PRELIMINARY REPORT ON A STRUCTURAL STUDY IN THE MUSEUM EMBAYMENT, TUCSON MOUNTAINS, ARIZONA

Evans B. Mayo
Department of Geology, University of Arizona

ABSTRACT

Structural mapping of an area of approximately nine square miles in a large reentrant on the western side of the Tucson Mountains is reported. Based on the nature, the geometrical relations and the deformation of the several geologic formations, it is suggested that the structural features are essentially the results of igneous action which was controlled by four "framework" directions. Many anticlines and domes were lifted from below. The principal syncline and some other depressions were formed by lagging behind the general uplift, active sinking because of removal of support, or (were formed) by some combination of these mechanisms. Many small and some large folds are the results of gliding off uplifts, or of squeezing aside by uplifts.

Intrusions appear to have lifted large blocks, mostly of Permian limestone and quartzite, together with some Lower Cretaceous (?) rocks and a few smaller pieces of older formations. At some places, the intrusions are bordered by a fringe of highly disturbed Amole Arkose in which appear many of the exotic blocks. These mixtures are the Tucson Mountain Chaos of Kinnison.

A more satisfactory interpretation of the origin and extrusion of the Cat Mountain Rhyolite should follow more extensive and intensive study of the Tucson Mountain Chaos and the Rhyolite.

If the results of the present study are broadly applicable, then it should follow that the structure of the Tucson Mountains is the result of a dominantly vertical volcano-tectonics and attendant gravitational adjustments. The concept of a "compressive phase of the Laramide Orogeny" finds little support in the data mapped.

More extensive structural mapping is still the greatest need, and detailed stratigraphic, sedimentologic, and petrographic studies would be most helpful.

INTRODUCTION

Objective

In a paper entitled "volcanic orogeny of the Tucson Mountains" (Mayo, 1963) evidence was presented which indicated that the structure of these mountains, far from being the result of compressional and overthrust tectonics (Brown, 1939), was actually the denuded ruin of sub volcanic and volcanic structures. To test this suggestion the great need for further field work was stressed.

Proposed Work

It was planned to map an east-west trip across the range some two and a half miles wide at five inches to the mile (1056 feet to the inch). The southern edge of this strip was to cross the crest at Gates Pass and the northern edge was to be located about 500 feet south of the Gould Mine (Pl. 1). The western boundary was to lie just beyond the west end of the Red Hills, and the Camino del Oeste was to be the eastern boundary (Fig 1).

Field Work Accomplished

Before the field work was started in July 1964, it was decided to change the mapping scale to ten inches to the mile (528 feet to the inch). Parts of the San Xavier Mission and Cortaro U.S.G.S. topographic sheets were enlarged by the method of squares to serve as base. Also, the strip was broadened northward to overlap the southern edge of a large intrusion of Amole Granite and "Quartz Monzonite" (Brown, 1939), thus increasing the width to three miles. Because of these changes, only that part of the proposed section lying west of the crest was actually mapped. The area so covered amounts to approximately nine square miles, including about one square mile that had previously been mapped. The area includes parts of the Tucson Mountain Park and Sahuaro National Monument and extends northeastward beyond the park lands. The field work, excepting spare time visits, was terminated January 15, 1965.

The data have been reduced to five inches to the mile and generalized (Pl. 1). The long, curved strike lines do not mean that a single stratum, or bed, can be followed so far, but that many measurements which could not be plotted separately were extended and combined to form the curves.

Acknowledgments

For the six months sabbatical leave which made the field study possible the writer is indebted to the Board of Regents and Administration of the University of Arizona and to his colleagues in the Department of Geology and College of Mines.

Professor Donald L. Bryant kindly read and constructively criticized that part of the report which deals with geological formations. Professor Paul E. Damon generously read the entire manuscript. To both of these colleagues I extend sincere thanks. It is a pleasure, also, to recall field trips into the investigated area with Professor Damon, Professor O. F. Tuttle of Pennsylvania State University, and graduate student Michael Bikerman. My indebtedness to other graduate students follows from citations of their

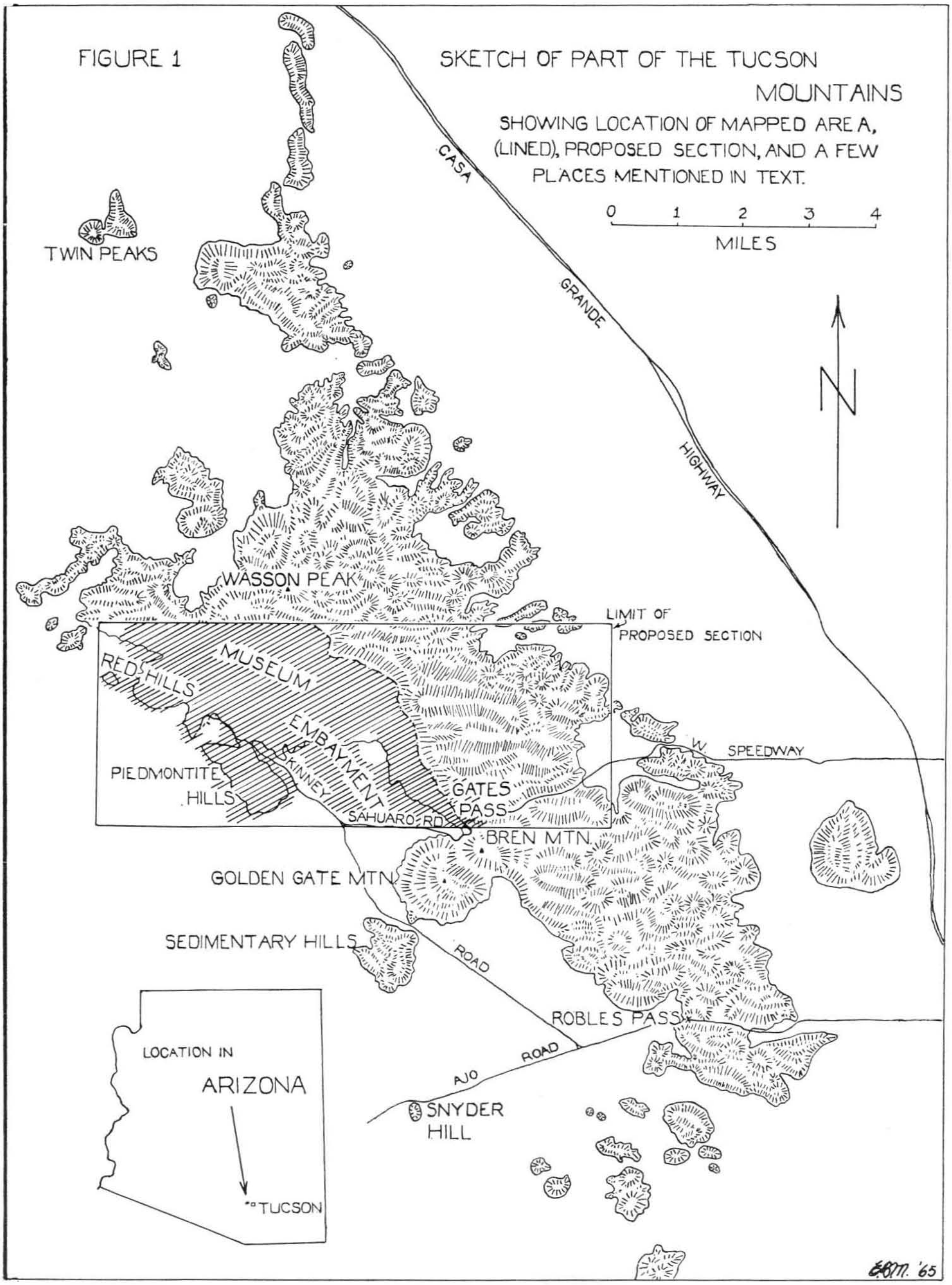


FIGURE 1

SKETCH OF PART OF THE TUCSON MOUNTAINS SHOWING LOCATION OF MAPPED AREA, (LINED), PROPOSED SECTION, AND A FEW PLACES MENTIONED IN TEXT.

theses. For courtesies extended in the field, I wish to thank Messrs. Ralph Gomez and San Tantillo, park ranger and caretaker of the Tucson Mountain Park, and Mr. Glen E. Henderson, park ranger of the Sahuaro National Monument, western division. Finally, Professor Robert L. DuBois efficiently edited manuscript and illustrations.

GEOGRAPHY

Tucson Mountains

The Tucson Mountains, west and northwest of Tucson, rise to their extreme elevation of about 4,600 feet at the summit of Wasson Peak, giving a maximum relief of some 2,300 feet above the San Cruz Valley. The northwest trending range is 20 miles long, and its greatest width is some six or seven miles.

Museum Embayment

On the western slope, west and northwest of Gates Pass, is a broad, basin-like reentrant, elongated northwest and bordered on the east by steep, jagged cliffs. On the north this basin is bordered by what used to be called the Amole Mountains (Jenkins and Wilson, 1920), on the west and northwest by the colorful Piedmontite Hills and Red Hills and on the south and southeast by three northeastwardly-aligned groups, the Sedimentary Hills (Bennett, 1957), Golden Gate Mountain (Assadi, 1964) and Bren Mountain (Geiser, 1964). The Arizona-Sonora Desert Museum (Pl. 1) is situated in the northwest part of this reentrant, for which the name Museum Embayment is proposed. To date, almost all of the writer's field work in the Tucson Mountains has been done in, or marginal to, the Museum Embayment.

Orographic Framework

The eastern rampart of cliffs, the west-trending northern barrier, the chain of the Red Hills and Piedmontite Hills, and finally the northeastward-aligned groups on the south and southeast, all enclose the Museum Embayment within an angular frame. The impression is strong that relatively weak, easily eroded rocks have been removed from the center of this area, whereas more resistant formations remain as the raised rim that frames it. The enclosing rim trends locally northwest, northeast, west, and north. It is breached most widely on the southwest where much of the drainage escapes from the Embayment.

Accessibility

The Museum Embayment is accessible from Tucson via paved roads over Gates Pass and over Robles Pass to the Arizona-Sonora Desert Museum. Rough secondary roads, leaving the pavement, penetrate to various parts of the reentrant. The numerous washes are at once avenues of access and natural sections of the structure. Except in these washes, in a few road cuts, and on the most rugged slopes, exposures are limited. As a rule, much has to be inferred from many relationships interpolated between isolated outcrops.

GEOLOGIC FORMATIONS

Precambrian

The older Precambrian Pinal Schist and Oracle Granite crop out at the northern end of the Santa Catalina Mountains, some 30 miles northeast of the Museum Embayment, and Precambrian granite is known in the Sierrita Mountains, some 22 miles southwest. In the Tucson Mountains a small exposure of Pinal Schist is known at the southwest base of the Twin Peaks (Picachos de Calera, Brown, 1939) about eight miles north-northwest of the Embayment. Blocks of shining mica schist, presumably Pinal, and reaching ten feet or more through, have been found in highly disturbed Cretaceous sedimentary rocks on both sides of the Tucson Mountain crest in, east, and southeast of the Museum Embayment. Small chips, of apparently the same mica schist, have also been found in fragmental volcanic rocks in the Piedmontite Hills.

No rocks of the younger Precambrian Apache Group have been recognized in the Tucson Mountains. Accordingly, the Precambrian basement rocks of Museum Embayment probably consist of Pinal Schist. This schistose basement may have been intruded by coarsely porphyritic Precambrian quartz monzonite, similar to the Oracle Granite as described by Banerjee (1957). The Palezoic succession was probably deposited on the peneplain (Lance, 1959, p. 14) that truncates the older Precambrian.

Paleozoic

At most places in the Tucson Mountains the Paleozoic section is covered by Mesozoic and/or Cenozoic deposits. Various-sized blocks, reaching perhaps 100 feet in diameter, apparently of Permian limestone and quartzite, can be found enclosed in fragmental volcanic rocks, in latite intrusions, in highly disturbed Cretaceous sedimentary rocks, and in intrusive ignimbrite or tuffisite marginal to the Museum Embayment.

The most nearly complete section of Paleozoic rocks exposed in these mountains is in the Picachos de Calera (Twin Peaks). Permian rocks are exposed at Snyder Hill, about three miles south of the Museum Embayment. Both the Picachos de Calera and Snyder Hill sections were described by Bryant (1952, p. 34-40). The following is based on his description, modified after consulting him.

Picachos de Calera section:

	Feet
Bolsa Quartzite (Middle Cambrian)	
Unconformable on Pinal Schist. Light brown to purple, fine-grained to coarsely conglomeratic ortho-quartzite, commonly cross-bedded	700
Abrigo Formation (Middle and Upper Cambrian)	
The basal sandstone, four feet thick, containing a distinctive trilobite fauna, rests conformably on the Bolsa Quartzite. Then follows about 300 feet of light brown to gray, highly micaceous, thin-bedded siltstones and sandstones in units up to ten or twelve feet thick, separated by foot-thick, bluish gray, gnarly limestones. These rocks are overlain conformably by twelve feet of quartzite on which rest about 188 feet of blue-gray limestone that is present as relatively thin, gnarly beds, separated by thin beds of micaceous, shaly siltstone and fine-grained sandstone. This in turn is overlain conformably and gradationally by 40 feet of thick-bedded, massive, coarse-grained pink limestone containing abundant fragments of trilobites	Ca. 640
Martin Limestone (Upper Devonian)	
The basal thin bed of yellowish sandstone rests paraconformably on the Abrigo Formation and is overlain by 40 feet of bluish-gray limestone, 25 feet of dark gray dolomite and another thin bed of yellowish sandstone. On this rests 100 feet of gray, brown-weathering limestone, cherty in the lower portion, 25 feet of brown, calcareous sandstone, and 150 feet of massive, gray limestone	Ca. 350
Escabrosa Limestone (Lower Mississippian)	
Grades downward into Martin Limestone. Dominantly medium to dark gray, coarsely crystalline limestone	Ca. 600
Horquilla Limestone (Pennsylvanian)	
Rests paraconformably on Escabrosa Limestone. Limestones and siltstones alternate in units three to 15 feet thick	1,000

Snyder Hill section:

Concha Limestone; possibly some Rain Valley Formation (Permian)	
Consists of 118 feet of very fosilliferous limestone overlain by 108 feet of dolomite and dolomitic limestone	226
Total exposed Paleozoic section	Ca. 3,516

The total is no doubt too low, because some units of the Permian sequence are not exposed, for example the Scherrer Formation which underlies the Concha Limestone and which contains two white sandstone or quartzite members (Bryant, 1959, p. 41). Even so, the older Precambrian basement beneath the Museum Embayment may have been covered at the end of Permian time by a Paleozoic succession little more, and perhaps even less, than 4,000 feet thick. These slowly-accumulated shelf or shallow sea deposits were followed in Mesozoic time by accumulations of a very different kind.

Mesozoic

W. H. Brown (1939) divided the layered rocks, then thought to be of Mesozoic age, into three formations which he considered to be Cretaceous. The stratigraphically lowest of these formations was called by Brown the Cretaceous Volcanic Rocks. This formation was overlain by the Recreation Red Beds, followed by the Amole Arkose formation. It is now known that a fourth stratified formation, the Cat Mountain Rhyolite, assigned by Brown to the Tertiary, is Upper Cretaceous in age. The Amole Arkose is intruded irregularly by the Amole Latite (Pl. 1). The Red Buds, the Arkose and the Latite are intruded by the large Amole Pluton, and the layered Cat Mountain Rhyolite has erupted through Amole Arkose and Latite. Finally, all four of the stratified formations have been transected by a nearly east-west dike swarm, the Silver Lily dikes, and intruded locally by small, intermediate to felsic masses.

The Cretaceous volcanic rocks crop out at many places in the Tucson Mountains, especially in the northern part. One of the principal exposures is in the Piedmontite Hills (Pl. 1) where Brown (1939) measured a section 248 feet thick. He thought, however, that the maximum thickness might amount to two to five thousand feet. The volcanic rocks appear to be mostly andesites, but there are local, rhyolitic-appearing portions. The rocks are dominantly fragmental, but Brown reported some lava flows, and some small intrusions are known.

The Recreation Red Beds overlie, and to some extent interfinger with, volcanic rocks. This unit is essentially a sequence of red siltstones, reddish or reddish-brown sandstones, and common three- to eight- or ten-foot beds of conglomerate. There are local tuffaceous members also. Brown (1939, p. 716) measured a section 1265 feet thick in this formation, but the base of the section was not exposed.

The principal exposure of the Red Beds is in the Red Hills, and a narrow strip of them extends down along the northeast side of the Piedmontite Hills. Many isolated blocks of Red Beds occur in the fragmental volcanics (Pl. 1), and some thin Red Beds also occur interlayered with the volcanics. Moreover, small areas or blocks of Recreation Red Beds associated with fragmental andesites are present here and there on both sides of the crest of the Tucson Mountains.

R. E. Colby (1958), following his study of the Red Hills and Piedmontite Hills, recommended that Red Beds and volcanic rocks be combined into one Recreation Red Beds Formation composed of a volcanic conglomerate member, a sandstone-siltstone member, and a tuff member (the ignimbrite, pl. 1). Although this proposal may cause difficulty when broader studies are attempted, it is adopted temporarily in this report. The age of this colorful volcanic and volcano-sedimentary formation is not known precisely. It underlies the Amole Arkose Formation at places unconformably and locally even in interfingering contacts which according to Halsey Miller (Mayo, 1963, p. 78) include sedimentary rocks of Lower Cretaceous age. Therefore, the Recreation Red Beds Formation may be Lower Cretaceous and/or older.

The Amole Arkose Formation, the uppermost division of Brown's Cretaceous section, consists of pale gray, feldspathic sandstone, fine-grained graywacke sandstone, greenish-gray siltstone, dark gray to black shale and mudstone, and rather thin beds of dark to light gray limestone. On the southwest edge of the Piedmontite Hills, the basal Amole consists of very coarse-grained arkose with a little conglomerate. In the northern part of the Museum Embayment the formation appears to contain very considerable admixtures of volcanic ash. Brown (1939, p. 718) measured a 2,275 foot section in the Amole Arkose Formation, but this thickness was only part of the total. Assadi (1964, p. 26) thought the formation to be about 4,000 feet thick at Golden Gate Mountain, and Kinnison (1958, p. 15-21) estimated more than 4,500 feet of Amole strata in the southern part of the Tucson Mountains. More carefully measured stratigraphic sections are badly needed. It may be that the Amole Arkose, by itself, is thicker than the entire Paleozoic section.

This formation crops out in broad areas over much of the Tucson Mountains. As already mentioned, it crops out at the southwest corner of the Piedmontite Hills, and there is another limited exposure west-southwest of the Desert Museum. Besides these small areas, the formation floors almost the entire Museum Embayment, where it crops out in nearly every wash and on many a slope and crest. The Cretaceous age of these rocks can scarcely be questioned. Brown (1939, p. 719) quotes Stoyanow to the effect that fossils collected from this formation are "almost certainly" of Upper Cretaceous age and, as previously mentioned, Halsey Miller considered one Amole fauna to be Lower Cretaceous. Further, (Damon, Mauger, and Bikerman, 1964, table 2) K-Ar dating of feldspar concentrates from the overlying Cat Mountain Rhyolite yielded the ages 70 and 65 million years. Mayo (1963, p. 79) has suggested that some part of the Amole Arkose may have been present before emplacement of the Recreation Red Beds Formation, but this is a mere possibility, with little supporting evidence.

The Cat Mountain Rhyolite, youngest of the stratified Cretaceous formations, makes up the imposing cliffs of the eastern rampart and covers extensive areas on the eastern slope. This formation consists of many hundreds of feet of pyroclastic flows, at least part of which could be termed ignimbrite, or ash flow tuff. The age of the formation, according to the data quoted above, is uppermost Cretaceous Campanian or lower Maestrichtian.

The western contact of the Cat Mountain Rhyolite is at many places very steep, and it seems that some of the sources of this material lie along the contact. At many places, but not everywhere, the Rhyolite is separated from "normal" Amole Arkose by a border zone of variable width in which the Arkose is highly disturbed and seems to have been partly disaggregated and mixed with foreign materials. Among the foreign materials are pebbles and cobbles of andesite and other fine-grained igneous rocks, Recreation Red Beds, limestone and quartzite. Huge blocks of probable Permian limestone reaching hundreds of feet in length, are locally present, as well as blocks of "Cretaceous Volcanic Rocks," Recreation Red Beds, some of quartzite, and a very few small blocks of what appears to be Pinal Schist. A few small intrusions of Cat Mountain Rhyolite, Amole Latite (?), and andesite appear in this border zone. This curious mixture seems to be identical with Kinnison's (1959, p. 50-57) Tucson Mountain Chaos.

The Amole Arkose is very irregularly intruded, along the northern edge of the Embayment, by the Amole Latite. This intrusive rock varies considerably in appearance from place to place, and it seems that the Latite forms an intrusive complex that may have been emplaced over an appreciable time interval. At a few places at the base of the cliffs in the northern part of the eastern rampart, Cat Mountain Rhyolite can be seen to have intruded what appears to be Amole Latite.

Brown (1939) mapped and described a large, composite intrusion consisting of granite and "quartz monzonite" in the mountains north of the Museum Embayment. According to Professor O. F. Tuttle (oral communication) the "quartz monzonite" is probably quartz diorite. In the present report this composite intrusion is named the Amole Pluton. Marginal portions of this mass cut into the northwestern corner of the map (Pl. 1) where it can be seen that the quartz diorite contact locally cuts off structures in both the Amole Arkose and the Amole Latite. According to Damon, Mauger, and Bikerman (1964, table 2),K-Ar dates from "Amole Quartz Monzonite" and from granophyre of this pluton yielded the ages 73 and 75 m.y.

The Silver Lily dikes obviously cut across the Cat Mountain Rhyolite, but one of the dikes, northwest of Mam-a-gah (Pl. 1) opens out to become a mass of Amole Latite! As already mentioned, the Latite was probably emplaced as several successive increments. Probably no serious error would be involved in the statement that Amole Latite, Amole Pluton, Cat Mountain Rhyolite and Silver Lily dikes are products of one Upper Cretaceous igneous episode. The statement might also include the little masses of spherulitic rhyolite and related rocks (Pl. 1), many small andesitic intrusions, and the ignimbrite of the Piedmontite Hills. It is tempting to speculate that the Recreation Red Beds Formation may represent the initial stage of the above igneous episode, but it is probably best at present to leave this question open.

Tertiary

No rocks known to be of Tertiary age crops out in or marginal to the Museum Embayment.

STRUCTURAL GEOLOGY

General

Inspection of the map (Pl. 1) reveals the salient features of the district structure. The Museum Embayment is essentially a complicated syncline, or structural trough, rimmed by areas of upwelling, intrusion, extrusion, and locally, e.g. on the northwest, down-sinking. Obvious units of this district structure are (1) The Piedmontite Hills and (2) the Red Hills, parts of an irregular dome with intrusive centers along its axis; (3) the Eastern fault, which separates this irregular dome from (4) the central trough and broad floor of the Embayment; (5) the northern, mountainous border, injected and dilated by the Amole Latite and down-sunk toward and into the Amole Pluton; (6) the eastern rampart, composed of rhyolitic upwellings and outpourings, and (7) the Silver Lily dike swarm. These major units will be considered in the above order.

The Piedmontite Hills

A study of the porphyritic andesite at the northwestern end of these hills and a preliminary account of the structural geology of the hills have been published (Mayo, 1961; 1963, p. 68-75). In the first account, some evidence relating to fluidization and entrainment of sedimentary wall rocks was presented. In the second paper the principles of fluidization and entrainment were exploited in an attempt to explain the structural relations of the fragmental volcanic rocks and the red silstones. Perhaps it would be well also to refer to the rise of hot, viscous magma, as evidenced by andesitic and other intrusions, as well as of hot, stiff fragmental masses through the stratified deposits. These hot masses, of course, would supply the energy for fluidization. The considerable alteration of all the Piedmontite Hills rocks, except the flanking Amole Arkose, suggests that intrusion took place under water, or at least into water-soaked materials.

As shown on the map (Pl. 1) the core of the Piedmontite Hills, with its minor intrusions of andesite, rhyolite, and ignimbrite, and its coarse fragmental upwellings, seems to have lifted and broken up the overlying fine-grained red siltstones. In local exposures, details of the attack and break-up of the red beds by the fragmental volcanics can be observed. Further, although it is not possible to trace out all stages in the field, it seems very probable that some of the disaggregated red material was redeposited to form strata conformable with the stratified fragmental volcanics. Some idea of the intrusion, upwelling, and uplighting of the stratiform deposits can be gained from the cross section (Fig. 2). This section shows, also, that at some stage at least a partial cover of Amole Arkose slipped eastward off the rising volcanic welt.

Although the Piedmontite Hills trend northwest, much of their internal structure (bedding, faults and tuff-filled fissures) trends nearly north. This is especially the case in the southern half of the hills. Just west of the center of Section 7, a north-trending, quartz-filled fracture dips westward at 78, 75, and 76 degrees. Toward the north, this fracture bends westward, and it may coincide with the northeastern edge of the large mass of intrusive ignimbrite (Pl. 1). If this is so then the course of this fracture resembles the trace of a landslide scarp. Perhaps the southwest flank of the rising volcanic welt slipped down on this, and possibly on other, scoop-shaped surfaces. Similar structures, but on a far larger scale, have been described by van Bemmelen (1934; 1937, 1949, p. 610, 641-644). The large body of ignimbrite may have utilized such surfaces, perhaps where they were intersected by other fractures. The small mass of ignimbrite just above the "I" in PIEDMONTITE HILLS (Pl. 1) and just south of the weather station (Fig. 2) is possibly situated on a north-trending fissure from which rubbly andesite issued.

In the southernmost quarter or third of the hills, the north-trending structures are traversed by many east-west fissures, some of them occupied by Silver Lily dikes. The ignimbrite at the very southeast corner of the hills was probably emplaced along fissures having a trend slightly north of east.

Throughout the Piedmontite Hills the rocks are in many places divided by a steep to vertical sheeting that strikes roughly parallel to the northwest trend of the intruded core of the welt. This sheeting, or close-joints cleavage, probably accommodated the differential uplift. On gently-inclined, slickensided surfaces, striations plunge, mostly northeastward but also southwestward, approximately at right angles to sheeting and to the trend of the core. These surfaces accommodated the stretching over the rising welt. It is thought that sheeting and stretching surfaces accommodated a final stage of uplift at a time when the hills were rising as a unit later than the small, local upwellings and at this time, perhaps, the Amole cover slipped off on the northeast side.

The Red Hills

These hills, which lie northwest of the Desert Museum, are the type locality of the Recreation Red Beds (Brown, 1939, p. 715-716). In spite of this, the characteristic, massive red siltstones are a relatively modest portion of the entire assemblage. Much of the section is composed of laminated

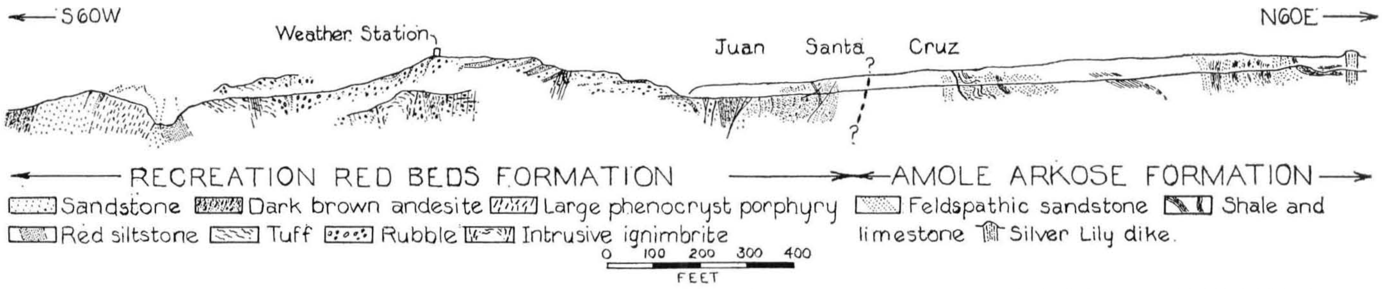


FIGURE 2 - STRUCTURE SECTION ACROSS NORTHWEST END OF THE PIEDMONTITE HILLS

and cross-laminated sandstones of various, usually reddish, colors. A small part of the total volume consists of the previously-mentioned conglomerates, and the relatively small remainder is fragmental andesite and tuff. Study of these rocks creates the impression that they are closely related genetically to the rocks of the Piedmontite Hills. The obvious difference is that in the Red Hills the fine-grained components are greatly augmented and the coarse-grained ones drastically reduced.

A few observations suggest that the stratigraphic section in the Red Hills may be more disturbed than it appears at first. In section 36, near the figure 87, south of the word "windmill" (Pl. 1) and again east of there near the Figure 3, masses of andesitic pebble conglomerate, accompanied at the second place by rhyolitic tuff, appear to have welled up through red beds and sandstones. These two localities should receive further study. In the northeastern corner of the Red Hills, just east of the dip figure 48, a small area of rubbly andesite appears amidst reddish sandstones. "Nested" in this andesite is a six-foot block of probable Paleozoic limestone. Examined closely, the limestone itself is seen to be a shattered, rubbly mass. Seemingly, this Paleozoic (?) block was carried upward through soft, wet sand by the andesite. About 700 feet north and 10 degrees west of the Desert Museum, coarse, purplish sandstone and andesitic granule conglomerate cross-cuts and interfingers with the red beds in a manner that suggests that the red siltstone was intruded and dispersed by the coarser-grained clastics. Finally, the intrusive core of the Piedmontite Hills plunges beneath the Recreation Red Beds west of the Desert Museum. The masses of andesite at the plunging end of this core are encased in a shell of nearly massive, steeply inward-dipping sandstone that is structurally discordant with its sedimentary surroundings. This environment seems to have been a fluidized shell that reached the entrainment stage (Leva, 1959, p. 15-17). If so, it should have expelled sand and possibly coarser debris to the surface.

The above observations suggest that the area of the present Red Hills was once underlain by hot, intrusive, magmatic and fragmental materials. Perhaps if the hills could be eroded away, one would see the condition now exposed in the Piedmontite Hills. Hot fluids, mainly water and/or steam, may have risen through the section at various times and at varying rates.

The origin of the massive red siltstone has for years presented a vexing problem. Was this massive red material somehow "cooked" out of underlying oxidized volcanics? And are the red layers some sort of sediment "fall out" from red clouds suspended in still water? Perhaps further studies will answer these questions.

Measurements of stratification in the Red Hills, generalized in (Pl. 1), reveal a generally northeast-dipping flank that seems to close around the above-mentioned plunging core. The steep sheeting, noted in the Piedmontite Hills, trends northwestward through the Red Hills, where it is expressed as a well-developed axial plane cleavage in the massive red siltstones. The striations on gently-dipping, slickensided surfaces are not common features in the Red Hills, but they are sparingly present. Here, also, they trend approximately at right angles to sheeting or cleavage and usually plunge gently northeast, but at a few places they plunge southwest.

The strike lines of the stratification bend into near conformity with the southern contact of a granite lobe of the Amole Pluton, but the contact very locally cuts across the strike lines (Pl. 1). The dip of the granite contact seems almost everywhere to be nearly vertical. The only exception seen is east of the windmill, where the contact dips 48 degrees south. The red sedimentary wall rocks usually dip at low to moderate angles into the contact. It seems, therefore, that the intrusion did not lift or thrust aside the Red Beds. In fact the structural relations suggest that, at some time probably previous to emplacement of the granite the Red Beds subsided into the space now occupied by the granite. Perhaps a large red block broke off on a steep west-trending fracture and foundered, allowing granite to take its place. There is a very slight alteration of the red rocks within a foot or two of the contact.

The Eastern Fault

The Red Hills and Piedmontite Hills, flanked by Amole Arkose on the southwest, are separated from the same formation on the northeast by a narrow, disturbed zone. Colby (1958, p. 34-37) named this zone the Eastern Fault. It can be traced from the southeast corner of the Piedmontite Hills to the northeast corner of the Red Hills (Pl. 1).

In the southeastern part of its known course the narrow zone, or surface, usually dips steeply westward, but at one place it dips steeply eastward. Poorly-preserved stratification in volcanic rocks of the Recreation Red Beds Formation bends down sharply toward the fault surface, and stratification in the Amole Arkose dips very steeply, here toward, there away, from the fault. The rocks appear to have been strongly compressed, and excepting the one eastward dip the fault would appear to be a steep, westward-inclined upthrust.

Northwest of the above-described segment, the trend of the displacement surface is nearly due west. South of the main fracture, some north-trending, steeply east-dipping red beds have been displaced a few feet, apparently by left-lateral strike slip, on minor fault strands. The same kind of displacement on the main fault is suggested by the manner in which the tightly folded stratification of the Amole Arkose curves from the north into the east-trending shear surface. These relations could possibly be explained as results of a purely vertical uplift of the Piedmontite Hills, but it is difficult to dismiss the suggestion of strike-slip movement.

Beyond the west-trending segment, the northwest-trending fault dips steeply southwestward. Some sheared lenses of breccia, as much as 50 feet thick and several hundred feet long appear along the displacement surface in this segment and in the turn between this and the west-trending segment. The presence of these breccia lenses suggests tension, or at least absence of severe compression across this part of the fault. The volcanic rocks can still be seen to bend down sharply toward the fracture trace, but the Amole Arkose here dips at moderate angles into the fault. Primary sedimentary structures indicate that these Amole strata are in normal sequence. Further, local slump folds indicate that certain Amole beds once flowed *up* the present dip. This suggests that while parts of the Amole were still soft they slumped *away* from the fault trace. Perhaps this slumping records an early stage in the uplift of the Piedmontite Hills. If so, the Amole strata may eventually have broken along the fault and then have subsided toward the continuing uplift, reversing the dip of the strata. Possibly the fault had initially an eastward dip which was rotated and reversed by expansion of the rising volcanics. In this way the breccia lenses could have been emplaced during an early, tensional stage when the fault dipped east, and have been sheared and squeezed when the fault was overturned.

In the vicinity of Juan Santa Cruz picnic area, the displacement zone turns northward. Here again there is evidence of compression. The volcanic rocks are strongly sheared and bleached over a width of many yards (Fig. 2). The Amole Arkose in this area usually dips at high angles away from the displacement zone, but at a few places it is inclined 80 degrees or steeper toward the zone. Primary sedimentary structures indicate that the west-dipping strata are inverted.

Between Juan Santa Cruz picnic area and the Desert Museum, the fault trace is covered with illuvium. The next exposures are in King Canyon wash, north of the museum. Here the steep displacement surface, poorly exposed, seems to dip eastward. The red beds bend down eastward toward the fault, but here a mildly deformed Amole Arkose, disposed in irregular, very gentle undulations, inclines flatly away from the fault.

In Mine Canyon, or Gould Gulch, the next wash to the north, evidence is very weak for any displacement at the fault trace. This is the locality where, as previously stated, the Recreation Red Beds are interbedded with the overlying Amole Arkose. The stratification in both formations dips gently and conformably eastward. In the Amole, perhaps 50 yards east of the fracture trace, there is a broad shatter zone in which a mass of angular, unrotated fragments of dark gray siltstone is held together by a network of calcite. This condition suggests extension of the gently eastward-dipping Amole. Surely there has been no appreciable compression here.

North of Mine Canyon, the steep fault surface describes a sharp curve, convex toward northeast. This curve may possibly be related to strike-slip in the Silver Lily dike zone, but no supporting evidence could be found in this poorly exposed place. Between this curve and the southeast corner of the Amole Granite some peculiar features were observed along the fracture trace. First, a lens-shaped mass of probable ignimbrite seems to have been inserted along the movement surface, in a manner similar to insertion of the breccia lenses on the northeast side of the Piedmontite Hills. Secondly, what appear to be andesitic agglomerates occupy a narrow zone along the fault trace. At two places these supposed agglomerates were seen to become progressively finer and to grade eastward and upward into chloritized siltstones of the Amole Arkose Formation. No sign of a fault was seen at these places.

In this segment perhaps the Eastern Fault once existed as a fissure into which the probable ignimbrite and agglomerate rose from below. The finer grained portion of the agglomerate may have become fluidized and mixed with the siltstone, thus effectively destroying all evidence of a former fracture.

As the Amole Granite is approached, the shears that normally accompany the fault trace appear again, and can be seen to curve rather suddenly to parallel the southern edge of the granite. In so doing the Eastern Fault swings into a west-trending fault zone that extends eastward to Mam-a-gah and beyond.

It seems that the Eastern Fault functioned as a surface of adjustment between two major petrographically and mechanically dissimilar rock groups. One of these, the Recreation Red Beds Formation, seems to have been actively rising, especially in the Piedmontite Hills, where the intrusive and coarsely fragmental core is broadly developed and the mechanical difference between the two formations is greatest. Here the Amole Arkose seems to have been squeezed and pushed aside and the Eastern Fault is an upthrust. Northwestward, as the core becomes narrower, evidence of compression diminishes and the Amole seems to have slipped off the rising uplift, yet the fault is still an upthrust. Still farther northwestward, where the core has plunged beneath the Recreation Red Beds, the fault seems to be normal with displacement diminishing northward. Beyond this, again, it may have been merely a fissure, filled and healed by materials from depth.

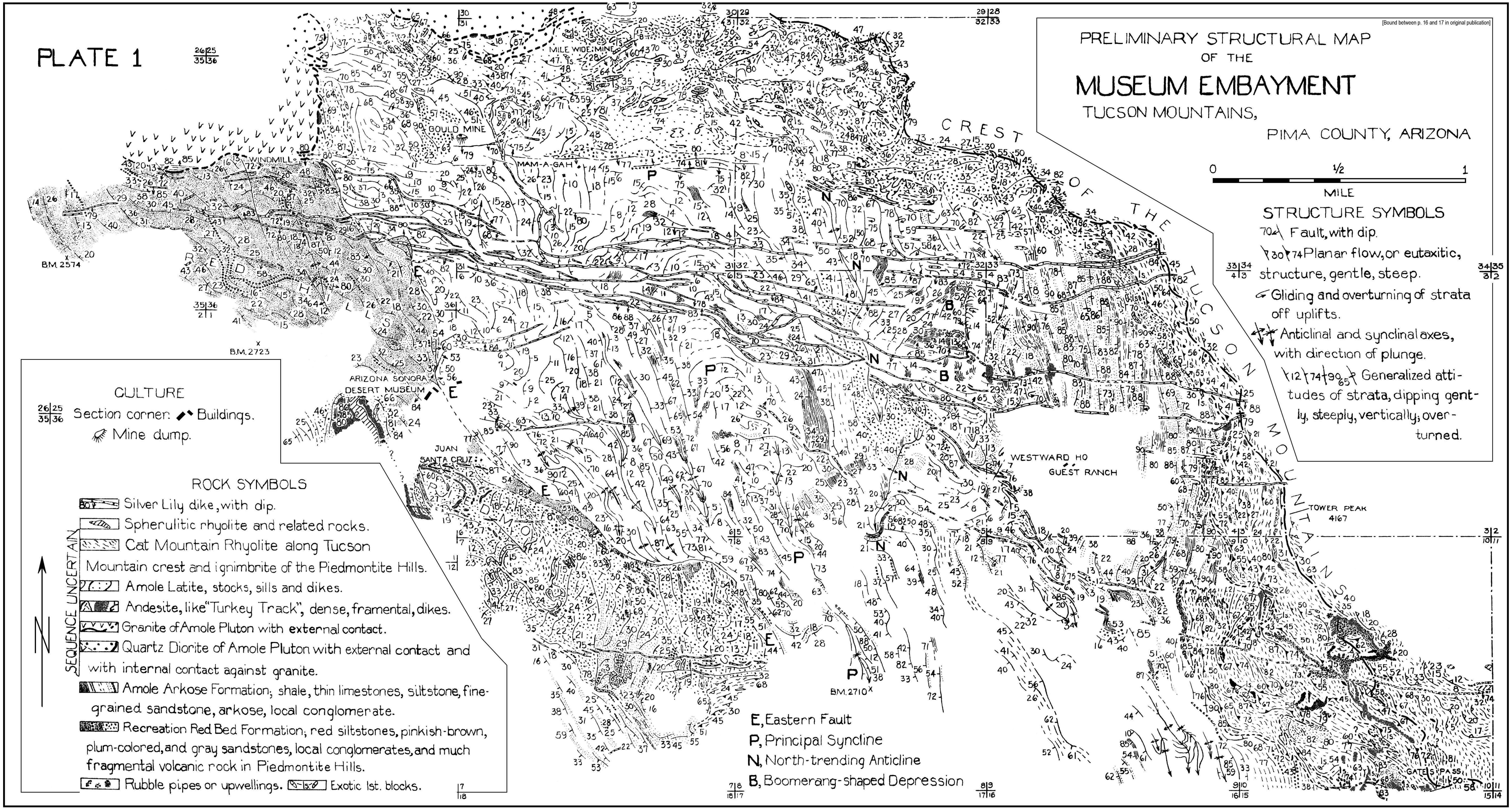
The Floor of the Embayment

This is the area between the Piedmontite Hills-Red Hills uplift and the eastern rampart. It is considered to extend from the northeast-trending chain of the Sedimentary Hills-Golden Gate Mountain-Bren Mountain centers (Fig. 1) northwest to the west-trending line of faults at Mam-a-gah (Pl. 1). The embayment floor is somewhat less than two miles wide, and about two and one-half miles long. It is flat in the southeast part but becomes increasingly hilly toward the northwest and north.

As previously stated, the principal rock in this area is the Amole Arkose Formation. The prevailing strike of bedding is somewhat north of northwest, and as a first approximation the structure is a north-northwest trending trough that plunges south-southeast. The axis of the trough, or "principal syncline," has been followed from about 500 feet east of Mam-a-gah (Pl. 1) to a position some 2000 feet east of the southeast end of the Piedmontite Hills. This "keel" of the structure is situated nearer the southwestern edge of the embayment floor than to the eastern side, and particularly so oppo-

[Bound between p. 16 and 17 in original publication]

PLATE 1



PRELIMINARY STRUCTURAL MAP
OF THE
MUSEUM EMBAYMENT
TUCSON MOUNTAINS,
PIMA COUNTY, ARIZONA

0 1/2 1
MILE

STRUCTURE SYMBOLS

70 Fault, with dip.

30 74 Planar flow, or eutaxitic, structure, gentle, steep.

Gliding and overturning of strata off uplifts.

Anticlinal and synclinal axes, with direction of plunge.

12 74 90 65 Generalized attitudes of strata, dipping gently, steeply, vertically; overturned.

CULTURE

26|25 35|36 Section corner. Buildings.

Mine dump.

ROCK SYMBOLS

SEQUENCE UNCERTAIN

Silver Lily dike, with dip.

Spherulitic rhyolite and related rocks.

Cat Mountain Rhyolite along Tucson Mountain crest and ignimbrite of the Piedmontite Hills.

Amole Latite, stocks, sills and dikes.

Andesite, like "Turkey Track", dense, framental, dikes.

Granite of Amole Pluton with external contact.

Quartz Diorite of Amole Pluton with external contact and with internal contact against granite.

Amole Arkose Formation; shale, thin limestones, siltstone, fine-grained sandstone, arkose, local conglomerate.

Recreation Red Bed Formation; red siltstones, pinkish-brown, plum-colored, and gray sandstones, local conglomerates, and much fragmental volcanic rock in Piedmontite Hills.

Rubble pipes or upwellings. Exotic lst. blocks.

E, Eastern Fault
P, Principal Syncline
N, North-trending Anticline
B, Boomerang-shaped Depression

site the southern part of the Piedmontite Hills. The syncline is, in the vicinity of Mam-a-gah, a very broad, gentle flexure. South-southeastward, this fold gradually narrows, its sides steepen, and at least one minor anticline appears near its axis. Finally, opposite the southeast end of the Piedmontite Hills, the syncline appears to be a narrow, steep-flanked crease.

West of this principal syncline, and between it and the Eastern Fault, deformation in the Amole Arkose changes remarkably from northwest to southeast. In the northwest, along the Silver Lily dike swarm, the strike of bedding in the Amole Arkose averages nearly west; but eastward this stratification lies in gentle, nearly north-trending folds. South of the dike swarm, as mentioned before, the Amole Arkose is deformed into irregular, broad, very gentle folds. These folds are succeeded eastward by strata that dip rather uniformly into the principal syncline. One northwest-trending anticline complicates this easterly dip, which at one known place steepens to 67 degrees.

South of the lone Silver Lily dike, near the Juan Santa Cruz picnic area, deformation of the Amole Arkose becomes much more intense. This area is opposite the strong Piedmontite Hills uplift. The adjustment between structures north and south of the Silver Lily dike is suggested by the strongly curved trend of the anticline near the east end of the dike. It seems that the Amole block south of the dike has moved relatively eastward. Several tightly appressed anticlines and synclines intervene between this block and the principal syncline.

Opposite the southeastern "bulge" of the Piedmontite Hills, it is difficult to locate fold axes, and possibly the limbs of folds have become isoclinal, at least locally. At one place it has been observed that Amole strata dip almost vertically into the principal syncline, then flatten with astonishing abruptness in its trough.

Most of the above-mentioned changes in structure could probably have been anticipated after a study of the Piedmontite Hills-Red Hills uplift and the Eastern Fault. They seem to demonstrate a close relation between vertical upheaval and horizontal compression.

The principal syncline is bordered on the east by a broad, approximately north-trending uplift that consists essentially of two offset anticlines (Pl. 1). This uplift can be followed from the southwestern quarter of Section 32, across Section 5, a distance of about a mile and a quarter. Except in its northernmost part, the structure plunges southward. In one of the washes that furrow its western flank, it can be observed that a shaly member of the Amole Arkose may have served as a "lubricating layer" over which more sandy members have glided off the uplift. This gliding movement appears to have generated a number of minor folds in the sandy members on the floor of the syncline at the lower edge of the anticlinal flank. These are indicated on the map (Pl. 1) from 1,000 to 1,500 feet east-northeast of the corner of Sections 6, 5, 7 and 8.

The core of the uplift consists of rocks foreign to the Amole Arkose. The rocks are purple and red sandstones, and rubble consisting mostly of rounded andesite clasts, and occasional concentrations, or "nests" of limestone cobbles. In general, these materials closely resemble the Cretaceous Volcanic Rocks of the Piedmontite Hills. Even a few pieces of red siltstone were found in the coarse rubble. The colors, however, are somewhat less brilliant than those in the Piedmontite Hills.

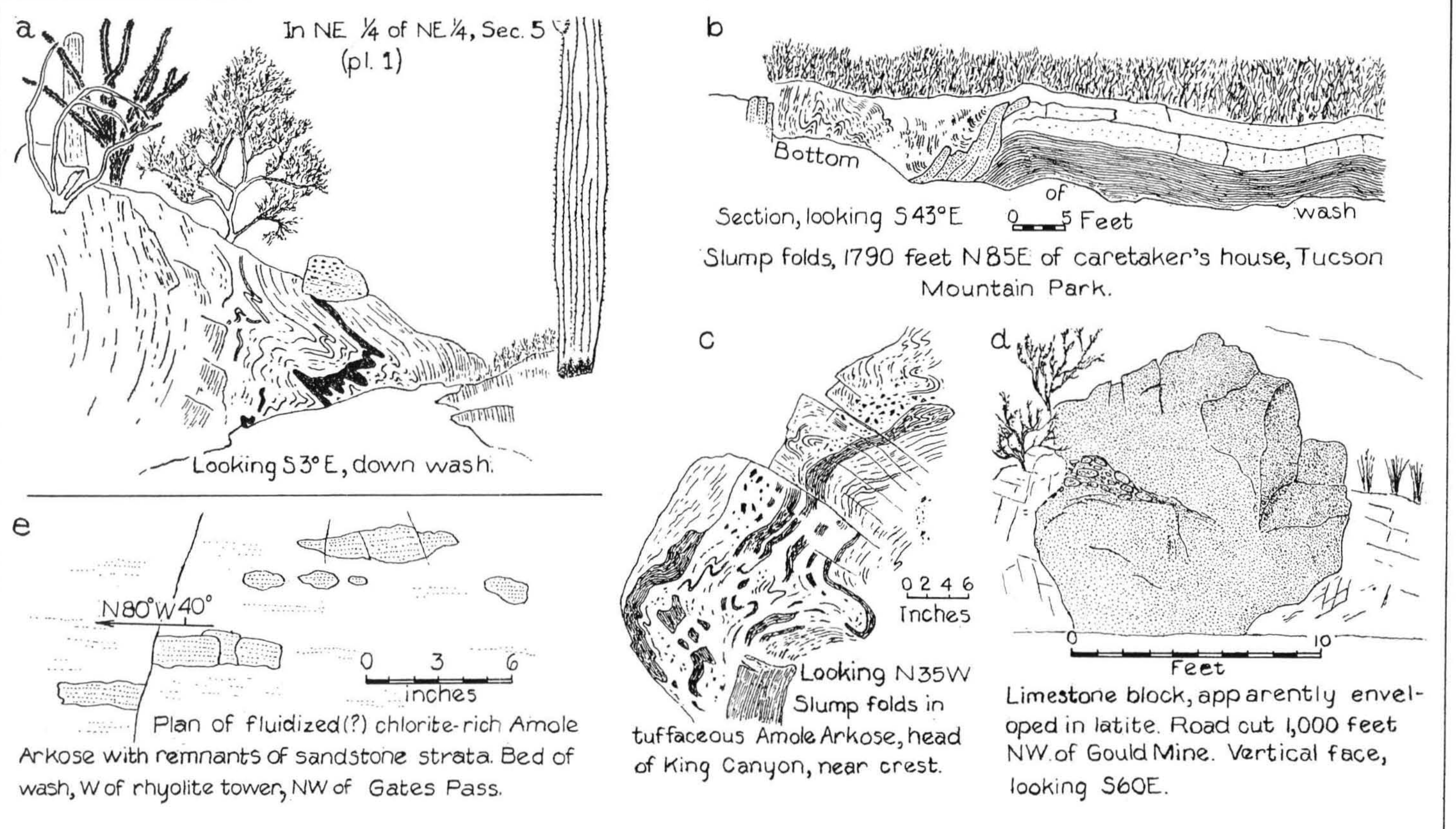
A sharp contact was found between the coarse clastic core and a basal sandstone or quartzite member of the overlying sedimentary rocks. Directly under the contact, the uppermost material of the core is a fine-grained laminated, tuffaceous-appearing rock with sparse one eighth- to one half-inch pebbles, apparently of volcanic origin. On the contact a few small lenses, or possibly elongate deposits, of granule to pebble conglomerate occur. The clasts in this conglomerate appear to be identical in composition with the sparse clasts below. Accordingly, this was an erosion surface for a brief time at least. The erosion was followed by deposition of sand and of the overlying gray silts and muds.

It seems significant that the rocks of the core are thermally metamorphosed. Epidote and chlorite are plentiful there; a little fine-grained pyrite, garnet, and specularite were seen, and other metamorphic minerals may be present. If the thermal effects do not end at the above-described contact, they are very subdued in the overlying sedimentary rocks.

Apparently, the rise of this "north-trending anticline" was somehow related to the escape of heat from depth. Perhaps the anticline was lifted by the rise of magma along an underlying, north-trending fissure. So seen, it is a welt like that of the Piedmontite Hills but much less pronounced.

In the northeast quarter of Section 5 the eastern flank of the north-trending welt appears to have subsided. The coarse, fragmental core rocks do not appear where they would be expected, and their place is taken by the overlying Amole siltstones, fine-grained sandstones, and shales. The shales in particular seem to have accumulated in a peculiar, boomerang-shaped depression at the eastern foot of the anticlinal flank. One arm of this depression trends slightly east of north, passing just west of the corner of Sections 32, 33, 5 and 4. The southern arm turns east-southeastward along some Silver Lily dikes.

At many places peripheral to this strange depression, poorly exposed slump folds indicate that before complete consolidation the Amole sediments flowed from all sides toward the lowest part. The eastern edge of the northern arm of the "boomerang," a few hundred feet west of the fence between Sections 4 and 5, is a faulted monocline. A rather deep wash, eroded along this structure, exposes excellent examples of gravitational flow into the depression (Fig. 3-a). Many more illustrations, as good or better, could have been obtained in this wash. For comparison an example is shown from



a. Looking S3°E, down wash.

b. Section, looking S43°E. Slump folds, 1790 feet N85E of caretaker's house, Tucson Mountain Park.

c. Looking N35W. Slump folds in tuffaceous Amole Arkose, head of King Canyon, near crest.

d. Limestone block, apparently enveloped in latite. Road cut 1,000 feet NW. of Gould Mine. Vertical face, looking S60E.

e. Plan of fluidized(?) chlorite-rich Amole Arkose with remnants of sandstone strata. Bed of wash, W of rhyolite tower, NW of Gates Pass.

FIGURE 3,—SLUMP FOLDS, FLUIDIZED(?) ARKOSE AND A LIMESTONE BLOCK the western side of a small anticline near the center of Section 6 (Fig. 3-b). Obviously, the Amole sediments were poorly consolidated at best when deformation was in progress.

East of the just-discussed depression there is a broad, north-trending belt in which alternating strips of coarse, feldspathic sandstones and of shales and argillaceous limestones dip very steeply, here eastward, there westward. The reversals of dip and the repetitions of rock type suggest that the belt is a bundle of very tight, almost isoclinal folds. In fact, some of the dark, andesitic, or fine-grained dioritic intrusions shown in black along one of the Silver Lily dikes (Pl. 1) occupy the cores of anticlines. It may be questioned, however, whether the entire north-trending belt is tightly folded.

At a few places, cross-bedding in the sandstones indicates that the steeply west-dipping beds are inverted. At many places slump structures reveal that the strata have slipped or settled down toward the east. Evidence of similar motion toward the west was found only near the boomerang-shaped depression and near the above-mentioned dioritic intrusions. Apparently, then, the north-trending belt is a thick sequence of alternating coarse and fine-grained clastic rocks. These seem to have been tilted eastward, perhaps partly by uplift along the western margin of the belt, but mostly by profound sinking of the eastern side. The tilting must have been very gradual, for otherwise a chaotic structure should have resulted. It seems, then, that these rocks tilted and sank very slowly toward the present eastern rampart, that is, toward the very place that now stands high.

The north-trending, steeply dipping belt seems to narrow rather rapidly southward, but a much reduced, steep zone follows the western contact of the Cat Mountain Rhyolite to the southern edge of the mapped area. There is some cross-folding along the Silver Lily dikes in the northern part of Section 9, and in the southeast part of the same section, a belt of folds was revealed by tracing out several distinctive limestone beds. This same belt of folds continues beyond the mapped area, where they were found by Assadi (1964) on the northeast slope of Golden Gate Mountain. The folds seem to be genetically related to emplacement of the Cat Mountain Rhyolite on Golden Gate Mountain; they die out northwestward, away from this disturbance.

The Northern Border

As mentioned under "Museum Embayment" the central lowland is closed on the north by a barrier of mountains. This northern border is obviously structural (Pl. 1) as well as topographical.

North of the Silver Lily dike swarm and on line with the southern edge of the Amole Granite there is, as already mentioned, a major, nearly east-west fault, or zone of faults. This zone can be traced eastward from the windmill past Mam-a-gah nearly to the crest of the Tucson Mountains. It probably crosses the crest. All structures traced up from the southeast or south seem to die abruptly, or to undergo some drastic change, at the fault zone. Accordingly, this Mam-a-gah belt of fractures must be a fundamental feature. Even so, it may be merely the southern edge of a broad, west-trending structural belt.

The eastern part of the fault zone and the country north of it have been intruded irregularly by many large and small masses of Amole Latite. The arrangements of these intrusive masses plainly suggest the presence of some west-trending control, but they also suggest interference by other fracture (?) directions. Thus, near the Mile Wide mine the trend is east of northeast, and northwest of the Gould mine it is west of northwest. On the east contact of the Amole Granite the trend is nearly north, as is the case east of the "C" in CREST OF THE TUCSON MOUNTAINS, (Pl. 1). Perhaps this area of many Amole Latite intrusions is situated where a major west-trending structural belt crosses a mosaic formed by the other trends.

Because of the heat introduced with the intrusions, and perhaps of the ash discharged by those that gained the surface, a number of lithologic changes take place as the Amole sediments are followed northward out of the Embayment.

First, there is a northward increase in what appears to be fine- to coarse-grained tuff in the Amole Arkose Formation. Perhaps some rocks interpreted as fine-grained tuffs are merely bleached mudstones or shales, but even so, a general northward increase in the "volcanic aspect" of the Amole Arkose can hardly be questioned. This situation was first called to my attention by Professor O. F. Tuttle (oral communication).

In the mountains along the northern wall of the Embayment there are numerous large and small areas of coarse breccia or rubble in which the clasts are dominantly andesitic or latitic, but are locally pebbles, cobbles and boulders of crystalline limestone, quartzite, and granite.

Finally, there is a general, but irregular northward increase in thermal metamorphism. Shales become first brownish hornfelses and finally peculiar dark bluish-gray hornfelses. Sandstones become quartzites and limestones are changed to marbles and are locally silicated. Epidote becomes common. All rocks become harder and more resistant to erosion. This metamorphic gradient seems to be the reason that the Museum Embayment is closed off on the north by a barrier of mountains.

The Amole Latite intrudes the areas of coarse clastic rocks as well as the dark, blue-gray hornfels and the tuff-like rocks. Effects of intrusion of the latite into fine-grained, possibly tuffaceous Amole Arkose can be studied in natural sections on the road from Mam-a-gah to the Mile Wide mine, and in King Canyon wash perhaps three quarters of a mile east of Mam-a-gah. The intrusive contact is sharp, but very irregular in detail. The latite is replete near the contact with drop-like and various oddly-shaped inclusions of the supposed tuff. These relations suggest that the tuff(?) was water-rich and very soft when the latite was emplaced. If so, then the latite was introduced at these places before heat and recrystallization had had time to stiffen the soft sediments.

About a mile east of Mam-a-gah, exposures in King Canyon reveal surprising relations of the Amole Latite to the dark, blue-gray hornfels. This hornfels retains little or no trace of primary stratification, yet near the latite there appears in the hornfels a condition that seems best termed "tumultous." Here and there are vague wisps of probable flow structure with highly variable attitudes. Occasional feldspathic schlieren appear, and roundish, or oval areas, from a few tens to a few hundreds of feet across, consisting mostly of feldspar grains, are locally present in the dark hornfels. At first it was thought that these feldspar-rich areas represented feldspathic sediments that had been activated and injected diapirically into overlying muds. However, one of these light-colored areas was found to have a porphyritic core! It seems that a latite magma, well advanced in crystallization, has been disintegrated and perhaps fluidized on contact with wet mud. Some of the latite has been strewn through the mud as feldspathic schlieren. Where such a body of crystallizing magma was large enough, or hot enough, its central portion retained the porphyritic, igneous texture.

Some rather large "arkosic" areas within larger masses of coarse breccia, or rubble, have margins that display what appears like a faint eutaxitic structure. The vague, dark, drawn-out or flattened inclusions may be the remains of pieces of andesitic rubble. At a few places a planar parallel arrangement of these platy relics persists to the very center of a mass of "arkosic" latite. Many of the symbols shown in these intrusions (Pl. 1) are based on measurements of this structure.

In addition to the "arkosic phase" the Amole Latite has porphyritic phases, and others that are felsitic or almost aphanitic. Some rather large masses appear to be re-healed rubble. This intrusive rock was difficult to map because of its several types and because of extensive cover. The contacts as shown (Pl. 1) will require changes as the area becomes better known.

Judged from steep contacts and steep internal flow structure, much of the Amole Latite has welled up almost vertically. At a number of places, however, flat contacts and moderately dipping internal structures indicate that the magma spread laterally as sill-like injections. Some mechanical consequences of the vertical rise of the magma, and of the resulting upheaval of the overlying strata are exposed at many places in the northern part of Section 32 and the northeastern part of Section 31. The cover of thin-bedded, tuff-like sediments, becoming unstable, slipped off the growing "uplifts." These bedded rocks now contain much epidote, and it seems that at the time they were in motion they were being heated, metamorphosed, and stiffened. The result, now exposed (Fig. 3-c) is a mixing of the effects of plastic flow and brittle fracture.

In this area, where the latite magma welled up in such volume, many large and small limestone blocks are found. These are especially numerous in the vicinity of the Mile Wide mine and east and northwest of the Gould mine. The blocks seem everywhere to be closely associated with intrusions of latite (Fig. 3-d). In other places the blocks appear to be at least partly enclosed in Amole Arkose with latite very close by, so that the intrusion could still have played a part in emplacing the limestone. Such a mode of emplacement was first suggested by Gerald Greenstein (1961, p. 25-27).

Brown (1939) indicated on his geologic map that the limestone blocks were Permian in age. This may not apply to every block, but in a recent study made to the east and southeast of this area Scott McCoy (1964) found that where the age could be determined it ranged from Devonian to Permian. Many of the blocks described by McCoy had been derived from the Concha Limestone or the Rainvalley Formation. In the northern border area many of the blocks are too metamorphosed to allow correlations to be made with confidence. In general, however, they have a "Paleozoic aspect." Where least metamorphosed, some of them, as for example the big block that crops out about 500 feet south of the Mile Wide mine, closely resemble the Concha Limestone.

From what was said above it seems that the northern border is one aspect of the Tucson Mountain Chaos.

Tuttle has shown the writer gradational contacts between the Amole Latite and the Amole Quartz Monzonite (quartz diorite). And yet there are places, as about 800 feet west of the corner of Sections 30 and 31, where the quartz diorite contact abruptly cuts off Amole Latite-Amole Arkose contacts and the stratification of the arkose. In spite of this local crosscutting there seems to be a rough, general tendency for both arkose and latite to dip toward the quartz diorite; but the pluton contact may be everywhere steeper than the wall rock structure. Perhaps the curved quartz diorite apophysis shown west on the Mile Wide mine (Pl. 1) filled a huge slump fissure that opened in the inward sagging walls. If so, the map provides a "still" of the engulfment. The inward sagging appears also to have been accompanied by related antithetic faults, an example of which is the fracture on which is located the Mile Wide mine.

A striking exception to the evidence of subsidence and engulfment is along the north-trending eastern contact of the Amole Granite in Section 36. Here the wall rock structure dips very steeply away from the granite contact, as though here the wall had been dragged upward by the rising granite. Conflicting evidence of lifting and engulfing seems to be present where other large igneous masses closely approached, or reached, the surface (H. Cloos, 1917, 1931; Korn and Martin, 1954).

The Eastern Rampart

From the eastern end of the northern border southeastward to Gates Pass, the Museum Embayment is bounded by a bristling wall of cliffs, composed of the Cat Mountain Rhyolite. W. H. Brown (1939, section CC′) showed the rhyolite to rest as a gently east-dipping layer on a second east-dipping layer of Cretaceous Volcanic Rocks. The volcanic rocks were shown to rest in turn on a gently east-dipping overthrust which truncated the steeper strata of the Amole Arkose. The succession volcanic rocks-arkose had been reversed by the overthrust.

The existence of the Tucson Mountain Overthrust is probably no longer accepted by any local geologist, and the "Cretaceous Volcanic Rocks" in this part of the area can be equated with Kinnison's Tucson Mountain Chaos. Accordingly, the task at hand is to discuss the relations between arkose, chaos, and rhyolite. Talus and alluvium conceal the bed rock at many places along the base of the cliffs, yet the incomplete exposures leave no reasonable doubt concerning the structural relations among the three rock units just mentioned.

As stated under "the floor of the embayment," the Amole Arkose Formation just west of the cliffs seems to have subsided and tilted slowly toward the present cliffs. As the rampart is approached across the steeply dipping strata, significant changes are observed to take place in the Amole Arkose. The stratification becomes disturbed; it may disappear altogether, or remnants of strata may remain in a rock that shows faint, wispy laminae (Fig. 3-e). Coarse clasts may become very abundant. These are commonly pebble- to cobble-sized, usually well-rounded pieces of andesite, but pieces of limestone, quartzite, and even of the Amole Arkose itself are locally abundant. In this "chaos," and in fact at many places on the side toward the undisturbed Amole Arkose are the previously-mentioned huge limestone blocks. Huge inclusions of Recreation Red Beds and of volcanic rocks like those of the Piedmontite Hills are locally present. Perhaps this is why Brown mapped this "chaos" as "Cretaceous Volcanic Rocks." Pebbles and cobbles released from these volcanics probably supplied the andesitic clasts to the disturbed, fluidized(?) Amole Arkose.

The mixture just described does not seem to be present everywhere along the base of the cliffs. It is strongly developed in the northern part where in Section 4 it may attain a width of 500 feet. At some places farther south it is very narrow or absent, but near the southern margin of the mapped area it reaches a width of several hundred yards.

At many places it is difficult to detect any ordered structure in the chaos, but where any definite arrangement can be seen, it is planar and it dips eastward little if any less steeply than does the undisturbed arkose to the west. No gently-dipping chaos layer lies upon, or truncates, the Amole Arkose. The chaos seems to have been generated by whatever caused the slow down-bending of the arkose.

Many small masses of intrusive rock, indistinguishable in the field from the "ignimbrite" phase of the Amole Latite, occur in the chaos. As in the northern border zone the association of limestone blocks with these intrusions makes the assumption reasonable that the rising magma lifted the blocks. In the vicinity of Gates Pass some of the limestones may have been emplaced by rising masses of andesitic magma. Of course the blocks of red beds and volcanic rocks could have been emplaced in the same way.

The contact between the Cat Mountain Rhyolite and the chaos, or the Amole Arkose, can actually be seen at very few places. The contact where seen is sharp, or if there is a transition it takes place within very few inches. The dip is toward the east or northeast, and at three localities measured 78°, 53°, and 65°. Flow structure in the rhyolite near the contact suggests that at some places the contact may be almost vertical, and at a few places may flatten to 30 degrees or less. The trend of the contact is irregular, especially in the south, where the rhyolite extends westward across the strike of the steeply dipping Amole Arkose. At one place in the southeastern part of Section 4, the rhyolite, first breaking westward across the strike of the Amole, seems to have been inserted as a long, narrow, south-trending strip parallel to strike and dip of the Amole. This rhyolite insertion encloses a number of limestone blocks.

It must be obvious at this point that the rhyolite does not lie flatly on either the chaos or the arkose. Its steep contact, and its near-contact internal structure, seem to carry out the steep down bending first detected in the near-by Amole strata. Further, at three places it was observed that thin, platy cavities, apparently formed by weathering-out of inclusions of chloritized Amole Arkose, were deformed as though dragged downward by the subsidence of overlying parts of the rhyolite. At one locality drag folds in the flow structure of the rhyolite very plainly indicated the same relative motion, and at another place this motion was suggested less clearly. Protracted search would probably have revealed many more examples. Because the rhyolite is thought to have welled steeply, and sluggishly (?) upward along its contact, the presence of structures indicating relative downward motion of the inner portions seems at first to be an enigma. How can the interior of the rhyolite have been moving relatively down if the entire mass was rising?

Differential upward flow might provide the answer, but in that case layers nearest the contact should have moved most slowly because of drag of friction. Precisely the opposite seems to have been true. Perhaps the magma found exit to the east and, flowing out rapidly, removed support from one side of the rising column, causing a sinking back. This is, at present, no more than a suggestion, but it is supported to some extent by the rapid eastward flattening of the flow structure (Pl. 1). The suggestion gives rise to two significant questions: Did the Amole Arkose to the west sag into its near-vertical position because support was being slowly removed from below? And did the igneous action, including generation of the chaos, somehow "climb up" the steep strata?

The presence of elongated, steep strips, or septum-like masses of Amole Arkose far within the rhyolite adds cogency to the second question. One such septum, seemingly fluidized almost beyond recognition, trends northward at the base of the cliff of Tower Peak (Pl. 1). Another is the great, northward-elongated Amole block at Gates Pass, and what may be another piece of this same septum coats the eastern side of the spherulitic rhyolite intrusion on the crest some 2,000 feet northwest of the pass. Other examples are present in this area. These steep septa are like downward projecting remnants of the belt of steep dips in the Amole Arkose.

The rather close association of steep septa, steep flow structure, and gently-dipping flow structure in the rhyolite is puzzling. It is suggested that the areas of gentle dips are places where the rhyolite, released from restraint and becoming highly mobilized, flowed rapidly eastward, perhaps to form extensive sheets. Such outflows may have over-ridden the septa with their border zones of steep flow layers, but more probably broke through them.

Associated with the septa, with the chaos, and distributed irregularly through the rhyolite are many large and small masses of dark andesite. Much of this andesite is quite dense, but some of it is porphyritic, and large masses of it are fragmental. The relations of this dark rock to the rhyolite are various. At some places it is obvious that the andesite domes up or intrudes the rhyolite, and is therefore the later. At many other places, however, the rhyolite is charged with countless small and many huge inclusions of andesite. Either the intermediate and acid magmas were active essentially simultaneously, or there were several episodes of andesitic injection some earlier, some later than the rhyolite.

As pointed out by Bikerman (1963, p. 87), final gas-poor increments of the rhyolite magma appear to have risen sluggishly into place wherever a favorable channel was present. These late-comers solidified as spherulitic rhyolite and related rocks. The resulting masses are mostly small, steep-sided, and lens- or plug-like.

The Silver Lily Dikes

Brown (1939, p. 742) said of these dikes "Probably the rock should be classified as a latite porphyry." It is usually cream or light gray in color, but is locally medium greenish gray. The texture varies from aphanitic to fine-grained, perhaps even medium grained, and is commonly porphyritic. At many places the rock has a planar flow structure, which may be intricately folded. The individual dikes vary in thickness from a few inches to 50 feet or more. The strike is usually west-northwest, and the dip is steep, usually to the south.

The pattern of these dikes is obvious (Pl. 1). Some of them are present here and there in the embayment and in the Piedmontite Hills, but most are concentrated into a swarm that trends south-southeast, from the western end of the Red Hills to the Tucson Mountain crest. The swarm fans eastward so that it is much broader and less dense on the crest than it is near the Red Hills. Cretaceous Volcanic Rocks, Recreation Red Beds, Amole Arkose Formation, and Cat Mountain Rhyolite are all traversed by the dikes.

Because the Silver Lily magma was obviously emplaced after the Cat Mountain Rhyolite had solidified, it may be that at that time the rhyolite and the steeply dipping Amole on the west formed one relatively strong, rigid unit. Such a unit should fracture fairly uniformly in tension if up-arched on a nearly west-trending axis. This may be the reason why the members of the dike swarm are so broadly distributed near the crest of the Tucson Mountains. West of the crest and west of the belt of steep dips in the Amole Arkose, the dike swarm encounters such structures as the "boomerang," the north-trending, rubble-cored anticline, and the principal syncline. As already mentioned, these structures appear to have been formed by true active or relative up and down movements. If these movements were still in progress at the time the now dike-filled fissures were opening, the movements must surely have interfered with arching about a west-trending axis. Of course, the present dike pattern would show corresponding modifications. This deduction is appropriate.

The second dike north of the Westward Ho Guest Ranch had to cross the eastern border of the "boomerang" where adjustments already illustrated (Fig. 3-a) may have been in progress. The dike wriggles like a snake in crossing this disturbed area. The next dike on the north stops at the western edge of the boomerang and is not seen again. The next two dikes swerve aside slightly as though to avoid the worst of the structural quagmire. The dike in the northwest corner of Section 9 appears to terminate on the eastern flank of the north-trending anticline, but it reappears on the eastern flank of the principal cyncline. That is, the intrusion "jumps across" the anticline. On the eastern flank of the principal syncline the dike is diverted toward the northwest, along the strike of some fine grained sandstones, but it resumes the nearly west trend across a belt of shale. This dike seems never to "make it" across the synclinal trough. The tendency for many of the dikes to avoid the southern, most deeply down-folded part of the principal syncline appears to be responsible for convergence of the swarm toward the northern edge of the Red Hills.

In the western part of Section 31, as previously mentioned, a single dike splits away from the swarm, follows the strike of bedding along the western flank of the principal syncline, and connects with intrusions of Amole Latite east of the Gould mine. As previously mentioned the Cat Mountain Rhyolite has been observed to have intruded part of the Amole Latite. This apparent anomaly is easily explained if emplacement of the Amole Latite complex required considerable time.

Just as the apparently still moving structures in the Amole Arkose greatly modified the pattern of the dike swarm, so emplacement of the dikes seems to have modified the structure of the Amole Arkose. For example, the principal syncline, where crossed by the dike swarm, is seen to broaden and flatten, as though the bottom of the southeast plunging trough had been warped upward along the dike trend. Farther west, toward the Red Hills, the stike of Amole strata bends into approximate parallelism with the dike. In Section 5, the peculiar en echelon pattern of the two arcs of the north-trending anticline, and the serpentine trace of the northern axis, may be interference effects of crossed uplifts. The southern end of the "boomerang" swings abruptly eastward, parallel to the dike trend. In the northwestern part of Section 9, the southwestern corner of Section 4, and the southeastern part of Section 5, there is cross folding of the arkose along the dike trend. Other examples can be found (Pl. 1).

In view of the above observations, it seems reasonable to conclude that after the Cat Mountain Rhyolite had consolidated, adjustments within the Museum Embayment were still in progress. These adjustments took place along several intersecting trends, and one of the results was the emplacement of the Silver Lily Dikes.

DISCUSSION

Igneous Action and Deformation

The close association of intrusive and extrusive igneous rocks with deformational structures in the sedimentary rocks of this area probably needs no further argument. The relation seems obvious. The deformation must have been brought about by magma movements and accompanying phenomena. Indeed, one might wonder with some reason if the vast difference between Paleozoic sedimentation and the much more rapid, "orogenic" Mesozoic accumulation is not somehow related to the rise of magma from depth. Whether this be true or not, magmatic activity was of supreme importance as a producer of structure.

Magma from depth would have had to rise through the metamorphic and granitic Precambrian basement. That the magma did rise through the basement is indicated by the presence of blocks and chips of probable Pinal Schist in the chaos, in the Cat Mountain Rhyolite, and in the volcanics of the Piedmontite Hills. In the northern border area, and in the area of the north-trending anticline (Pl. 1, Section 5) a few pipes were found that contained mostly pebble- or cobble-sized pieces of granitic rock. These pipes may have derived their fillings from the Precambrian basement.

Once the magma had cleared the Precambrian it would still have had to penetrate the Paleozoic section. McCoy's (1964) results are pertinent in this regard. As already mentioned, he found that most of the identifiable limestone blocks associated with andesite intrusions in the Tucson Mountain Chaos were from the Permian Concha Limestone and Rainvalley Formation. Associated with these blocks are large masses of quartzite, probably from the Permian Scherrer Formation. The Permian section, besides being nearer the surface and hence under lower confining pressure, offers favorable planes of entry along contacts between mechanically unlike quartzites and limestones of the Scherrer Formation. Perhaps the rising magma was able to spread along such surfaces and to lift and partially disrupt the overlying Concha and Rainvalley in the manner already suggested (Mayo and McCullough, 1964, p. 86).

Structural Framework

The structural map (Pl. 1) reveals a pattern that, at first glance, recalls the play of kittens beneath a rug. It soon becomes obvious, however, that there were serious restrictions to this play. The motion of the kittens was mostly upward or downward; moreover they were rather exclusively oriented to certain fairly definite directions.

The principal syncline and some of the anticlines that accompany it, the intrusions southwest of the Desert Museum, and the general course of the eastern rampart all are oriented northwest, or perhaps a little north of northwest. This is the general trend of the Tucson Mountains.

The structures near the Mile Wide mine trend northeast, or east of northeast. The same is true of the aligned centers of the Sedimentary Hills, Golden Gate Mountain and Bren Mountain (Fig. 1). In general, evidence of this direction is weak in the embayment area.

The northern border with its latite complex, the southern margin of the Amole Granite, and the Silver Lily Dikes are all nearly west-trending. The southern end of the Piedmontite Hills may have broadened eastward along this trend. The southernmost mapped part of the Cat Mountain Rhyolite may in part have risen along cross-trending and cross-cutting fissures.

The eastern edge of the Amole Granite, the tuff-filled fissures in the southeastern part of the Piedmontite Hills, the north-trending anticline, the northern arm of the "boomerang," the latite intrusion some 800 feet west of the first "C" in CREST OF THE TUCSON MOUNTAINS, the belt of steep dips west of the eastern rampart, and the fluidized septum just west of Tower Peak, all trend north, or nearly so.

The structural pattern would seem to have formed as a result of adjustments — uplift, outpouring, subsidence, gravitational gliding, and possibly strike-slip, along this four-directional mosaic.

An attempt has been made (Mayo, 1958) to show that essentially the same structural directions, mentioned above, are developed regionally in southwestern United States.

Significance of the Framework

Many years of observation and much searching of the literature have convinced the writer that the four directions mentioned above were developed early in the structural history of the crust. Moreover, this primordial criss-cross network seems to have provided a "multiple grain," or fabric to be utilized by all later deformations. That the fabric could have been considerably changed by later events must be admitted. The nature of the intersecting elements is by no means clear; they may be folds, upwarps, downwarps, zones of steep sheeting, faults or fissures. It seems simplest to assume that at depth they are fractures of some kind. If this can be admitted, then the framework elements could serve as zones along which adjustments would take place between basement blocks. More importantly, the elements might, under certain conditions, serve as channels for heat-carrying fluids, including melts. In this way the well-known slow rate of heat conduction in rocks might be circumvented and large amounts of thermal energy be transferred relatively rapidly from the hot, high pressure depths to the cool, low pressure surface.

Activation of the Framework

There may be a number of ways in which the structural framework could have been so activated that heat and melts from depth could gain the surface. The writer can visualize the process most clearly, however, by assuming a slow, long-continued swelling of the mantle, perhaps involving the lower part of the crust. Suggested reasons for this expansion are known to perhaps every graduate student in geology, and will not be discussed here. Suffice it to note that such a deep-seated swelling would ultimately bring the upper crust, that is the Precambrian basement, under tension. The framework elements, in part at least, would be opened and the probably long, slow task of transferring materials from depth to surface would begin.

The Orogeny

In what follows, the word orogeny is used to mean the building of mountains, regardless of how this was accomplished. Unless the writer has completely misinterpreted what he has seen and mapped in the field, then the Late Cretaceous orogeny in the Tucson Mountains was accomplished under crustal tension, *not* under crustal compression. Any compressional effects appear to be strictly local and are related to collapse or to uplift. Perhaps it is premature to extend this impression beyond the confines of the mapped area, yet the writer strongly feels that the burden of proof rests on any geologist who glibly speaks of the "compressional phase of the Laramide Orogeny" *in these mountains.*

FUTURE WORK

Enlargement of the Mapped Area

Perhaps all of the conclusions suggested in this report would be better supported if the mapping were extended eastward, as planned, to the Camino del Oeste. It would also be well to broaden the present section, both northward and southward, incorporating the results already obtained by several graduate students. Among the objectives of such extended field work would be to arrive at a better understanding of the origin and mechanics of emplacement of the Tucson Mountain Chaos and the Cat Mountain Rhyolite. Another objective would be to gain a more complete picture of the mechanics of emplacement of the Amole Pluton. Finally, one might hope to be able to fit the Tucson Mountain structure more accurately into the framework of the surrounding region, and perhaps even to be enabled to say why this particular place became the site of the "volcanic orogeny." Accordingly, it would appear that more extensive field work is still the greatest need.

More Detailed Studies

Although the Museum Embayment and its immediate surroundings were mapped at approximately 500 feet to the inch, such is the wealth of detail displayed even in these usually poor exposures that the writer feels as though he has accomplished a mere reconnaissance. To re-map the area, say at 100 feet to the inch, would probably not be feasible. On the contrary, large-scale mapping of selected, critical localities might be rewarding. Further, a number of accurate stratigraphic and structural sections must be made in order to give the field work a better quantitative basis. Many more observations and measurements are also needed if directional current structures and slumping or gliding directions in the Cretaceous sediments. Finally, petrographic and petrologic studies, which at present are almost completely lacking, would greatly assist in approaching an understanding of the origin and nature of the various formations.

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