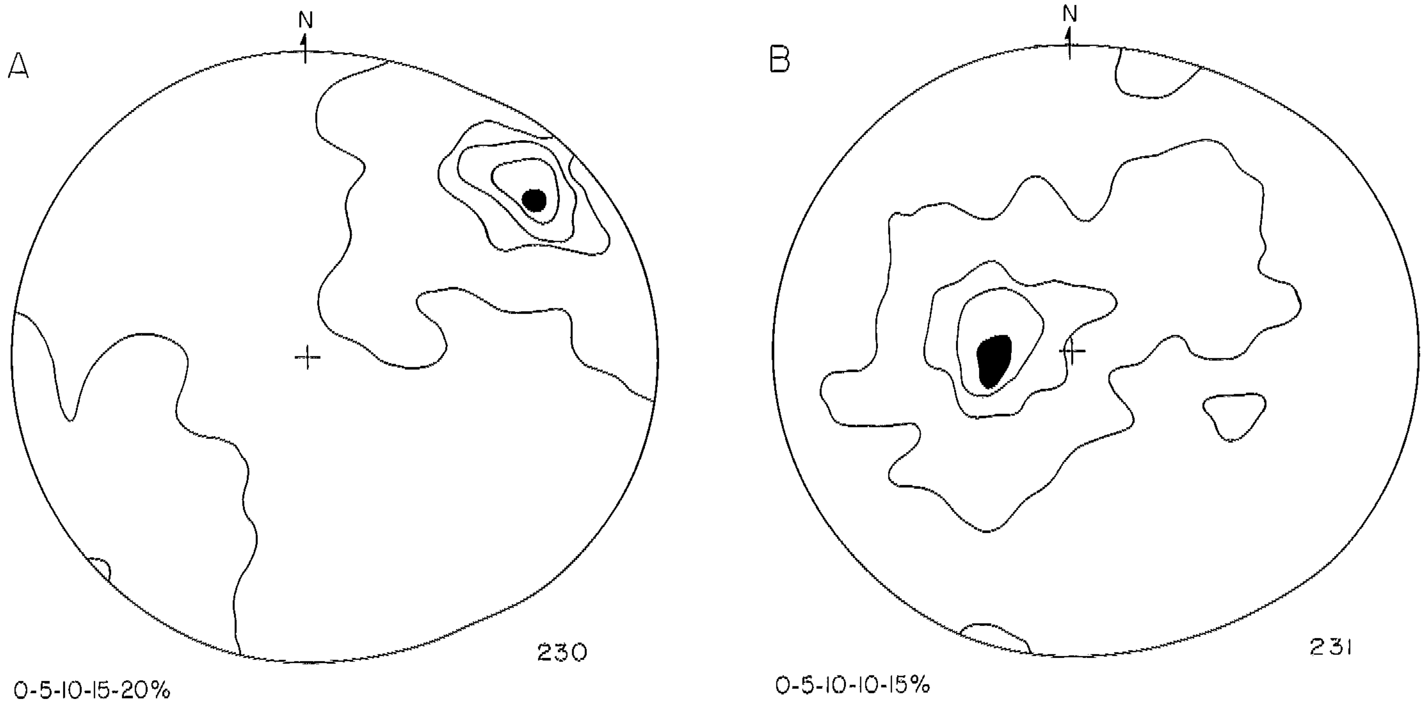

Figure 12. Lower hemisphere equal-area projections of (A) striations and (B) poles to stretching surfaces in the Piedmontite Hills.

arching uppermost shell of the rising, consolidating granite. Although strikes and dips of the surfaces varied widely, trends of striae were much more uniform and lay in the direction of somewhat older stretching, formed during a hotter plastic stage of the rising massif. Cloos called these striated surfaces Strekflachen (stretching surfaces).

The similarities between the surfaces in Silesia and those in the area mapped by us suggest to us that the striated surfaces in these hills served the same mechanical function as the stretching surfaces in the Silesian granite. Accordingly, in Laramide (or mid-Tertiary ?) time, on the site of an earlier, Jurassic(?) doubly plunging dome, the volcanic floor, beneath its thick Cretaceous cover, began to swell and to rise as an elongate, north-northwest-trending welt. In earlier stages, the uplift was to some extent accomplished under moderate compression by shear and flow on axial plane cleavage. As the core rose to a higher cooler level, the top arched and was extended by shearing on stretching surfaces. A dynamic relationship between arching of the strata and the development of stretching surfaces and striations is clearly supported by the stereographically plotted fabric elements for the Piedmontite Hills. Poles to bedding (Fig. 5) and poles to stretching surfaces (Fig. 12A) define common great circles and common π-axes of rotation (or in the case of the stretching surfaces, apparent rotation) (Fig. 12B). The modal orientation of striations in the Piedmontite Hills is 18° N 52° E (Fig. 12B). Significantly, the modal striation orientation and the orientations of the π-axes are mutually perpendicular (Fig. 13).

Faults in the Volcanic Core

The faults mapped in the volcanic core (Fig. 3) are, with little doubt, only a fraction of those that exist there. The trends are: northwest to north-northwest, about parallel to the axes of the Jurassic(?) and Laramide, or mid-Tertiary(?) uplifts; northeast or east-northeast, parallel to the postulated Jurassic(?) cross warp; and north-south or slightly east of north and nearly east-west, parallel to the Silver Lily dikes. All of these faults appear to be normal, or gravity, displacements. They suggest that at some time(s) during the structural history, this area has been under tension.

The northwest-trending faults are oriented about perpendicular to the extension that caused the striated surfaces. Furthermore, one of these faults displaces intrusive tuff in the Piedmontite Hills (Fig. 3, P, Q-22, 23). Perhaps the northwesterly faults are Laramide, if not even younger. A north-south fault displaces a Silver Lily dike in the southern part of the Piedmontite Hills (Fig. 3, W, X-29), but a north-south quartz vein, some 2,000 feet to the west, does not cross the core boundary and enter the Amole Arkose. Apparently, meridional fractures were formed at times many millions of years apart.

The northeasterly fractures have nowhere been observed to displace the pre-Amole unconformity (including the Eastern fault). Therefore, they may be Jurassic in age. On the contrary, faults with this same trend have been found in the Amole Arkose. Adjustment in Jurassic time on nearly east-west faults probably accounts for some of the complicated structure south of the southernmost Silver Lily dike, but again, nearly east-west fractures are also present in the Amole Arkose. The most reasonable interpretation may be that the principal fracture directions were established early and the faults have been reactivated from time to time.

The faults appear to add considerably to the testimony of other structures in favor of overall tension. Moreover, they suggest that at

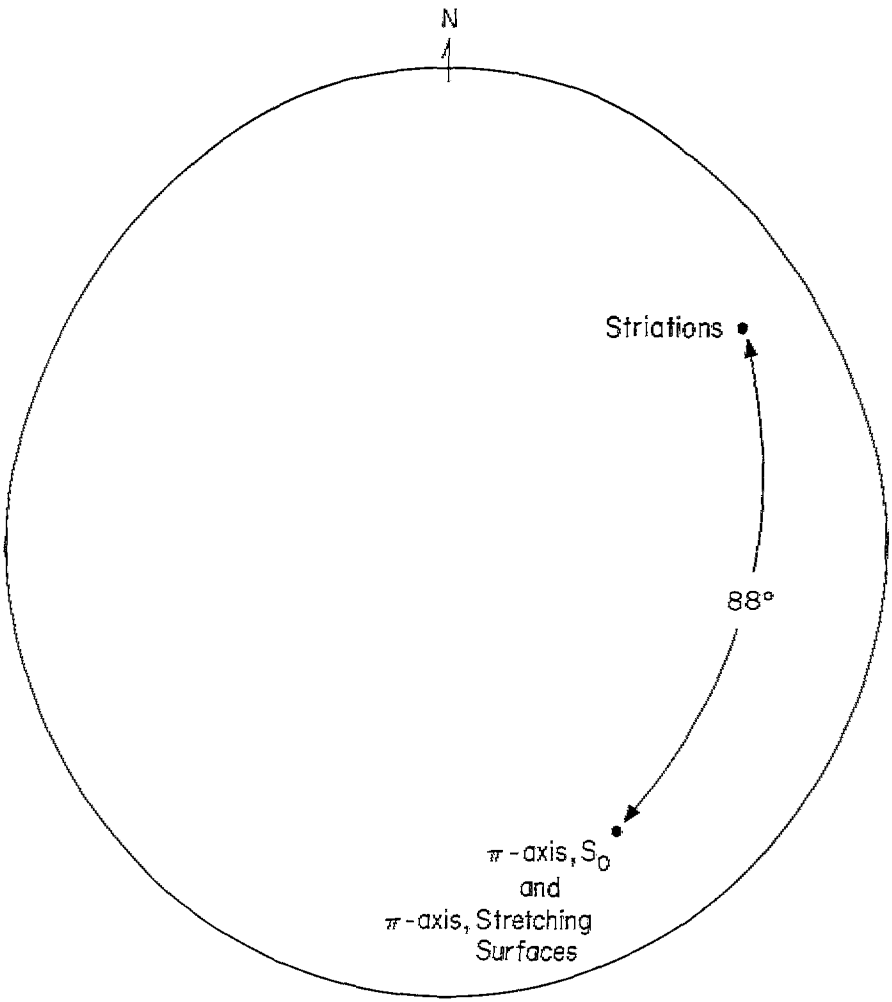

Figure 13. Lower hemisphere equal-area projection showing orthogonal relationship between the average orientation of striations and the π-axes of poles to bedding and stretching surfaces in the Piedmontite Hills.

the levels now exposed tension may have prevailed since Middle Jurassic time.

Effects of Uplift on Adjacent Cover

In profile, the Red Hills—Piedmontite Hills uplift resembles a tilted fault block (Fig. 7), and indeed it seems to be a deeply eroded, fault-block mountain. On the southwestern back slope, tilting of Amole strata might be the only expectable result of uplift, although at one place (Fig. 7, profile D-D; near southwest end) slump folds were formed. However, on the northeast steep faulted flank, Amole strata, unless firmly consolidated, might be expected to glide or slump off the uplift. The greater the amount of uplift, the greater should be the gliding tendency. Furthermore, as already mentioned, where a prominent hill or ridge existed on the pre-Amole surface, the Eastern fault should turn to form an eastward-convex bulge in the side of the volcanic core. The sides of the bulge should transect and turn, counterclockwise or clockwise, the Amole strata, and in front of the bulge these strata should appear to have been compressed as though to make room for the protuberance.

No reliable estimate of the amount of core upheaval seems possible, but judging from abundance and distribution of striated surfaces, the Piedmontite Hills, which incidentally are the site of most of the tuff intrusions, were uplifted most, the Red Hills less and the Gap perhaps least.

There is, however, an alternative. If, during Laramide uplift, the striated surfaces were formed in an upper tensional shell of the volcanic core and if subsequent erosion lowered the Red Hills more than the Piedmontite Hills and the Gap most of all, the resulting distribution of striated surfaces might be precisely what we now find and therefore no indication of relative uplift.

In order to test the above alternatives, eight structure profiles (1-1'—8-8', Figs. 14, 15) were measured across the Eastern fault and adjacent Amole Arkose. Profile 1-1' is at the northernmost place favorable for making such a section and profile 8-8' is at the southernmost favorable locality.

The dip of the Eastern fault and the shapes of folds in the Amole Arkose are shown on the profiles. Except in the western part of profile 8-8' where much thickening of strata has taken place on fold hinges, the principal fold mechanism appears to have been flexural folding. Axial-plane slip has been local and minor throughout most of the profiles.

To compare the eight measured profiles with one another and with the inferred relative uplift of the several parts of the volcanic core, the data have been assembled in Table 1 and some have been plotted on the graph accompanying Figure 15. To obtain the percent minimum apparent shortening, the shapes of the folds were sketched above and below the line of each profile, using the style suggested by the measured data. The length of a folded horizon was then measured, using a piece of string, and the percent minimum apparent shortening was calculated according to the equation

$$\frac{W_o - W_p}{W_o} \times 100 = \text{\% minimum apparent shortening},$$

where W_o is the length of the deformed horizon and W_p is the present width of the belt in which the deformed horizon was measured.

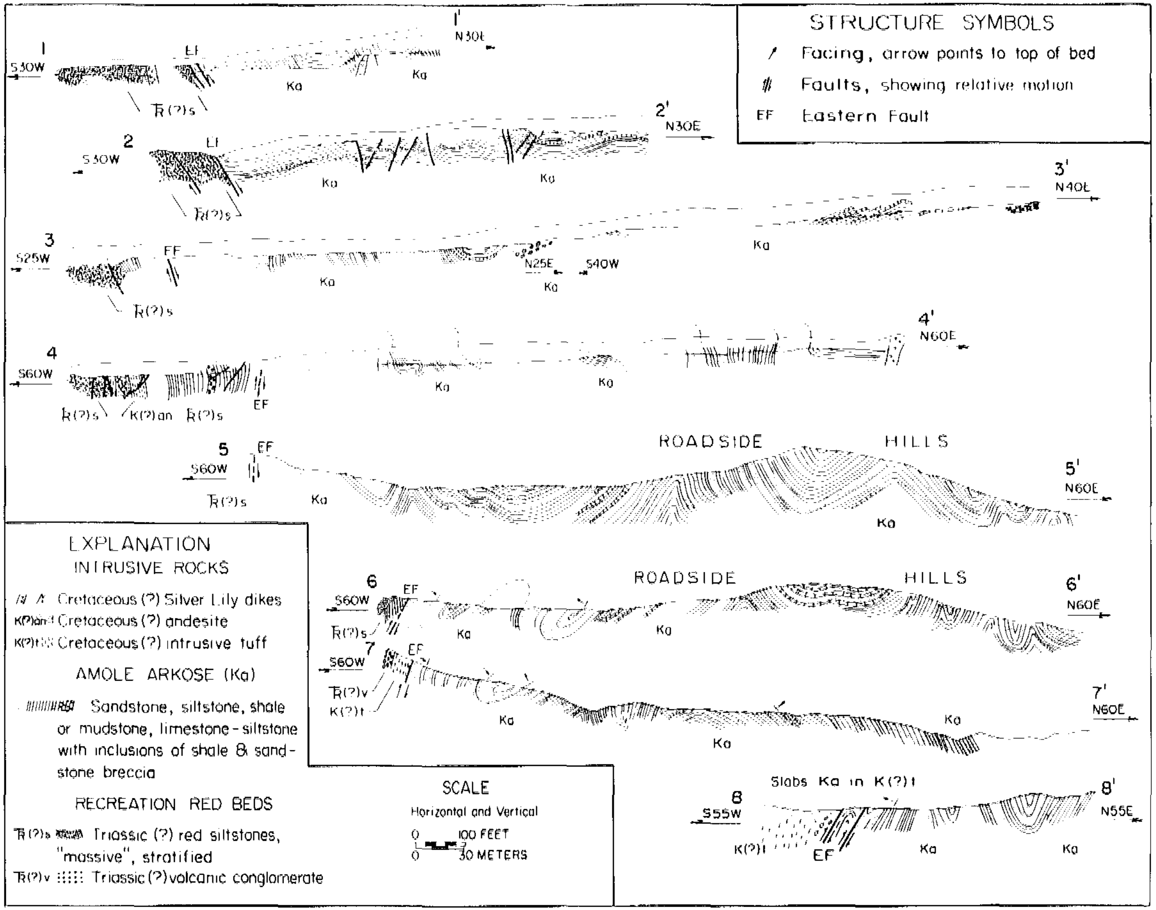

Figure 14. Eight structure profiles across the Eastern fault and adjacent Amole Arkose.

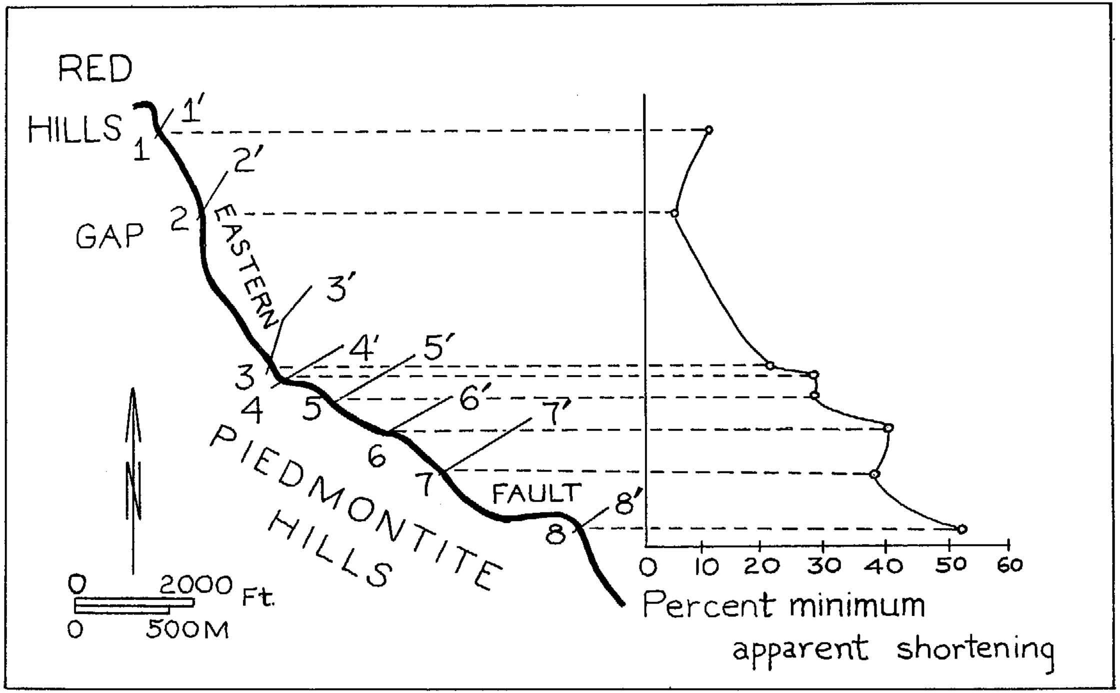

Figure 15. Locations of profiles and percent minimum apparent shortening.

Table 1. Comparison of profiles across Eastern fault

Profile No.	Nature of Eastern Fault	Style of Folding	Inferred Relative Uplift of Core	Minimum Apparent Shortening
1-1'	steep normal	"steps" with flat treads and steep, NE-facing risers	moderate	11%
2-2'	steep normal	broad, gentle, broken arch	slight	5%
3-3'	steep normal	cascade folds	moderate	21%
4-4'	upthrust	cascade folds	moderate	28%
5-5'	upthrust on slight bulge	broad syncline on SW, appressed concentric folds on NE	moderate	28%
6-6'	upthrust on moderate bulge	overturned concentric folds on SW appressed concentric folds on NE	strong	40%
7-7'	upthrust on flank, moderate bulge	appressed concentric folds	strong	38%
8-8'	upthrust on strong bulge	near-isoclinal folds with pervasive shearing	very strong	52%

The map and graph (Fig. 15) reveal an obvious correlation between the attitude and trace of the Eastern fault and minimum apparent shortening. There also seems to be a definite correlation between minimum apparent shortening and inferred relative uplift (Table 1). The alternative suggestion that differential erosion controlled the present distribution and number of presently exposed striated surfaces, which therefore have nothing to do with relative uplift, is rendered untenable by these correlations. Likewise the possibility is precluded that the Eastern fault has merely dropped an already folded Cretaceous sequence alongside the volcanic core. We suggest that the deformation in an adjacent shell of Amole Arkose is an adjustment to differential uplift of the pre-Cretaceous volcanic floor which had considerable relief.

Tectonic History

Based on our accumulated data, as we presently interpret them, the sequence of tectonic events at this locality might have been as follows:

1. In early Mesozoic time, possibly during the Triassic, this area was marginal to a region in which volcanism was in progress. Coarse clastic volcanic rocks were deposited there, perhaps largely as subaqueous avalanches, mud flows, or lahars. These deposits graded into and interfingered with finer detritus, now represented by red sandstone, siltstone, and mudstone. The finest grained materials probably once comprised extensive mud flats on which were eroded shallow but steep-walled channels which filled with coarse sand, gravel, and volcanic breccia. These deposits accumulated to a thickness probably no less than 3,000 feet (914 m).

2. In late Middle Jurassic time, about 150 m.y. ago, there was emplaced in the detrital volcanics an intrusive complex consisting of andesite porphyry, andesite, and rhyolite (Fig. 3). At this time, perhaps, the older Mesozoic volcanic deposits were uplifted to form a north-northwest-trending, doubly plunging dome with a culmination immediately beyond the north end of the intrusive complex. With some subsequent modification, most of the structure now revealed in the attitudes of stratification in the volcanic core may date from this time.

3. There followed an interval of erosion, during which the relief resulting from Jurassic disturbance was greatly changed. If a hill or a mountain once marked the site of the culmination, this was erased and in its place a valley might have formed. The relief on this Upper Jurassic (?) surface might have been several hundreds of feet (tens of meters).

4. In Early(?) Cretaceous time, Amole deposition began. The pre-Cretaceous landscape became buried beneath at least 2,275 feet (690 m) of mostly arkosic sediments. There was some erosion of hills comprised of Recreation Redbeds, and the resulting red debris became interbedded in basal Amole strata. Most of the Amole, however, seems to have been derived from granitic uplifts which had never made important contributions to the red beds succession.

5. During the Laramide (or perhaps the mid-Tertiary orogeny?), beneath the thick Amole mantle and on the site of the Jurassic dome, the pre-Cretaceous floor began to swell. Apparently, later stages of uplift were accomplished under tension, thus bringing about the tilted fault block character (Fig. 7). Much of this uplift was accomplished by displacement on the Eastern fault and an unknown but apparently lesser amount by slip on cleavage and by flexing of strata. The extension re-

sulting from up-arching of the volcanic core was accommodated, at least in part, by "normal" movement on the striated surfaces.

Some adjustment between core and mantle is now recorded as folds in a shell of the mantle adjacent to the Eastern fault. Apparent shortening in this shell appears to be related to relative uplift of the several parts of the core as well as to relief on the pre-Amole erosion surface. For example, in the Piedmontite Hills, where uplift has been greatest, apparent shortening of the Amole Arkose has been greatest.

At about the same time, apparently, as the above uplift, the region immediately north of the mapped area, greatly dilated by intrusive magmas, rose strongly. Adjustments between this pronounced upheaval and the Amole sequence to the south appear to have been made largely in the Mam-a-gah fault zone where most of the faults are normal, south side down. The reaction of the poorly consolidated Amole strata to these displacements probably accounts for the confused pattern of these layers along and near the northern border of the mapped area (Fig. 4).

6. Perhaps the latest Mesozoic tectonic event was the opening of a swarm of fissures south of and parallel to the Mam-a-gah fault zone and the filling of these cracks with quartz latite porphyry (the Silver Lily dikes).

Conclusions

At levels presently exposed our observations almost exclusively support the thesis that this has, in general, been a place of tension, uplift, and gravitational response.

Compression, as expressed by shortening perpendicular to cleavage, might have controlled the deformation at a deeper level at the beginning of Laramide uplift. Minimum apparent shortening, as we have seen, is related to uplift of the volcanic core and probably expresses both slumping off the core and "shouldering aside" by the core. Even in an environment of overall tension, then, local compressional effects can be generated. Rising masses have to win space; slumping units may be forced to spend their energy in crumpling. The presence of local structures formed by compression is not conclusive evidence of intense regional compression.

Following Guild's (1935) suggestion we infer that the cause of uplift was the emplacement of igneous intrusions and the accompanying effects of heat and fluids.

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