VOLCANIC OROGENY OF THE TUCSON MOUNTAINS
(A Preliminary Report)

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INTRODUCTION

The Tucson Mountains are that desert range which forms the western wall of the Santa Cruz Valley west and northwest of Tucson, Arizona. During the past 6 years, graduate students of the Department of Geology, University of Arizona, and the writer have made observations in local areas of these mountains that appear to be critical to an understanding of the orogenesis. The objective of this report is to present these observations in relation to pertinent previous work here and elsewhere.

Unfortunately it is not practicable in a communication of this length to acknowledge all who have contributed to an understanding of the Tucson Mountains geology. For this reason, only those papers that contribute most directly toward the present objective are mentioned at appropriate places below.

In relation to the information still to be obtained, not even a good beginning has yet been made. Clearly then, those conclusions presently offered, while suggestive, are necessarily tentative.

FUNDAMENTAL REPORTS ON TUCSON MOUNTAIN GEOLOGY

Jenkins and Wilson

The Arizona Bureau of Mines bulletin by Olaf Jenkins and Eldred Wilson (1920), based on fieldwork done for the first Geologic Map of Arizona, appears to be the earliest account of the geology of the entire range. The geologic formations, representing parts of Precambrian, Paleozoic, Mesozoic, and Cenozoic time, were described in a general way. Concerning the structure these authors wrote (1920, p. 9): "The structure, therefore, consists of a tremendously upheaved and intruded region about the center of Amole Peak with a flanking rim of extrusive volcanic flows."

It now appears that this initial idea of the structure of the Tucson Mountains, gained by reconnaissance, was closer to the truth than were some subsequent interpretations.

In 1939 a second paper was published on the geology of the entire range. That report, by Brown, was based on much more detailed fieldwork than was its predecessor, and it was accompanied by a colored geologic map. Formations and sequence were discussed in more detail than before. Of special interest was the establishing of three Mesozoic formations, all of which were assigned to the Cretaceous. These were, in order from oldest to youngest: Cretaceous volcanic rocks, largely andesitic, clastic, water-laid volcanics; Recreation Red Beds, fine-grained, brick-red to maroon sandstones and siltstones; and Amole Arkose, coarse arkosic sandstones, fine-grained graywacke sandstones, shales, and thin, argillaceous limestones.

A Tertiary sequence of volcanic rocks was recognized also, and of these the oldest formation, the Cat Mountain Rhyolite, was thought to rest on a surface that had been eroded on deformed Cretaceous. This younger volcanic sequence was assigned to the Tertiary partly on the basis of an assemblage of plant fossils found in the Safford Tuff, a formation said to grade downward locally into Cat Mountain Rhyolite, and in part because of the angular unconformity thought to separate these younger volcanics from deformed Cretaceous.

Some intrusive igneous rocks were assigned to the Cretaceous or early Tertiary. Of these a huge composite mass of quartz monzonite and granite intrudes Amole Arkose, Cretaceous volcanic rocks, and Paleozoic formations in the mountains north of the Arizona-Sonora Desert Museum. Associated with this large intrusion are smaller masses of a fine-grained, light-colored igneous rock termed by Brown the Amole Latite. Among intrusions supposedly of Tertiary age are the Spherulitic Rhyolite which intrudes Cat Mountain Rhyolite, and a set of nearly east-west fracture fillings, of probable latite porphyry, called the Silver Lily dikes.

In the discussion of structure two very important concepts were developed: (1) In "Laramide" time a great overthrust had carried Cretaceous volcanic rocks as well as blocks, or slices, of Paleozoic limestone from southwest to northeast over the Amole Arkose. This overthrust sheet had been largely eroded before the Cat Mountain Rhyolite poured out. (2) After most of the Tertiary volcanic succession had accumulated, block faulting took place. The present tilted aspect of the younger volcanic rocks is a result of the block faulting.

Tucson Mountain Chaos and Tucson Surface

Two papers of especial importance to the present discussion were published by John E. Kinnison (1959a; 1959b). The jumbled mixture of Amole Arkose, Cretaceous volcanic rocks, Recreation Red Beds, and occasional blocks of Paleozoic limestone, which Brown thought to be the remains of an overthrust sheet, was regarded by Kinnison as a sedimentary formation and named by him the Tucson Mountain Chaos. Kinnison considered this chaos to be coarse debris accumulated by the erosion of a fault scarp. Concerning the Tucson Mountain overthrust, he wrote (1959b, p. 150): "If this interpretation is correct, then there is no direct evidence of large scale overthrusting in the Tucson Mountains."

According to Kinnison, the Tucson Mountain Chaos was deposited on the

Tucson surface, which had been established by erosion on the deformed Cretaceous rocks. Therefore the surface between chaos and older rocks was an angular unconformity such as the one on which Brown thought the Cat Mountain Rhyolite to rest.

PRELIMINARY STUDIES IN THE DESERT MUSEUM AREA

Cretaceous Volcanic Rocks and Recreation Red Beds

In 1958 Robert E. Colby, a graduate student in the Department of Geology, University of Arizona, submitted a Master's thesis entitled "The Stratigraphy and Structure of the Recreation Red Beds, Tucson Mountain Park, Arizona." The area investigated included the Red Hills and Piedmontite Hills, respectively northwest and southeast of the Arizona-Sonora Desert Museum (fig. 1). The Red Hills are the type locality of Brown's Recreation Red Beds, and the Piedmontite Hills contain important exposures of the Cretaceous volcanic rocks.

Brown had mapped a fault that separated red beds from volcanic rocks between the two groups of hills (fig. 1-A); but he mentioned (1939, p. 714-715) that some red beds were interstratified with water-laid volcanics. He also recorded in his Piedmontite Hill section of part of the Cretaceous volcanic series (ibid., p. 714) the presence of a "light pinkish-white dense rhyolite" among darker, andesitic rocks.

Colby found no fault separating the two older Cretaceous formations. Instead, the fault at the eastern edge of the Piedmontite Hills continued northward, separating Recreation Red Beds from Amole Arkose along the eastern edge of the Red Hills (fig. 1-B).

The red beds were seen to interfinger with the volcanics. Also, blocky red-bed inclusions as well as obviously water-deposited red beds and laminae, or films, were found in the volcanics. To explain these relations, Colby wrote (1958, p. 49-50): "Evidently something like a huge cut and fill channel formed in part of the older red beds." Floods in the channel were supposed to have transported the coarse and fine andesitic debris from some volcanic source. The included red-bed blocks were thought to represent caved-in portions of undercut banks, while the red material interstratified with the volcanics was considered to be fine-grained debris transported from a distant source or eroded from nearby deposits and laid down during quieter intervals between floods. According to this interpretation, volcanic rocks and Recreation Red Beds were essentially contemporaneous.

Colby suggested that the Recreation Red Beds be redefined as a formation consisting of three members. He proposed that the Recreation Red Beds as defined by Brown be termed the sandstone-siltstone member, that the andesitic volcanics be called the volcanic conglomerate member, and that the rhyolite, recognized by Colby as ignimbrite, be designated the tuff member. Perhaps these different rocks could as well have been regarded as facies of one formation. Their close association hints of a common origin.

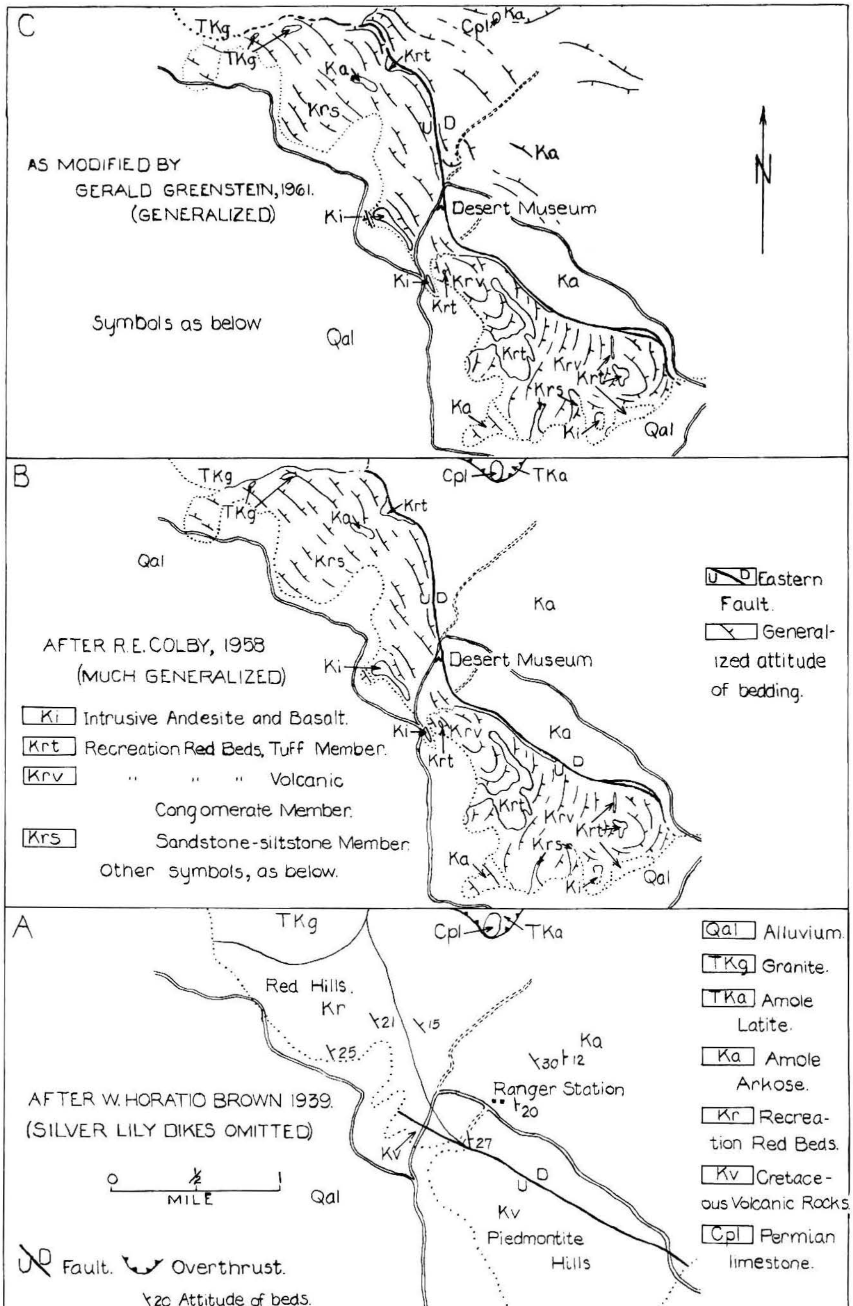

FIGURE 1.- REVISIONS OF GEOLOGY- PIEDMONTITE HILLS -RED HILLS

Arkose-Red Bed-Limestone-Granite Relationships

While the present writer was remapping the Piedmontite Hills, Gerald Greenstein (1961) studied the relations between the sandstone-siltstone member of the Recreation Red Beds, the Amole Arkose, the Paleozoic (Permian) limestone blocks, and the granite in a small area adjacent to the Red Hills on the northeast (fig. 1-C).

According to Greenstein, the structure of the red sandstones and siltstones conforms somewhat better to the shape of the intrusive granite than Colby had thought. Colby's Eastern fault (fig. 1-B) is not cut off by the granite, but turns westward to form the granite-red bed contact (fig. 1-C). Both red beds and arkose dip into the granite at most places, as though the sedimentary formations had subsided before or during emplacement of the granite. And yet, there was local evidence, not shown on figure 1-C, that the granite had lifted the Amole Arkose.

Of even greater interest were Greenstein's observations on the Tucson Mountain overthrust, the Permian limestone blocks supposed by Brown to be thrust slices, and the Amole Latite supposed to occupy locally the hanging wall of the overthrust (fig. 1-A, B). As indicated (fig. 1-C), Greenstein found no evidence of the overthrust. He found only a few small dikes of Amole Latite in and near the block of Permian limestone, which was surrounded by highly disturbed Amole Arkose. These same relations were observed at other Permian limestone blocks located beyond the edge of figure 1-C. Greenstein concluded, therefore, that the Permian blocks might have been punched upward into the Amole Arkose by rising masses of Amole Latite. Whether or not this conclusion was correct, it seems that the limestone blocks were somehow pushed or carried from below to their present positions.

THE INFLUENCE OF PAPERS ON OTHER REGIONS AND FIELDS OF INQUIRY

General Statement

Before presenting some of the results of a restudy of the Piedmontite Hills, it seems best to discuss a few accounts of research that furnish the basis for interpreting the geology of this area. These highly suggestive reports were read while the fieldwork was in progress.

Fluidization

The most thorough treatise on this subject known to the present writer is the book by Leva (1959). In this book Leva discusses the mechanical and some chemical effects of the passage of fluids, usually gases, through granular aggregates. In the chapter on the fluidized state he describes the fluidized-state spectrum leading, with increasing gas velocity, from the fixed bed through the expanded bed and the dispersed phase into pneumatic transport. Irregularities of the "spectrum" such as channeling, slugging, and the spouted beds are also discussed.

Regarding the last-mentioned feature, an experiment by Mr. William D. Green of Professor Damon's laboratory is of interest. In attempting to purify an aggregate of magnetite grains, Mr. Green passed a column of water upward through the aggregate in a separatory funnel. At a certain velocity of the rising current a column of entrained magnetite grains rose through the center of the aggregate, while marginal portions sank. Thus a sort of convection circuit was set up. The experiment reproduced exactly the spouted bed as figured by Leva (1959, p. 170).

In her paper on fluidization as a geological process, Reynolds (1954) gives further details of the commercial operation and supplements these with geologic examples. An important feature is the abrasion suffered by the larger particles in the expanded bed. Because of this phenomenon, pieces from the walls of a pebble dike or pipe could become rounded in the expanded-bed phase of a fluidized system without transport. The abrasive action and extreme mobility of a gas-solid fluidized system has the important consequence that the system can penetrate into minute cracks, enlarge them, and cause the overlying rock to collapse. Finally, fluidized systems can include the gas-solid, liquid-solid, gas-liquid droplet, and three-phase systems.

The Swabian Tuff Pipes

A beautiful series of geologic examples that illustrate the effects of fluidization in the Swabian tuff pipes, southeastern Germany, was investigated by Hans Cloos (1941). One of these examples, the Aichelberg, is reproduced here as figure 2.

The sedimentary formations that crop out at the Aichelberg are Brown Jura, the oldest, followed by the White Jura with members Alpha, Beta, Gamma, Delta, and Epsilon, capped by the Tertiary Bohnerz Clay. The fine- or coarse-grained products of the fluidization of these materials consist largely of blocks and lesser pieces of the sedimentary rocks, mixed with varying amounts of small droplet- or lapilli-like pieces of basic lava. Cloos called this mixture "tuffisite" to distinguish it from ordinary volcanic tuff, consolidated from ash. The process of generating this tuffisite he called tuffisierung (tuffisitization). Apparently he was not acquainted with the principles of fluidization.

On the east side of the Aichelberg (fig. 2), the Brown Jura is exposed as wall rock of the large tuff pipe. Next to the west is "normal tuff," composed mostly of lapilli of melilite basalt. Beyond this is a debris slope, and next are outcrops of White Jura Beta, at first with gentle westerly dips. Westward, these dips increase to vertical. Small, east-dipping antithetic normal faults displace the White Jura beds and attest the downbending of the huge sedimentary block. Cloos called this part of the structure the outer fore zone. In this zone the White Jura had only been displaced, i.e., bent downward.

In direct contact with the outer fore zone on the west is the inner fore zone, consisting of a shattered mass, mostly of White Jura Gamma and Delta. Beyond this is the main mixing zone, a tuffisized (fluidized) mass of White Jura Delta, possibly mixed with Epsilon, containing a few basaltic lapilli and having slabs of Tertiary clay on its western border. Beyond this again was more tuff like that in contact with Brown Jura on the east. This western tuff, in turn, extends to a contact with Brown Jura on the western side of the pipe.

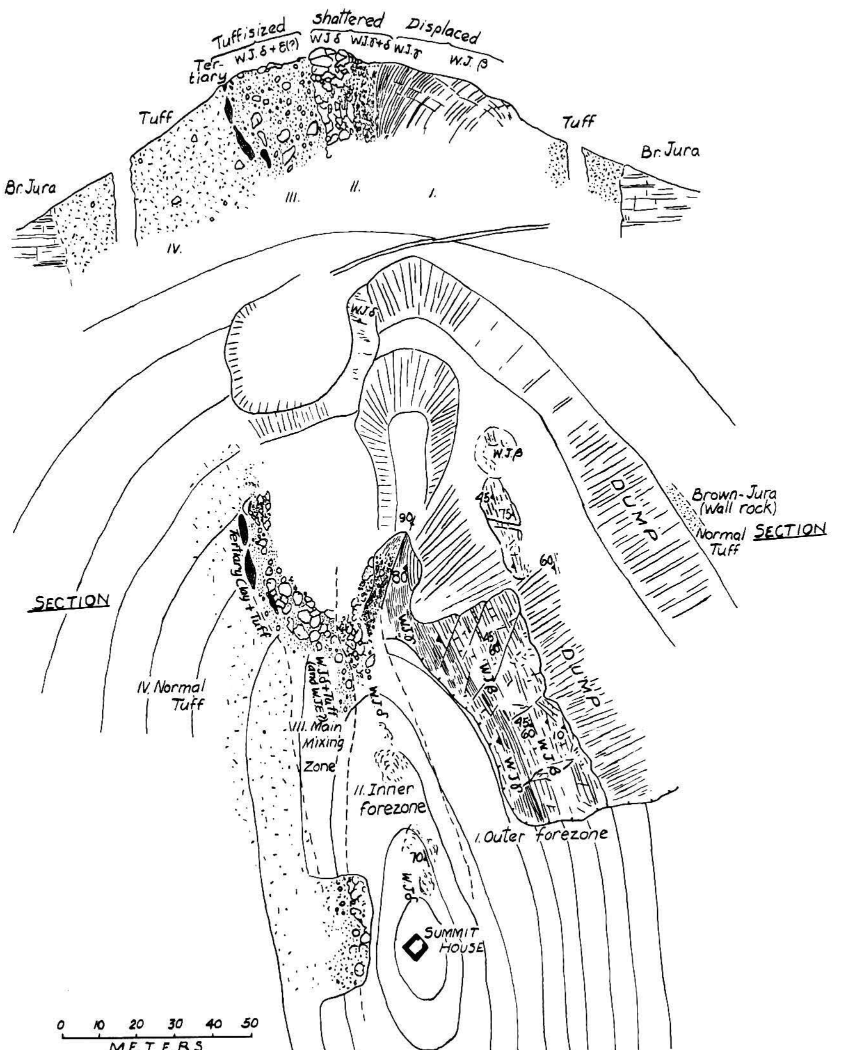

FIGURE 2 - SKETCH MAP AND CROSS SECTION OF THE AICHELBERG IN THE SWABIAN ALB, GERMANY

AFTER HANS CLOOS, GEOLOGISCHE RUNDSCHAU, BAND XXXII, TEXTTAFEL III.

In spite of what seems at first to be intense disturbance and violent mixing, the stratigraphic succession is preserved. Accordingly, the great White Jura block: (1) was tilted; (2) sank; and (3) was partially tuffisized by some slow, continuous, relatively gentle and orderly process. To borrow an expression from Reynolds, "the block subsided gradually as though through quicksand." This result might have been achieved by a fluidized system in the expanded-bed or boiling-bed stage, perhaps with local and temporary entrainment. Cloos pointed out that if the block could be rotated back to its initial position, it would effectively seal the pipe. Early stages in the abrasive enlargement of fracture nets, preparatory to undermining and collapse, were described and illustrated many years ago by Stahlecker (1926).

Blocks from lower formations (including the crystalline basement) in the centers of some of the tuff pipes indicate strong upward movement. And yet, structures in marginal portions of the same pipes indicate subsidence. Accordingly, the motion in these pipes must have resembled that in the spouted bed.

Although the above discussion is not as thorough as could be desired, perhaps it will assist in viewing the geology of the Piedmontite Hills in a new light.

RESTUDY OF THE PIEDMONTITE HILLS

General Statement

A series of maps would be necessary to present all of the new observations made in these hills. Even so, further fieldwork is needed. A number of small, but diagnostic, structures should be separately mapped on a large scale, and many sketches should be made of critical exposures. Some of the data now at hand are summarized on figure 3, and eight structure sections are shown in the upper part of figure 4.

The rocks indicated (fig. 3) are quartz veins, Silver Lily dikes, dark and light phases, large phenocryst porphyry (Mayo, 1961), and Amole Arkose to the northeast and southwest. Of Colby's Recreation Red Beds formation, there are the ignimbrite (the tuff member), Cretaceous volcanic rocks with associated sandstones (the volcanic conglomerate member), and Recreation Red Beds (the sandstone-siltstone member). Only this last-mentioned formation requires further description.

Members of the Recreation Red Beds Formation

The sandstone-siltstone member consists of brick-red to maroon fine-grained sandstone and siltstone, and relatively thin beds of light-gray or varicolored pebble conglomerates and coarse-grained sandstones. The fine-grained red rocks are massive at most places; only locally are they laminated, and there is no bedding fissility. The pebbles in the conglomerate beds are of various compositions, but most are of volcanic origin. A small amount of fine-grained volcanic debris can be recognized at some places, even in the siltstones. Reconnaissance in the Red Hills by the writer shows this red unit to be surprisingly complicated in lithology. Pending detailed field and petrographic study, it can

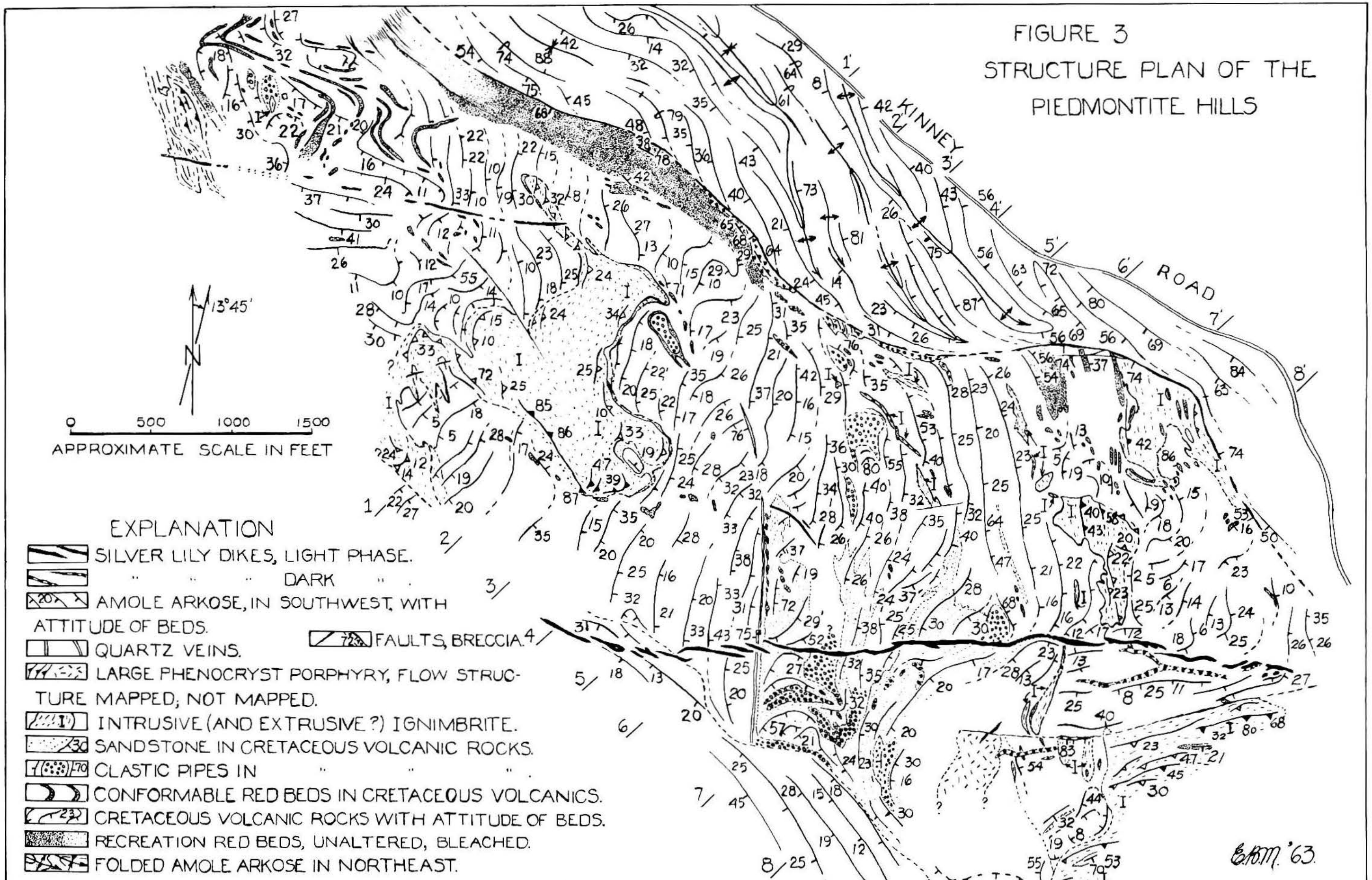

FIGURE 3
STRUCTURE PLAN OF THE PIEDMONTITE HILLS

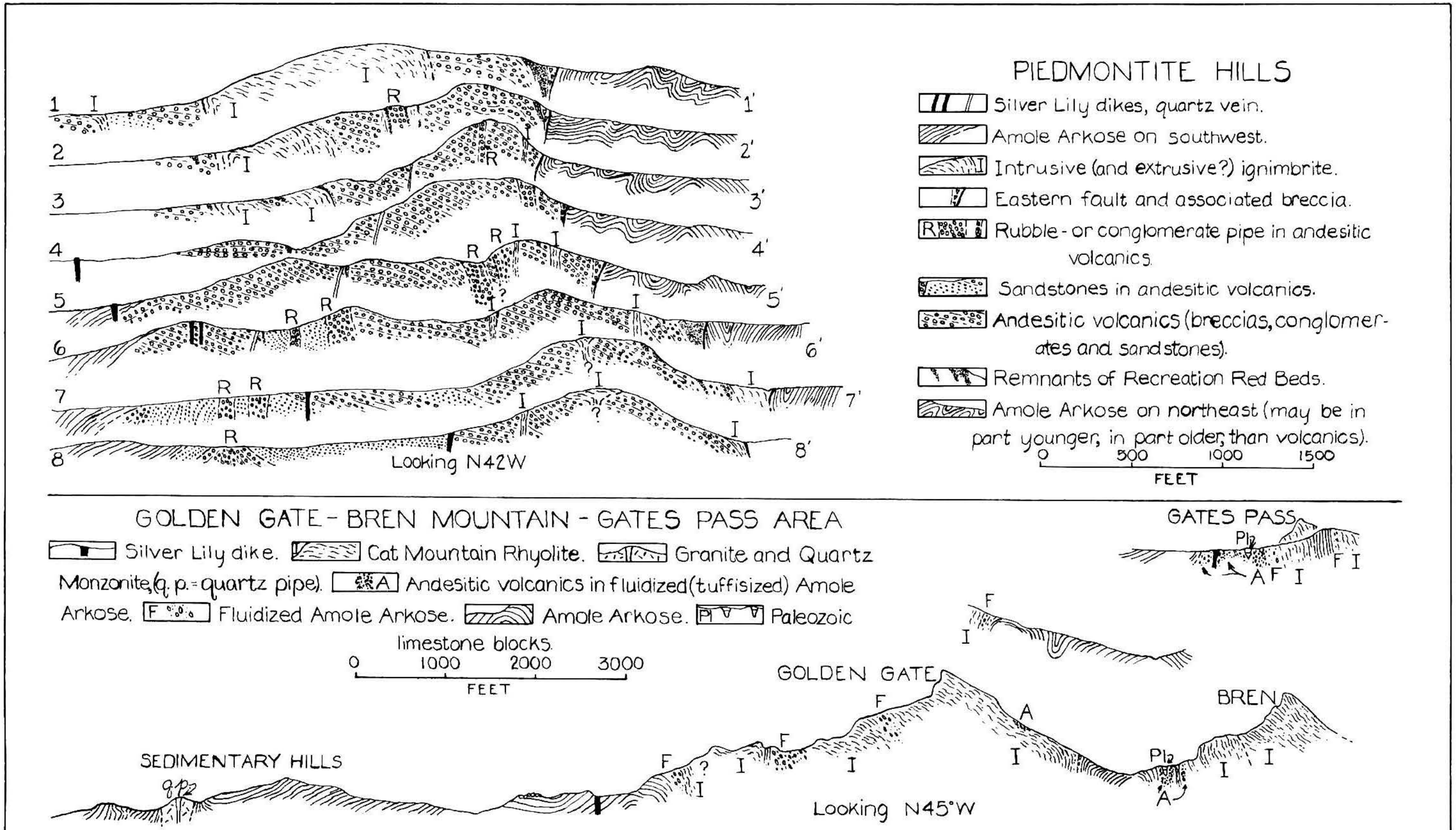

FIGURE 4-STRUCTURE SECTIONS

be only tentatively suggested that these red rocks were somehow formed as a result of volcanic activity.

The coarser, more obviously volcanic rocks of the volcanic conglomerate member (Cretaceous volcanic rocks, fig. 3) are all fragmental. No lava flow has yet been recognized in the Piedmontite Hills. These apparently andesitic rocks are breccias and pebble, cobble, and boulder conglomerates, usually with thin interbeds of tuffaceous sandstone. No gas pores or amygdules have been noticed in this material, and lapilli seem to be absent. Most of the structural measurements generalized on figure 3 were made on the interbedded sandstones. In the southern part of the hills the sandstone, usually present only as thin layers in coarser material, occupies rather extensive areas and has accumulated to unusual thicknesses.

The color of the coarse volcano clastics varies from place to place. Plum color is common; much of the rock is purplish brown, and at many places it is greenish gray because of the reduction of ferric oxide and the formation of epidote. The associated sandstone may be plum colored, light pinkish brown, reddish brown, purplish gray, or greenish gray.

As already mentioned, the tuff member is an ignimbrite, and it may be rhyolitic. The rock is everywhere much altered. The color varies from white through cream or buff to pink. In fact, most color phases have a faint pinkish cast, due to the presence of finely disseminated piedmontite. Viewed from the crest of the Tucson Mountains to the east, the outcrops of ignimbrite in the Piedmontite Hills have a definitely rosy hue.

Structural Relations Between Coarse Clastic Volcanics and Red Beds

The field relations (fig. 3) support the impression of two different associations of coarse clastic volcanics and red beds. First, the long, narrow belt of red beds on the northeastern edge of the hills has, where it can be observed, a very irregular contact with the coarser volcanics. Further, some large red blocks, reaching 100 feet or more in length, appear to be isolated without loss of orientation within the coarser clastics. Smaller isolated red blocks appear far within the volcanics. The map cannot show the many still smaller red blocks and the thousands of red chips that are present almost everywhere throughout the coarse clastics. It is difficult to believe that such relations have come about through stream transport and the caving of undercut banks.

In the second association, red beds from a few inches to possibly 10 feet in thickness are interbedded with the coarser clastics. This relation is especially well displayed at the northwestern end of the hills (fig. 3). Such "conformable red beds" are always relatively thin. They may be laminated, at least locally, and they nearly always show some coarse admixtures. The local presence of thin red films along the stratification of the volcanics has already been mentioned. Some of these films, of very small extent, provoke the epithet "red mud puddles."

During the accumulation of all these materials, some process was at work which must account for both of the above-mentioned associations. In order to visualize this process more clearly, perhaps it is best first to look more closely at the so-called volcanic conglomerate, and then to consider in more detail the contacts of the discordant red beds with these coarser volcanics.

In a few unstratified exposures on the eastern slope of the Piedmontite Hills, the volcanics appear at first to be massive, but closer inspection shows them to be intensely shattered. The closely fitting fragments are separated by a small amount of light-colored sandy matrix. Nearby exposures reveal breccia with sharp-edged fragments embedded in varying amounts of matrix. Still other exposures reveal the fragments in what seem to be various stages of rounding. Abrasion by the matrix, as is characteristic of the expanded fluidized bed, is clearly suggested. Wherever these materials welled up under water the resulting currents should have sorted and stratified them.

On figure 3 are shown the places so far recognized where pipelike bodies of usually rounded, coarse fragmental material seem to have welled up vertically through the stratified volcanics. Among features that reveal the positions of these upwellings is the abrupt steepening of the dip of stratified material, or a reversal in the usual direction of the dip. At two places the strike of the stratification "boxes the compass" around such upwellings. At one place near the center of the hills and directly east of the north arrow (fig. 3) such a "rubble diapir" seems to have pierced and spread over a red layer. Now that these upwellings have been recognized, careful search may reveal more of them. They appear to be examples of the phenomenon of channeling which has been detected in commercial fluidizing operations.

What may be a large-scale example of elutriation was found in the southwestern part of the hills. Just east of the large quartz vein (fig. 3), the coarse volcanics end along a remarkably straight line, parallel to the vein. Along this line are many small bodies, apparently remnants, of red beds. East of the line, and beginning on it, are the previously mentioned areas of sandstone that has accumulated to unusual thickness. Possibly the straight feature is the trace of a fissure up which once rushed a liquid-solid system with velocity just sufficient to entrain sand-sized particles. The sand may have been derived in part by elutriation of the volcanics and partly by disaggregation of red beds. The local structure complications in the sandstone are thought to have resulted from upwellings of the volcanic surface on which the sand was deposited.

Near the contact between the coarse, fragmental volcanics and the long, narrow belt of red beds at the northeastern edge of the hills, many small and large steep-sided lenses, pipes, and irregular bodies of the fragmental volcanics are present in the fine-grained red rocks. At numerous places the same phenomenon can be seen also in the isolated red blocks. Apparently the fragmental volcanics have actually invaded the red beds, as is suggested also by the previously mentioned very irregular contacts.

The most active ingredient seems to have been the sandy matrix of the volcanics; this material appears in the smallest, initial(?) projections into the red beds. The matrix appears to have been followed, as the projections increased in size, by entrained pebbles. By continuation of this intrusive process the red-bed blocks must have become isolated, the red chips distributed throughout the volcanics, and large volumes of red beds completely disaggregated. Much of this disaggregated material may have been transported beyond the area, but surely some of it was deposited locally as the "conformable red beds."

The Tuff Member

On the northwestern spur of the Piedmontite Hills, near the weather station of the Arizona-Sonora Desert Museum, a small mass of altered ignimbrite rests on one of the above-mentioned upwellings of the fragmental volcanics. At first this ignimbrite appears to be a mere flake, perhaps an erosion remnant of a once more extensive ash flow. Supporting this impression, most of the planar structure of this welded tuff dips gently, but a few very steep elements were seen near the base of the deposit. This suggests that the tuff gained the surface at this place through a pipe of fragmental andesite.

The large body of ignimbrite to the southeast (fig. 3) has local steep to vertical contacts and flow structure. Further, truncated flow layers at one place show that some inner portions of this mass have welled up steeply through more nearly static marginal portions. Some parts of this large body appear to have been intruded in a sill- or laccolith-like manner into the stratified fragmental volcanics. Some of the ignimbrite may have flowed out on the surface, but no convincing evidence of this has yet been found.

Several of the smaller bodies of ignimbrite in the southern part of the hills obviously occupy steep, or vertical, fissures. The large mass of this rock in the southeastern corner of the area was formerly thought to be a down-faulted portion of an ash flow located higher in the hills. But even in this case, local steep flow layers and close association with fissures suggest upwelling essentially in place. It seems probable that intrusions of ignimbrite at high temperature caused at least some of the pipelike ejections of fragmental andesite.

Overall Uplift of the Volcanic Rocks

Gently dipping quartz-coated fractures as well as some quartz-coated bedding planes are distributed fairly uniformly over the area occupied by the fragmental volcanics. These surfaces are striated, and the striations trend rather uniformly northeast-southwest. Moreover, the striations plunge at angles that usually range from 0° to 30°, rarely as steep as 50°, mostly toward the northeast but occasionally southwest. These striated surfaces seem to be analogous to the surfaces of stretching described by Cloos (1922). Their presence, and the remarkably uniform trend of the striations on them, strongly suggest that the volcanic rocks were uplifted as a unit along a northwest-trending axis. This uplift, of course, must have been independent of the local upwellings discussed above.

In the southwestern part of the hills, Amole Arkose rests unconformably on the volcanics. Exposures in the big wash at the south end of the hills show the contact to be a disconformity, but farther northwestward (fig. 3) it is an angular unconformity. The dips of bedding in these southwestern exposures of the arkose are toward the southwest, away from the volcanics. Moreover, the dips become steeper with increasing distance from the volcanics, as though the arkose were a cover that arched upward as the volcanics rose. Exposures in the big wash reveal that the Amole deposited on the disconformity slumped down the present dip. Thus it seems that uplift of the volcanics was in progress while the arkose was being deposited, or while it was still unconsolidated. Near the unconformity the arkose contains considerable interbedded volcanic material.

On the northeast side of the hills, the Amole Arkose is separated from the volcanic complex by a steep fault that usually dips southwest but locally dips northeast. On this steep, faulted flank the arkose appears to have slumped off the rising volcanic mass and to have buckled into a number of tight, northeast asymmetrical or overturned folds (figs. 3 and 4, Piedmontite Hills sections 1-1' to 8-8').

Colby (1958, p. 54) suggested that the uplift of the volcanic rocks might have been the result of the emplacement of an intrusive mass beneath the Piedmontite Hills.

Summary of Results

The relations discussed above would appear to support the following conclusions:

1. In partial conformity with Colby's interpretation, the Cretaceous volcanic rocks, or volcanic conglomerate member, may be in part contemporaneous with, but obviously are largely younger than, the red sandstones and siltstones. The only alternative would be to suppose that the coarse fragmental rocks had already existed beneath the red beds and were later activated, i.e., fluidized.

2. The activated fragmental volcanics have intruded, disaggregated, and dispersed large amounts of the fine-grained red beds, and yet it may be that the red rocks themselves originally were deposited as a result of volcanic activity. In other words, the entire Recreation Red Beds formation as defined by Colby is possibly a single volcanic unit.

3. The fluidization, of which there is abundant evidence, may have been the result of the rise of hot magma into some sort of wet, porous medium. If the resulting activity took place mostly or entirely under water, the stratification of the fragmental rocks, including the "conformable red beds," is readily explained through the action of currents resulting from the upwellings and from differences in temperature.

4. The ignimbrite (tuff member) is intrusive into, and possibly extrusive onto, the fragmental volcanics and the red beds.

5. Although the sequence of Brown's Cretaceous formations can be questioned, no basis has been found for disputing his assignment of all these rocks to the Cretaceous.

6. The Amole Arkose on the southwest edge of the hills is definitely younger than the volcanics, and the same must be true of some of the Amole on the northeast side. However, there seems to be no compelling reason to think that lower parts of the thick Amole sequence may not be even older than the volcanics. Admittedly this statement is not quite satisfactory, because it is founded on negative evidence.

7. If the statement made above is not in error, it should be permissible to imagine that Amole sedimentation began perhaps in Early Cretaceous time, and that after an interval of unknown duration the continuing sedimentation was accompanied by volcanic or subvolcanic activity. The igneous action culminated with emplacement of the ignimbrite and terminated with the general uplift of the volcanic rocks and their cover of arkose. This sequence of events may have been completed by the end of Cretaceous time.

When the investigation and the interpretations had nearly reached the stage recorded above, it began to appear that the geology of the Piedmontite Hills might provide a key to the understanding of the geology of the main range of the Tucson Mountains. This impression was greatly strengthened as the result of a visit by a foreign geologist.

PRELIMINARY OBSERVATIONS IN THE MAIN RANGE, TUCSON MOUNTAINS

Field Trip With Professor S. O. Agrell

In March 1962, Professor S. O. Agrell of the University of Cambridge, England, Professor P. E. Damon of the University of Arizona, graduate student Michael Bikerman, and the writer visited the Gates Pass area of the Tucson Mountains and the southern end of the Piedmontite Hills. At Gates Pass is exposed a huge block, or septum, of Amole Arkose having nearly vertical bedding, flanked on either side by Cat Mountain Rhyolite showing equally steep flow structure. The rhyolite is no lava flow. Instead, it is an ignimbrite. Professor Agrell remarked that the setting reminded him somewhat of that at Ardnamurchan on the northwest coast of Scotland. He stated further that if the comparison applied it should be possible to find a gradation from Amole Arkose into Cat Mountain Rhyolite. Road cuts leading down the western side of the pass were examined with some care, and to the writer's surprise the Amole Arkose was seen first to appear disturbed, then to become progressively disaggregated and mixed with foreign material, including fragmental andesite. Finally, this Amole "tuffisite" did appear to grade into Cat Mountain Rhyolite! Some portion of this ignimbrite must be fluidized and partially melted Amole.

Next, all of us climbed part way into the little pass to the south, between Golden Gate and Bren Mountains. On the east side of the rough road to the pass were extensive exposures of coarse-grained arkose with bedding that dipped steeply eastward toward the Cat Mountain Rhyolite. The writer was much impressed with the similarity of this structure to that described by Cloos at the Aichelberg (fig. 2, outer forezone).

A week or two after this field trip a traverse was made across the last-mentioned steeply dipping arkose to the base of the cliffs of ignimbrite to the east. On this traverse, from west to east, the arkose was observed first to steepen to vertical and then to become tuffisized and mixed with foreign materials, including fragmental andesite and two large blocks of Paleozoic limestone (fig. 2, inner forezone and main mixing zone). Finally, as before, the tuffisized Amole appeared to grade into Cat Mountain Rhyolite with steep flow structure.

These observations have since been confirmed on several field trips with classes in structural geology. It has also become obvious that the tuffisized Amole with its foreign admixtures is none other than Kinnison's Tucson Mountain Chaos or Brown's imbricate thrust zone.

Studies by Students on the Cat Mountain Rhyolite

In the spring of 1962 Michael Bikerman completed, under Professor

Damon's direction, his thesis on these ash-flow tuffs. He concluded (1962, p. 25-29) that the mixture termed Tucson Mountain Chaos by Kinnison had formed on the Tucson surface as the initial products of "violent Pelean-type explosions." This phase of the activity was followed by "minor collapse of the surface accompanied by true ash flows." Bikerman's conclusions clearly reveal a recognition of igneous activity as the cause of the structural features. He seems, however, not to have realized fully the possibilities inherent in the process of fluidization.

At about the same time, Richard Champney (1962) finished an investigation of a peculiar member of the Cat Mountain Rhyolite which seemed to be essentially inflated and partially melted Recreation Red Beds. In this member the role of the rhyolitic melt had been reduced to that of a mere binding material. In a nearby area, some small intrusions of andesitic large phenocryst porphyry had updomed the Amole Arkose. A few large blocks of Paleozoic limestone were present also, and the field relations suggested that these had been pushed upward through possibly fluidized Amole by the large phenocryst porphyry. Thus there appears to be support for Greenstein's suggestion that limestone blocks were driven upward ahead of intrusions.

Reconnaissance Structure Sections in the Gates Pass Area

The relations of Amole Arkose to Cat Mountain Rhyolite at Gates Pass have already been mentioned, and are summarized in the Gates Pass section of figure 4. The road cuts at this locality plainly reveal the conversion of Amole to tuffisite and the gradation of this mixture into the basal member of the Cat Mountain Rhyolite.

The many washes in the relatively flat area west of the pass provide glimpses of a large expanse of tuffisized Amole intruded at several places by andesite and possibly by rhyolite. Stages in the shattering of the intrusive andesite and the rounding of the resulting fragments are here and there exposed. Small, beautifully rounded andesitic pebbles appear in the tuffisized Amole and dark, "cloudy" areas in the arkose strongly suggest intermixing with sand-sized grains of andesite. Perhaps a dozen Paleozoic limestone blocks have been found in this fluidized mixture.

Excepting one short gap in the cliffs below the summit of Golden Gate Mountain, the entire section from the Sedimentary Hills on the southwest to the summit of Bren Mountain on the northeast has been walked out (fig. 4, bottom section). Possibly this structure profile will be drawn differently when more details on either side have been mapped, but it is thought that the structure shown is a fair representation of what can be seen.

The dips of Amole Arkose in the Sedimentary Hills are mostly southwestward at gentle to moderate angles, except where disturbed by emplacement of a small mass of granite and quartz monzonite. These hills were mapped by P. J. Bennet (1957), but the present writer's measurements were used in constructing the section.

Kinney Road, in the little pass at the northeastern foot of the Sedimentary Hills, seems to be near the crest of an anticline. East of the road the Amole Arkose first dips northeastward, then reverses on a synclinal axis, only to become northeastward again on the crest of a second anticline. Beyond this second anticlinal crest the Amole beds steepen, are tuffisized, and appear to grade conformably into ignimbrite with steep flow structure.

Brown, on his map of the Tucson Mountains, showed this small area of ignimbrite as a block, faulted down from the rhyolite higher on the western slope of Golden Gate Mountain. This little mass of ignimbrite actually looks like a slumped block, but observations of the structure indicate otherwise. On the northeastern side of the mass the flow structure of the ignimbrite turns steeply down toward a strip of nearly vertical-dipping Amole Arkose. The northeastern side of this Amole strip is tuffisized. Next, there follows a covered interval, beyond which is rather gently northeast-dipping ignimbrite. No evidence of a fault was seen here and the observations do not seem to require the presence of a fault.

On top of the next group of cliffs is a third northeast-dipping zone of fluidized Amole, followed again by the ignimbrite which at first dips steeply northeast but becomes much flatter in the final cliffs just below the summit.

At the crest of Golden Gate Mountain the northeast dip of flow structure in the ignimbrite locally reaches 36°, and it is even steeper at nearby places northeast of the summit. By continuing northeastward, with decreasing elevation, the dip is seen at first to flatten, then to steepen to vertical, and even to reverse to a very steep southwest inclination at the contact with Amole Arkose. The arkose has been tuffisized within a very few feet of the contact only, and what bedding remains is approximately parallel in strike and dip to the contact. Within a few yards northeast of the contact the bedding flattens abruptly to a rather gentle southwest dip. With minor local complications, this gentle southwest inclination persists almost to the road at the northeast base of the mountain.

The structural relations on the southwest side of Bren Mountain have already been partly described, and it may be sufficient to mention the steep dips, reaching 62°, of flow structure in the ignimbrite at the top of Bren. Judged from surface forms, without supporting measurements, these steep inclinations on the northeastern slope may flatten gradually toward the base.

Results of the Preliminary Observations

The observations presented above and demonstrated in the lower structure sections of figure 4 may be summarized as follows:

1. Wherever the Cat Mountain Rhyolite (ignimbrite) is approached through the Amole Arkose the arkose, which so far has always dipped toward the ignimbrite, progressively steepens, becomes tuffisized and mixed with andesite and other materials, and finally grades into ignimbrite with steep flow structure. The gradation may be gradual, or abrupt. The similarity of these structural relations to those described by Cloos at the Aichelberg (fig. 2) is obvious.

2. The structural relations as so far known do not require block faulting. Indeed, such faulting could hardly explain the steep flow layers at the top of Bren Mountain. Even the dips shown at the summit of Golden Gate Mountain seem much too steep for the primary layers of ash flows. Accordingly, it seems necessary to suppose that after these first flows were emitted, they were lifted and tilted by insertion beneath them of domelike or laccolithic masses of the coarse, basal unit of the ignimbrite.

3. Amole sedimentation appears to have been interrupted and eventually terminated by andesitic subvolcanic activity that culminated in the emission of the Cat Mountain Rhyolite. This sequence is the same as that found in the Piedmontite Hills.

4. If the above is correct, the andesitic volcanics of the Gates Pass area are analogous to the volcanic conglomerates of the Piedmontite Hills, and the Cat Mountain Rhyolite is the analogue of the ignimbrite of the Piedmontite Hills. Further, in both areas Amole deposition, andesitic volcanism, and intrusion or emission of ignimbrite formed an overlapping sequence of events that could have gone to completion in Cretaceous time. This conclusion, suggested by the structural observations, requires the support of geological dates.

SOME GEOLOGICAL DATES

The Cat Mountain Rhyolite

Professor P. E.. Damon has generously given me permission to quote him to the effect that radioactive age determinations made in his laboratory on material from the Cat Mountain Rhyolite yielded an early Maestrichtian (Late Cretaceous) date. This assignment accords beautifully with reasoning based on considerations of structure.

A Fossiliferous Bed in the Amole Arkose

In the little pass between Golden Gate and Bren Mountains there is a calcareous sandstone bed, perhaps 2 feet thick, exposed in unfluidized Amole Arkose. This bed contains numerous small, oyster-like fossils. Professor H. W. Miller has informed me, and kindly permits me to quote, that comparison with material from well-known Cretaceous sections shows these Amole forms to be Early Cretaceous in age. It seems then that Amole sedimentation began far back in Cretaceous time.

These two dates became known to me after the conclusion given under (4) above had been tentatively formulated. They greatly strengthen the conclusion. It gives me great pleasure to acknowledge the work of Professors Damon and Miller and to thank them for permission to use their results.

OROGENY OF THE TUCSON MOUNTAINS

General Statement

Much remains to be done before a satisfactory account of the orogeny can be given. It is hoped that the continuing fieldwork will eventually make it possible to fill in many of the presently existing gaps in information. A program designed to determine the ages of the various Tertiary volcanic rocks is under way in Professor Damon's laboratory.

At present the greatest need seems to be for much more fieldwork. Next in importance is the need to understand thoroughly the physical phenomena that account for the relations seen in the field. It may be necessary to arrive at such an understanding through a combination of fieldwork and laboratory experiments. Finally, but very important still, is the need for petrographic and petrologic studies of fluidized and unfluidized rocks.

In advance of the fulfillment of these needs, an obviously imperfect account of the Cretaceous part of the orogeny as it now appears may be of some interest.

Volcanic Orogeny

The author does not know when Amole sedimentation began, but it is now known to have been under way in Early Cretaceous time. The thickness of the Amole Arkose is unknown. Brown (1939, p. 718) gives a partial section amounting to 2,275 feet. It would seem that the entire section must be very much thicker. On the basis of the lithology, times of slow accumulation of dark muds alternated with the relatively rapid deposition of coarse-grained arkosic sands. This sedimentation probably took place in a slowly subsiding basin.

At some time in the Cretaceous, and probably previous to Maestrichtian time, hot, mobile materials began to rise through the underlying basement. Their ascent may have been guided by fractures that previously had accommodated the subsidence of the basin of deposition. The hot intrusions rose through the Paleozoic section, and at, or perhaps somewhat above, the base of the Cretaceous sequence they encountered wet, poorly consolidated sediments.

Phenomena that may have resembled the ensuing reactions have been vividly described by Michel (1948, 1953) in his papers on the peperites of the Grande Limagne, Auvergne region, France. The present writer can only compare them with what happens when cold water is accidentally spilled into hot grease. The hot melt should have exploded into a spray of fragments, or droplets, wherever the confining pressure was too low to prevent the reaction. These fragmental materials should have been entrained, along with intermixed Amole sediment, in the rising gases and liquids. Where the Paleozoic floor had been most intensely shattered, isolated limestone blocks could have been "floated" up through fluidized Amole on hot masses of rising and reacting magma. According to observations this magma was andesitic.

Although the reaction of hot melt and wet sediment may have been violent at a certain level, the activity in general could have been comparatively mild at the surface. That is, with local exceptions, the surface activity may have resembled the expanded bed or the boiling bed in the spectrum of fluidization. This comparatively mild activity may have been punctuated here and there by entrainment, channeling, and the spouted-bed phenomenon. If the activity were long continued it would be expected that the Amole sediment be cleared out of the andesitic debris. This appears to have happened in the Piedmontite Hills.

Accordingly, it seems that the igneous activity began earlier and continued longer in the Piedmontite Hills, giving rise slowly and intermittently to the great bulk of the andesitic "volcanic conglomerates." At times this accumulation may have risen above water, thus favoring oxidation. Heated fluids rising through these volcanic deposits may have removed the fine-grained oxidized material, delivering it to currents that spread it over the surface. In this way the red, fine-grained sandstone and siltstone may have formed.

As already mentioned, the red sandstones and siltstones were in part intruded and dispersed by the continued, or renewed, activity of the "volcanic conglomerates." These coarse fragmental volcanics were in turn intruded by the ignimbrite.

The obvious difference between the geology of the Piedmontite Hills and that of the main range of the Tucson Mountains is that, whereas in the former andesitic volcanics are almost exclusively present and Amole Arkose now seems to have taken no part in the activity, in the main range the andesitic volcanics are present in relatively smaller volume and much Amole Arkose was fluidized. This suggests that the rise of hot, andesitic melt was somewhat later in the main range, but that the culmination—intrusion or emission of the ignimbrite—was reached at about the same time in both places. As a consequence of this timing, stages in the upwelling of the andesite into the arkose, destroyed in the Piedmontite Hills, were preserved in the main range.

That the upwelling in the main range of the Tucson Mountains was accompanied by marginal subsidence, in accord with the spouted-bed phenomenon, seems to follow from the steep downturning of the Amole Arkose as the Cat Mountain Rhyolite is approached. Of course, the central upwelling is proved by the intermixture of andesitic volcanics, the presence at a high level of the Paleozoic limestone blocks, and the outpouring of the Cat Mountain Rhyolite, or ash-flow tuff. A continuation, or renewal, of the upwelling is indicated by the uplifting and tilting of the first Cat Mountain ash flows and by the final uplift of the Piedmontite Hills. This tendency to rise, toward the end of Cretaceous time, may have ended the history of the area as a basin.

The time of emplacement of the granite-quartz-monzonite intrusion north of the Arizona-Sonora Desert Museum is not known, but it may have overlapped some of the events discussed above. The meager evidence at hand suggests that the emplacement was preceded or accompanied by peripheral subsidence. But, as mentioned before, Greenstein found evidence of local upwelling and lifting of the Amole Arkose "wall rock." The final result, as in the Piedmontite Hills and the Cat Mountain Rhyolite, was probably uplift. This would accord with the statement by Jenkins and Wilson, quoted under the heading "Fundamental Reports on Tucson Mountain Geology."

CONCLUSIONS

From the view point now reached the following inferences begin to emerge:

1. The Tucson Mountain overthrust probably does not exist.

2. The Tucson Mountain Chaos is the result of fluidization on a grand scale. The Cat Mountain Rhyolite and the ignimbrite of the Piedmontite Hills represent high temperature culminations of the fluidization process.

3. No Tucson surface seems to have been established by erosion previous to formation of the chaos, but locally the chaos could have flowed out on any available surface. This was obviously the case with the Cat Mountain ash

flows.

4. The cycle of Amole sedimentation and the volcanic activity went to culmination in Cretaceous time. The following Tertiary volcanic and tectonic activity may represent declining stages of the orogeny.

5. Eventually it may become possible to demonstrate conclusively that the Tucson Mountains are the result of the action of volcanic forces and that the present aspect of the mountains results from denudation of the volcanic and subvolcanic forms. If so, then these mountains will be seen as damaged records of reactions between hot melts from depth and the wet contents of a sediment-filled trough.

ACKNOWLEDGMENTS

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