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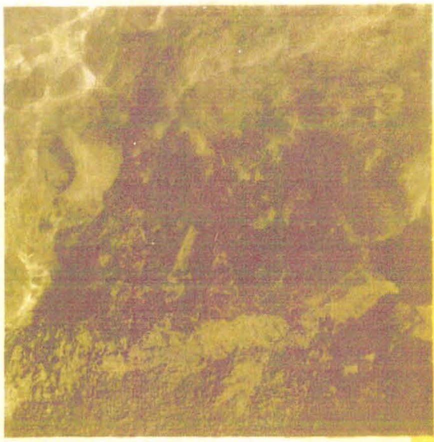
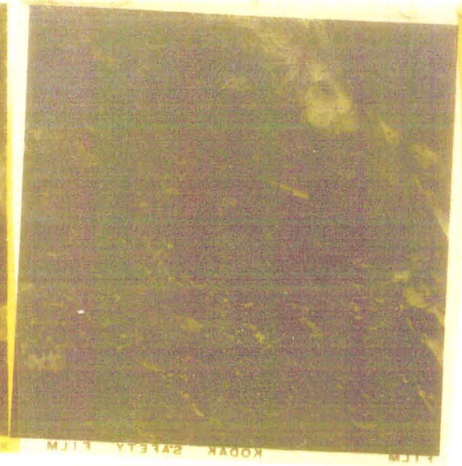

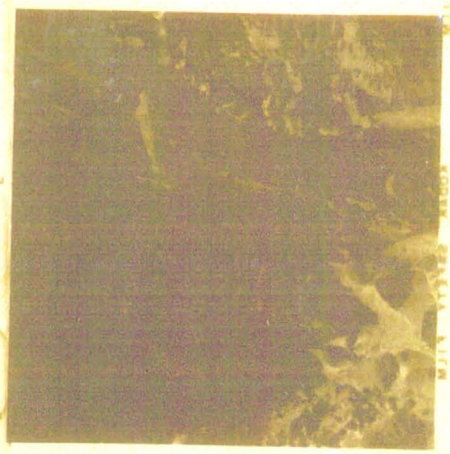
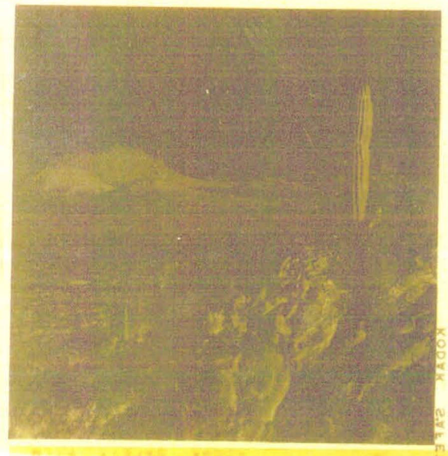
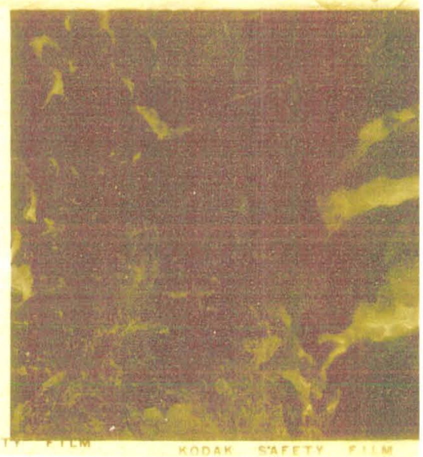
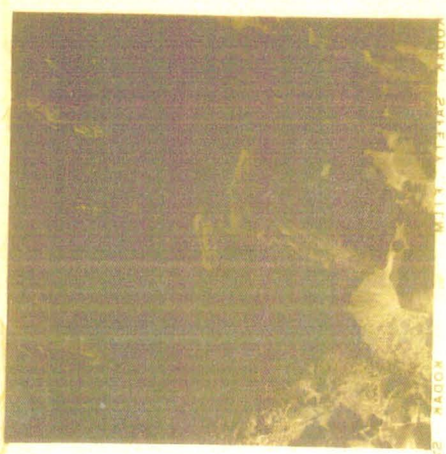


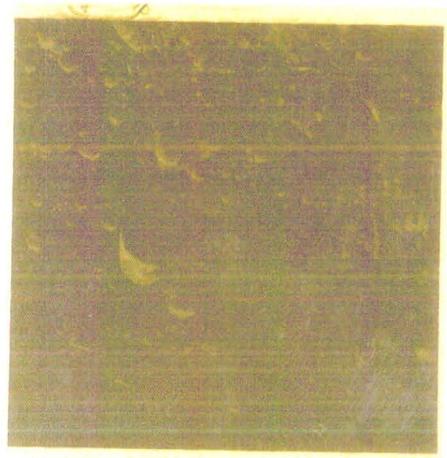


AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona
January 16, 1959

Mr. L. H. Hart
Chief Geologist
New York Office

PAPERS FOR G.S.A. MEETING

Dear Sir:

Attached are copies of two papers entitled "Chaotic Breccias in the Tucson Mountains, Arizona" and "Structure in the Saginaw Area, Tucson Mountains, Arizona", both by John Kinnison.

It is intended that these papers will appear in the Guidebook being prepared for the meeting of the Cordilleran Section, G. S. A., here in April this year. The paper on breccias probably will be read before the meeting. Mr. Kinnison requests permission for this from the publication committee of the Company.

The field work supporting this paper was done by Mr. Kinnison in connection with a master's thesis prior to his employment by the Company. The subject matter of both papers is largely academic and has no bearing on the Company's exploration activity. The papers are based on careful field observation; they are well written; and they will be good contributions to geological literature, particularly the paper on chaotic breccias. For these reasons I assume that Company permission will be forthcoming without question, and we are proceeding accordingly.

Yours very truly,

Original Signed By
K. Richard

KENYON RICHARD

Attachments
KR/ds
cc: JEKinnison

STRUCTURE IN THE
SAGINAW AREA, TUCSON MOUNTAINS, ARIZONA

John E. Kinnison

INTRODUCTION

Data presented in this paper were obtained during field mapping in the early 1950's and is discussed in more detail in a University of Arizona thesis (Kinnison, 1958).

The Saginaw area lies near and south of the Ajo Road in the extreme southern tip of the Tucson Mountains, about 6 miles southwest of Tucson, Arizona. Saginaw Hill, (Pl. 1 and Pl. 1, "Chaotic breccias in the Tucson Mountains", this guidebook) is the site of a porphyry intrusive plug and a surrounding weakly mineralized area. The general geologic setting of the Tucson Mountains is described in "Chaotic breccias in the Tucson Mountains", this guidebook, p. .

LARAMIDE STRUCTURE

Folds and Associated Faults

General Statement

The dominant elements of Laramide structure are folds, and associated thrust and tear faults (Pl. 1 and 1A). These structures pre-date the Tucson surface ("Chaotic breccias in the Tucson Mountains", p. , this guidebook) and were presumably formed during the late Cretaceous or early Tertiary. A complete understanding of these structures is retarded by the stratigraphic uncertainties within the Cretaceous Amole group, but enhanced by its generally well developed bedding.

There are four orders of folds, three of which are observable in the field. The first order is established by interpretation, i.e., I interpret the major structure to be a synclinorium on which are superposed folds of the other orders. Folds of the second order have wave lengths which range from 200 to over 1000 feet, and their asymmetry is controlled by the inferred synclinorium. On the limbs of these second order folds are smaller, third order, drag folds, not mapped precisely but shown diagrammatically on the cross-sections (Pl. 1-A). The asymmetry of each third order fold is controlled by a second order fold. Finally, fourth order drag folds, generally only a few feet in amplitude , are superposed upon and owe their asymmetry to third order folds. These relations should be considered in future studies of this area because, for example, the direction of asymmetry or overturning of third order folds is meaningless with respect to the first order synclinorium.

Associated with the synclinorium are thrust and tear faults, whose existence is largely a matter of interpretation of the surface outcrop pattern.

Synclorium

The existence of a large synclinorium is inferred from the direction of asymmetry and overturning of second order folds. Its axis is indefinitely located, but probably lies between the Five and Burger faults (Pls. 1 and 1-A). East of the Five fault the second order folds are asymmetrically inclinedand overturned to the east, and west of the Five fault they are overturned and asymmetrically inclined toward the west. West of the Five fault all of the folds plunge southeast, whereas east of it the plunge is northwest. The reason for this is not clear but it could be that the Five fault separated the active forces sufficiently to allow folds on either side of that fault to form separate plunge patterns.

Under the above interpretation, the Permian Snyder Hill formation exposed south of Cat Mountain (Pl. 1) is on the east limb of the synclinorium and at Snyder Hill is on the west limb. This interpretation is in disagreement with that of Brown (1939), who considered these Permian outcrops to be klippen.

The steeper dip of the beds on the west limb, compared to the gentler dipping and more open folds on the east limb, suggests that the synclinorium is asymmetrically inclined toward the northeast.

Normal Faults

It can probably be assumed that at least some high-angle normal faults were formed shortly after the Laramide folding, but I identified none in the field. The fault extending northeast from Saginaw Hill, occupied by the Saginaw porphyry dike, has definitely undergone displacement because the beds on either side do not match, but the magnitude is unknown. The displacement of the Tertiary Cat Mountain rhyolite along this fault is slight, if any. This may be, then, a pre-Cat Mountain rhyolite fault which was reactivated in the late (?) Tertiary with very slight displacement. Many of the other faults which cut the Tertiary rocks may have originated during Laramide time, but field mapping neither supports nor disproves this possibility.

TERTIARY STRUCTURE

High-Angle Faults

High-angle faults dominate the Tertiary structure, and although it is generally impossible to measure dips (few fault outcrops are present) at least most of them probably are normal faults. Such fault surfaces as are exposed show gently dipping slickensides, suggesting that horizontal movement may have been important.

The fault pattern is highly complex and it is not clear which faults formed first, or whether movement was contemporaneous on all of them.

Some faulting took place during Cat Mountain rhyolite time, and some structural deformation in the form of local tilting preceded slightly extrusion of the upper unit of the Tertiary volcanic pile (Shorts Ranch andesite). Most of the faulting is probably post-Shorts Ranch andesite, but a minimum age cannot be established. Faults displace the flat-lying basalts of Tertiary-Quaternary age at "A" Mountain (Brown, 1939), but enough time must have elapsed since the last period of faulting to permit erosion to form the extensive pediment on the western side of the range and remove much of the Tertiary strata. It is noteworthy in this connection that nearly all the faults form obsequent fault line scarps with the downthrown sides topographically high.

Tilted blocks and Folds

The Tertiary rocks generally dip at gentle angles. The measurement of structural tilt in the volcanic rocks is subject to error because part of the dip of the flow structure might have been due to original dip of the flow. I have observed, however, that the volcanic flow structure in the Tucson Mountains, as well as surrounding ranges, commonly dips gently (five to 35 degrees) in a northeast to east direction, which suggests that most of the dip is due to regional tilting. Also, the Tertiary sedimentary rocks, such as the Safford formation, show this same direction of dip. In consideration of these facts, the dip of flow structure may be assumed to have been essentially horizontal when formed, and its present dip may be considered to be a measure of the amount of structural tilting.

In the complexly faulted area south of the Ajo Road the Tertiary rocks exhibit folded structures and variable directions of dip; an apparently rare occurrence in other parts of the Tucson Mountains and in surrounding ranges. For the most part, however, these folds can be postulated to be the result of fault drag. Some of the small fault blocks show no relation to the adjacent folded structures, and exhibit independent homoclinal dips.

Where the rocks are not affected by these small folds, the dominant direction of dip is northeast to east.

Thrust Faults

The theoretical possibility of renewed activity along a Laramide thrust fault during deposition of the Tucson Mountain chaos is discussed in "Chaotic Breccias in the Tucson Mountains" (this guidebook). A small outcrop of lake beds, in the southern tip of the range, may be thrust over the Shorts Ranch andesite, a suggestion made by Brown (1939), or they may be deposited on the andesite, as suggested by Kinnison (1958). There are no other indications of Tertiary thrust faulting in the Saginaw area.

RELATION TO REGIONAL STRUCTURE

Laramide

The Amole group is folded into a broad, open syncline in the central part of the Tucson Mountains (Brown, 1939). The intricately folded synclinorium in the Saginaw area may be a part of that structure, but a positive correlation cannot be made with the data at hand.

As noted previously, the southwest limb of the synclinorium exhibits generally steeper and tighter folds, which suggests that the synclinorium is inclined asymmetrically to the northeast. It would then appear that any regional overthrust movement was toward the northwest.

Tertiary

The post-volcanic Tertiary structure is discussed at some length by Brown (1939), and although I do not concur with all of the implications of his remarks, I refer the reader to them for an excellent presentation of local and regional structure.

The principal elements of Tertiary structure are internal faults, inferred range-boundary faults, and tilted blocks.

The internal faults which displace Tertiary rocks are not mapped precisely or completely enough for detailed analysis, but the degree of accuracy is sufficient for some generalized conclusions. Brown noted (1939) that east or northeast faults are nearly always downthrown of the south. This is not true in detail in the Saginaw area, where many reversals occur, although the aggregate effect may still tend towards a downthrow on the south. Brown (1939) pointed out that this direction of throw was in harmony with the structurally high Tortillita Mountain block to the north.

Reconnaissance observations in the Roskruge Mountains to the west, and the Tortillita Mountains to the north, suggest that those ranges are tilted northeast or easterly. The Tertiary volcanics of the Santa Rita Mountains to the southeast dip northeast (Scharder, 1915). The Catalina Mountains to the east were believed by Davis (1931), on physiographic evidence, to have been tilted northeast or easterly. It is probable, then, that the Tucson Mountains are a part of a widespread pattern of northeasterly regional tilting. The folded structures of the Saginaw area, however, are of local origin.

There is little evidence to indicate whether the inferred marginal faults, covered by alluvium, are single faults along the borders of the ranges, or whether there are many faults distributed through the intermontane valleys. Of course, it is also possible that there are two separate systems of faults; those that initially distributed the tilted blocks, and others of a later age which are responsible for the present mountain-valley pattern. But certainly faults of some kind must be inferred to break the easterly tilt of the ranges, and form a series of mountain blocks with an aggregate downthrow progressing westerly.

CHAOTIC BRECCIAS IN THE TUCSON MOUNTAINS, ARIZONA

John E. Kinnison

ABSTRACT

The rock column of the Tucson Mountains, west of Tucson, Arizona, may be divided into two dominant sequences. These are (1) a thick sequence of Paleozoic and Cretaceous-Tertiary(?) sediment, overlain by (2) Tertiary volcanics and interbedded sediments. The older group was highly deformed during the Laramide revolution, and the younger group was affected by gentle tilting and block faulting.

Separating these two rock groups is a tabular breccia zone, named the Tucson Mountain chaos, which contains fragments of all of the pre-Laramide rocks disposed in a disoriented, or chaotic, manner. The chaos-fragments range in size from less than a foot to larger than 200 feet. The thickness of the Tucson Mountain chaos attains a maximum in excess of 400 feet, and is perhaps 200 feet on the average. The dip of the unit parallels that of the overlying volcanics. Locally a well-rounded conglomerate occurs at its base, and angular conglomerates are erratically distributed within.

Field observations have been ~~collected~~ principally of a reconnaissance nature, but from these observations I suggest that the Tucson Mountain chaos is a sedimentary breccia, and that it rests on a post-Laramide erosion surface, named the Tucson surface. Its origin is postulated to involve a seismically active fault scarp supplying the chaos-fragments which were transported and deposited

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by mudflow, landslide, and intermittent stream action.

Brown (1939) believed the chaos zone to be the remnant of a large Laramide overthrust sheet, and he only partly recognized its individuality as a distinct formation. The origin now proposed, therefore, involves also a new interpretation of the structural history of the Tucson Mountains.

INTRODUCTION

The Tucson Mountains, located a few miles west of Tucson, Arizona, comprise a relatively low elongate range trending northwesterly. Numerous writers have contributed to the general fund of geologic information; the most comprehensive work was done by W. H. Brown (1939), who published a geologic map and detailed report on the stratigraphy, structure, and geomorphology of the entire range. In a recent thesis (Kinnison, 1958), I recorded certain revisions in the southern part of the mountains, and described the subject formation in more detail than is presented here.

The object of this paper is to record a generally unrecognized and unusual formation, and to stimulate discussion and further study. I am aware that the opinions presented are based in part on incomplete data; they should be considered within that limitation.

Acknowledgement is gratefully given to J. H. Courtright, who materially assisted the preparation of this field trip and report, and to K. E. Richard, J. F. Lance, and L. A. Heindl who have offered many helpful suggestions. It should be understood, however, that these men do not necessarily agree with all of the opinions presented.

GEOLOGIC SETTING

Physiographically, the Tucson Mountains can be divided into 3 principal divisions (Brown, 1939): the pediments, western escarpment, and eastern dip slope. A well developed pediment, carved on clastic sediments of Mesozoic age, extends along the western margin of the range. Tertiary volcanics form an escarpment line on the west, and their gentle easterly dips provide the outline for a moderately incised dip slope. The range is surrounded by alluvium of the Santa Cruz and Altar valleys.

The rocks of the range record 3 distinct geologic episodes. Paleozoic rocks consist mainly of limestone, although the Cambrian and parts of the Permian consist dominantly of quartzite and shale. Outcrops of Paleozoic rocks are present in only a few localities, but measurements from these, and comparison with other nearby ranges, indicate that the Paleozoic section is somewhat over 4500 feet thick. The Amole group (Kinnison, 1958 and Brown, 1939), which consists mainly of arkose and shale, overlies the Paleozoic rocks with erosional disconformity, and may be in excess of 8000 feet. Its age is regarded (Kinnison, 1958) as spanning both Lower and Upper Cretaceous, and questionably extending into the early Tertiary. The Recreation redbeds (Brown, 1939) and possibly andesitic volcanics occur within the section of Amole group sediments (Kinnison, 1958), but their exact stratigraphic positions are debatable. The thickness of redbeds and volcanics is not established, but may be over 1500 feet.

The second division consists of Tertiary volcanics and an interbedded unit of lake deposits and tuffs. The chaotic breccias of this paper separate the first two divisions.

The third division, limited in areal outcrop and time span, consists of flat-lying Tertiary(?)-Quaternary basalts (Brown, 1939) which crop out on the eastern margin.

A granitic stock in the northern part of the range may be older than the Tertiary volcanics in that area (Brown, 1939). In the southern part a small monzonite porphyry intrusive is younger than the Tertiary volcanics and is the site of porphyry copper-type alteration and sulphide mineralization (Kinnison, 1958). Other intrusives which cut these volcanics but which are closely related to them in time, include rocks ranging from andesite to rhyolite.

Structurally, two events are dominant. The first consisted of broad folding in the northern and intense deformation in the southern parts of the range. This deformation, which affected the Cretaceous-Tertiary(?) Amole group and older rocks, is assigned to the Laramide revolution. The second event, which consisted of block faulting and tilting, began sometime later in the Tertiary and post-dates the Tertiary volcanic pile. Faulting continued through the time of basalt eruption.

The post-volcanic (second division) porphyry intrusions and mineralization in the southern area is of the type provisionally assigned to the Laramide by many writers. There is, of course, the problem of how far into Tertiary time the term "Laramide revolution" should be extended, but a discussion of that problem is beyond the scope of this paper. It is clear that in the Tucson Mountains intense deformation affecting the Amole group is separated from later volcanism and faulting by a period of extensive erosion which formed the Tucson surface (this guidebook p. 14). This surface of erosion marks a major change in the course of geologic events, and probably forms a surface of major unconformity throughout Southern Arizona. Post Tucson-surface structure, for present purposes, is distinguished from Laramide structure and referred to only as "Tertiary structure."

CHAOTIC BRECCIAS

General Statement

The Tucson Mountain chaos (Kinnison, 1958), a formational unit of speculative origin, separates the highly deformed Cretaceous-Tertiary(?) and older rocks (pre-Laramide) from the gently dipping Tertiary volcanic sequence. Its striking characteristic is that it contains very large fragments of all the pre-Laramide rocks in a disoriented, or chaotic, arrangement. Noble (1941), who first described a formation of this type, states: "The Amargosa chaos or features resembling it are widespread in the southern Death Valley region, and if they occur in other regions the term chaos, as a common noun, may prove to be a useful geological term." Thus this formation, which occurs throughout the Tucson Mountains, derives its name from its location and from the word chaos as used by Noble.

The Tucson Mountain chaos has been previously interpreted a complex overthrust block by Brown (1939) who said, in part:

"Along the western escarpment at the base of the cliff-forming lavas and at the top of the slope-forming Cretaceous sediments is a conspicuous belt of boulder-like masses of Carboniferous limestone as much as 100 feet in diameter and less conspicuous Cretaceous volcanic rocks....

"These masses of Carboniferous limestone clearly rest on the Cretaceous, and the Cretaceous volcanic rocks also rest on the Amole arkose in the same belt....

"These relations have been interpreted as a great thrust fault, which practically parallels the surface of pre-Tertiary erosion, and whose overthrust block was largely removed by erosion."

Brown (1939) was partly aware of the chaotic nature of this zone, because he states:

"....The distribution of outcrops along the covered base of the western escarpment suggests that this belt of overthrust masses is a jumble.... In this jumble zone....are many rubble breccias.... Recently, B. S. Butler has discovered on the eastern side of the range an outcrop which....is clearly a conglomerate....This conglomerate occurs between one of the larger limestone blocks and the Cretaceous formations, suggesting that the fault may have extended out onto the surface...."

The suggestion which I offer on the following pages is that this zone is a sedimentary formation, and that although it might have been accumulated from a thrust fault scarp, such thrusting would have been post-Laramide, of short duration, and not necessarily regional in character.

Distribution

The Tucson Mountain chaos crops out on the pediment and escarpment line south of the Ajo Road (Fig. 28). To the north are excellent exposures in steep gullies on the south slope of Cat Mountain. Although generally covered by talus, it is exposed at scattered points at the base of the western escarpment in the area between Cat Mountain and Gates Pass and possibly extends northwesterly to Amole Peak. It is also exposed on the eastern dip slope throughout the south and central portions of the range. In the northern part of the range, a few miles south of the Old Yuma Mine, the northern extent of the chaos is terminated in an unknown manner and below the Tertiary volcanics are dark colored andesitic rocks (Fig. 28).

Description

General Statement

Although the individual blocks are too small to map separately, the total of this heterogeneous mass comprises a tabular unit easily recognized as a distinct formation. Its thickness varies from a few feet in the very southernmost exposures to a maximum in excess of 400 feet on the central east side of the range. Its long dimension, trending northwesterly, in the Tucson Mountains is approximately 14 miles, and its short dimension, exposed to erosion on both sides, varies from 2 to 4 miles.

Its stratigraphic position is always the same, i.e., above the steeply dipping rocks of pre-Laramide age, and below the Tertiary Cat Mountain rhyolite.

The best exposures in the southern part of the range underlie the pediment south of the Ajo road, crop out in the steep gullies cut in the south slope of Cat Mountain, and also occur at the base of the western escarpment 1/2 mile south of Gates Pass.

In the southern part of the range the fragments of the Tucson Mountain chaos consist mainly of clastic rocks of the Cretaceous-Tertiary(?) Amole group, with numerous blocks of Paleozoic limestone and Cretaceous(?) Recreation redbeds. A few blocks of andesite porphyry are present and very rarely a block of granite. At widely scattered places are blocks of a gray sericite-quartz schist which resembles the pre-Cambrian Pinal schist. No members of the overlying Tertiary volcanic sequence are recognized, but farther north andesite and andesite breccias or conglomerates of Cretaceous or early Tertiary age are a common fragment type.

Because I made no attempt to analyze statistically fragment composition or size, the following observations are based on impressions gained in the field, and as such are subject to error. The size of the fragments varies greatly. Fragments of the Amole group constitute about 60 per cent of the total, and range in size from fragments of about 1 foot to large blocks with a long dimension greater than 200. Many are on the order of 100 feet. Blocks of Paleozoic limestone, although prominent due to differential weathering, rarely exceed 100 feet where exposed south of Cat Mountain; but farther north they occasionally exceed 200 feet. The blocks of thin-bedded Amole group or redbeds tend toward a tabular shape, and the more uniform Paleozoic limestones and other directionless rocks tend toward a more equidimensional shape. The majority of all blocks range in size between 10 and 40 feet, with a second abundant size ranging from 1 to 10 feet. These smaller blocks fill the interstices between the larger blocks. As seen in the exposures on Cat Mountain the blocks are separated by gouge or earthy material.

Individual blocks are randomly oriented within the formation. It is worthy of note that the bedding within the blocks usually is not distorted, even in the thin-bedded shales of the Amole group.

As exposed near Gates Pass and on Cat Mountain, the thickness of the Tucson Mountain chaos is about 200 feet. South of the Ajo Road it thins rapidly and may pinch out entirely farther south. The chaos is absent on the southwest slope of Golden Gate Mountain, only 1/2 mile west of the Gates Pass exposure. These differences may be be due chiefly to original variation in thickness, but they could be caused by pre-Cat Mountain rhyolite erosion.

Angular limestone conglomerate lenses(?) are erratically distributed throughout the Tucson Mountain chaos, but have no well defined boundaries. That they are conglomerates and not fault breccias is indicated by the rounded shape of some pebbles and by local stratification and sorting. The conglomerates are most prevalent near limestone blocks, and many are quite conspicuous due to weathering of pebbles which are surrounded by siliceous cases, which stand out as angular ribs. Some of the large limestone blocks are enclosed by a shell of angular conglomerate or breccia.

A few conglomerates consisting of pebbles and cobbles of dark colored andesite porphyry are present, and are distributed in the same erratic manner as the limestone conglomerates mentioned above. Some of these are chaos fragments of andesite-pebble conglomerate, but others may derive from nearby blocks of andesite in the Tucson Mountain chaos.

Light colored rhyolite which I tentatively correlate with the Spherulitic rhyolite (Brown, 1939) of Tertiary age intrudes the Tucson Mountain chaos with an irregular and intricate pattern. These small bodies of rhyolite commonly appear as poorly exposed patches up to about 30 feet in diameter. Spherulitic rhyolite also appears to intrude as ribbons between chaos-fragments with the flow structure curving around the fragments parallel to their edges. Larger bodies which are definitely Spherulitic rhyolite intrude the Tucson Mountain chaos as dikes and plugs, and frequently are crowded with inclusions of limestone, arkose, and redbeds.

Type Locations

Certain locations present typical examples and are worthy of individual discussion.

1. South of Ajo road (Stop 2). This area affords an excellent two-dimensional view of the Tucson Mountain chaos. The topography is gentle and rolling, and the effect of differential erosion on the various blocks is pronounced. This type of weathering, common to chaos outcrops, produces knobs rising slightly above the terrain, and separated by flat areas covered with loose debris. It is evident that the blocks are of different rock types, different sizes, and different orientations.

2. Cat Mountain. The base of the Cat Mountain rhyolite has been elevated in a fault block along the southern slope of Cat Mountain. There several steep gullies afford excellent cross-sectional exposures of the Tucson Mountain chaos, and in one (Stop 3) of these both its upper and lower contacts are exposed (Fig. 29A). At the base is a well-rounded, reddish-brown cobble conglomerate with numerous boulders. The basal portion of the conglomerate is poorly consolidated, and bedding is marked by sorted pebble lenses and aligned elongate cobbles. The cobbles and boulders consist of arkose and siltstone of the Amole group, Recreation redbeds, and dark andesite porphyry. The upper portion of the conglomerate contains more numerous boulders and is well consolidated (Fig. 30B). Above the conglomerate is a thin bed of arkose and a block(?) of andesite. Typical Tucson Mountain chaos above the conglomerate is about 150 feet thick and is capped by the Cat Mountain rhyolite. Near its base the rhyolite contains numerous blocks of the Amole group, some of which are as large as 10 feet.

The chaos fragments in this exposure are generally less than 5 feet in diameter and are surrounded by a thin layer of clastic material (Fig. 30A) which locally shows layering concordant with the block-outline. Other nearby gullies, however, expose larger fragments. Figure 30C shows the contact between a 100-foot long block of redbeds and a 30-foot block of siltstone. The thin bedding within the redbed fragment is not distorted, and the contact with massive siltstone is marked by a one-foot layer of pebbly material.

There is no evidence of erosion at the top of the Tucson Mountain chaos; the contact appears, in fact, gradational. The conglomerate at the base of the chaos appears to be thinner in adjacent gullies, but it is poorly exposed.

3. Gates Pass. A section of the Tucson Mountain chaos is fairly well exposed on the steep western slope of the peak south of Gates Pass and east of Golden Gate Mountain (Fig. 29B). The particularly interesting feature at this locality is the presence, in the basal half, of a crudely stratified conglomeratic unit consisting of rounded cobbles of arkose and volcanics with a small amount of sandy(?) matrix, and containing a few intercalated thin silty beds. The fragments within this unit are cobbles and boulders up to 10 feet in diameter, generally surrounded by a thin concentric layer of gouge. The overall appearance of this material is suggestive of mud flow accompanied by intermittent stream action. The mud flow(?) material rests on a limestone-cobble conglomerate, which may represent the base of the chaos. The total thickness of chaos is approximately 275 feet.

4. Sweetwater Drive. On the eastern dip slope in the central

Tucson Mountains, near Sweetwater Drive, a large area of rolling hills is composed of the Tucson Mountain chaos. In this area dark brown and purple andesites, andesite agglomerates, and andesite-pebble conglomerates comprise a common fragment type. As in other localities, arkose, shale, redbed, and limestone blocks are numerous. Near the Thunder Bird Mine, about 2 1/2 miles northwest of Sweetwater Drive, a remnant of Cat Mountain rhyolite is present to mark the upper contact and it is evident that unless unknown structural complications of considerable magnitude are present, the thickness of the Tucson Monntain chaos must be at least 400 feet, and may be greater, as the base is not exposed.

In the Sweetwater area two divisions are recognizable. The first, which constitutes most of the aerial exposure, may be considered as typical chaos, similar to that exposed at the localities described on preceding pages. The principal difference is that the blocks appear generally to be larger, especially near the Thunder Bird Mine, and there are fewer interstitial small blocks. One of the Paleozoic limestone blocks is approximately 225 feet long. The second division comprises a group of separated blocks of Paleozoic limestone which I believe may be correlated as a single unit. These blocks cap several small knobs which range in size from 200 to about 1000 feet. Although the contacts with the underlying chaos are not well exposed, they can be located closely enough to determine that the limestone blocks overlie the chaos with an approximately horizontal contact.

That this upper division, consisting of the limestone blocks of easterly strike and northerly dip, was once one continuous unit is suggested by their similarity of strike and dip, and similar elevation. In the entrance to a quarry cut in the north side of the largest block is an exposure of chaos deposited against a steep contact with the limestone block. Fragments in the chaos are limestone, redbeds, and andesite. The debris contains stratified silt and gypsum which dips northerly. This particular exposure may be interpreted either as material deposited against an advancing thrust fault scarp, or more simply as a huge landslide block in the chaos.

Associated Volcanics

Brown-and purple-colored andesite and andesite breccia and/or conglomerate crop out south of the Ajo road near Stop 2 (Fig. 28, and Fig. 31, Saginaw Structure), east of Stop 2 near Mission Road, and in a small basin northwest of the Mission and Ajo Road intersection. In the northern part of the range, andesites megascopically similar to those in the southern part crop out over a large area. As noted previously, rocks of the general type are common as chaos-fragments.

Near Stop 2 the andesites are overlain by the Tucson Mountain chaos, with a thin conglomerate along the contact, and similarly, in the basin north of the Ajo Road, the chaos appears to overlie andesite. The relation between the Tucson Mountain chaos and the andesites in the northern part of the range is not presently known. These northern andesites are overlain by Tertiary volcanics which may or may not be time-equivalents of the Tertiary sequence in the central and southern parts of the range.

The age of these various andesites and andesite breccias, and their relation to the Amole group and the Tucson surface, is not known. The steep dips of thin clastic beds in the andesites in the northern part of the range, and the large areal extent of these rocks, suggest that the series is several thousand feet thick (Brown, 1939). The relation of these rocks to any formations other than the unconformably overlying Tertiary volcanics is unknown, although future work may yet disclose their relation to the Tucson Mountain chaos, Brown (1939) regarded these rocks as Cretaceous, and believed that they underlie the Recreation redbeds. If so, they lie stratigraphically within the Amole group (Kinnison, 1958). In the southern part of the range, the andesites near Stop 2 lie on the strike-projection of folded Amole group sediments which crop out only 1/2 mile to the northwest. This suggests (Kinnison, 1958) that in depth these andesites lie on the truncated edges of Amole group sediments, and there form a thin layer between the Tucson Mountain chaos and the underlying folded Amole group (cross section C-C', Fig. 32, Saginaw structure). Whether or not this "slab" of andesite is above or below the Tucson surface is a completely speculative matter. It is possible that some of the andesites are intrusive, in which case they undoubtedly lie below the Tucson surface.

An eventual solution to the problems of age and origin of these andesites is pertinent to a complete understanding of the Tucson Mountain chaos. Some of the most pressing problems are: Do the andesites belong to only one series of rocks? Are they all extrusive? Are they part of the geological basement block below the Tucson surface? Do they form a thin slab between the chaos and pre-Laramide sediments, and if so how did they come to occupy such a position?

Origin of the Chaos

Any theory of formation of the chaos must explain the following facts which are fairly well established by field evidence.

1. The blocks include all of the pre-Laramide formations. The gray sericite schist and granite may be pre-Cambrian.
2. The blocks range in size from less than one foot to a maximum greater than 200 feet. The smaller blocks appear to act as interstitial filling between the larger blocks.
3. The thickness varies from zero to greater than 400 feet, but 200 feet is probably the most common. In aerial distribution it is 14 miles long and a minimum of 3 miles wide.
4. The size of the blocks appears to vary directly with the thickness of the chaos, i.e., the thicker sections have generally larger blocks.
5. The chaos rests on an erosion surface. This is demonstrated by the conglomerate at Cat Mountain. It also may overlie an erosion surface on top of the andesites south of the Ajo road.
6. Limestone conglomerates occur throughout the chaos. They are not continuous as would be expected in a well-developed stream, but rather are suggestive of essentially residual erosion and deposition along small irregular rills. But under any interpretation, these conglomerates show that the chaos was subjected to sedimentary action during its formation.
7. The unit dip of the tabular-shaped chaos is essentially parallel to that of the overlying Cat Mountain rhyolite.

8. The stratified material exposed on Cat Mountain and at Gates Pass dips in the same direction as that of the overlying Cat Mountain rhyolite, although possibly at a steeper angle.
9. The chaos locally overlies andesite.
10. The appearance of the chaos at Cat Mountain and Gates Pass suggests analogy to modern talus slopes. Also, the basal half of the chaos at Gates Pass is suggestive of a mud flow.

Of the above statements, numbers 2, 5, 6 and 10 collectively suggest a dominantly sedimentary origin for the Tucson Mountain chaos.

The large blocks of the chaos must have derived from a mountainous area or steep scarp. The most reasonable assumption is that the postulated high area resulted from a structural scarp; either a low-angle thrust fault, or a high-angle reverse or normal fault. The basic assumption in the following discussion, then, is that the chaos resulted from a combination of tectonics and sedimentation.

In the Tucson Mountains the pre-chaos orogeny (Laramide) of Early Tertiary time caused intense deformation of the pre-Laramide rocks, and produced both folds and local thrust faults (Kinnison, 1958). After this deformation, a period of erosion planed these deformed rocks to a surface of moderate or gentle relief, for which I proposed the name "Tucson surface" (Kinnison, 1958). A post-erosion fault scarp could be expected to expose rocks of diverse ages, because such rocks were brought together by the preceding complex structural deformation. Such a scarp, if it continued to move during the deformation of the chaos, would continue to expose a variety of rocks as the original scarp was eroded.

In front of this postulated fault scarp, a thick talus accumulated. The thickness of the pile and size of blocks within it were probably related to the height of the scarp. This talus pile, subjected to seismic activity associated with concurrent faulting, would be especially susceptible to landslide and mud flow movements. Even in an arid climate, large mud flows have resulted when semi-stable talus piles were sufficiently lubricated during torrential cloud bursts; and it may well be that the chaos was formed during a much wetter climate than now exists.

As each landslide or mud flow occurred, carrying with it the very large fragments accumulated near the scarp, the talus pile would be locally thinned, but expanded laterally. The muddy matrix of the mud flow or landslide mass would produce a breccia and gouge-like zone around the larger blocks of the chaos, and might even produce slickensided surfaces.

Under proper conditions of lubrication, extremely large blocks can slide for considerable distances, impelled by gravity, down a gradient of only a few degrees. It is further logical that if a single block can move by gravity along a gentle slope, so also can large masses of many rock fragments. Landslide and mud flow masses together with large single blocks would be set in motion by seismic vibrations along the active fault scarp, and would slide, in response to gravitational forces, down gentle slopes; the chaos would thus be spread in a thin layer for a distance of several miles from its source.

While the chaos was being deposited and spread out, it was subjected to erosion, and deposition of conglomerate took place along intermittent rills. The direction and location of these small water courses changed with each new earth movement, probably disrupting the conglomerates previously deposited.

The large limestone block with chaos piled along its edge (p. 11) may have formed in one of two ways: (1) it may represent a single large block which slid down the surface of the chaos, impelled by gravity; or (2) the second possibility is that it may represent a remnant of an overthrust scarp, with the chaos spread out in front, in an area in which the scarp had been thrust over previously deposited chaos. Of course, if a high-angle normal fault rather than a thrust fault were responsible for the formation of the Tucson Mountain chaos, the first possibility is required.

Referring again to the ten basic characteristics of the chaos (p. 13), No. 1 is satisfied by the assumption of an originally complex area which was elevated along a fault scarp; Nos. 2, 3, 5, 6, 7, 8, 9, and 10 by the suggested mechanism of formation; No. 4 by the probability that the thicker areas of chaos would be nearer the source. The origin of pre-chaos andesites (No. 9) has been discussed previously, and is admittedly not understood. The andesite blocks in the chaos must derive, however, from these pre-chaos andesites.

Subsequent to deposition of the Tucson Mountain chaos and the overlying Tertiary volcanics, an important period of structural deformation caused tilting and faulting. The chaos, lying between two geologic units of very different character, is a natural zone of weakness along which slippage and adjustment can take place. Rotation of the chaos-fragments during late(?) Tertiary faulting may have been an important factor in the origin of some or perhaps much of the contact-gouge surrounding the larger fragments.

Comparison to Other Chaotic Breccias

Chaos formations similar to the Tucson Mountain chaos have been described by numerous writers from other areas, only a few of which are mentioned here.

Noble (1941) first described a formation of this type and proposed the word "chaos". Noble's investigation in the Virgin Spring area of Death Valley, California, disclosed a chaotic sequence about 2000 feet thick, which is divisible into three units on the basis of fragment-type. Noble believed this formation, named the Amargosa chaos, to be tectonic in origin, and that it represented a brecciated overthrust sheet of post-Miocene age.

At a later date Johns and Engel (1950) summarized the chaos formations of southern California as follows:

"Tabular to lenticular masses of unusual breccias are widespread in both desert and coastal regions of Southern California...."

"Many of the breccias are sedimentary rocks, interlayered and intertongued with siltstones, sandstones, conglomerates, and tuffs.... These breccias resemble modern mud-flow and debris-flow accumulations...."

"Some of the breccias, including several types that have been described as 'chaos' have been interpreted as crackled ... parts of low-angle thrust faults...."

"Although certain breccias seem correctly interpreted as essentially tectonic in origin, others so interpreted are wholly sedimentary.... Only further studies, however, can accurately define the respective roles of faulting and sedimentation in the development of these rocks."

Jicha (1958) has mapped "landslide debris" in western New Mexico, which is similar to the Tucson Mountain chaos. He states, in part:

"...the northern flank of Mesa del Oro for a distance of 10 miles is an apron of slide blocks more than a mile wide.... Pico Pintado, an outlier of Jurassic and Cretaceous rocks, has on its east side two immense landslide blocks, more than one-half mile long and several hundred yards wide."

The relief of the basalt-capped mesas from which these landslides originated is relatively slight, and the surfaces on which they are deposited are of gentle gradient. These landslides are related to present topographic features, and they appear to be features of the late Pleistocene (Jicha, 1958).

An account of a recent debris flow by Sharp and Nobles (1952) illustrates the inherent mobility of mudflows on a gentle gradient.

"On May 2, 1941, --- community of Wrightwood on the north side of the San Gabriel Mountains was partly innundated by a series of debris waves ....

"...Debris was transported 15 miles by mass movement, and on a gradient as low as 75 feet per mile at the outer extremity.... Velocities of most waves did not exceed 3-5 miles per hour (estimated)."

It appears that the Tucson Mountain chaos, of probable early or middle Tertiary age, bears striking resemblance to other chaotic breccias, some of which were formed in recent geologic time. Any detailed study of the Tucson Mountain chaos should, therefore, include a program of comparison to similar formations of other localities.

John Kinnison

ARIZONA GEOLOGICAL SOCIETY FIELD TRIP
April 14, 1957

Breccias in the Tucson Mountains

Breccias of equivocal origin crop out extensively in the Tucson Mountains. These breccias are characterized by a wide variety of rock types, a range of size from sandy silt to house-sized boulders, and poor exposure. They occur in zones reportedly associated with faulting and are generally topographically above rocks of Cretaceous age and below volcanic rocks of possible Tertiary age (Cat Mountain rhyolite). The origins suggested for these breccias may be outlined as follows:

I. Tectonic, due to
   A. Normal faulting
   B. Thrusting, which may involve
      1) Paleozoic and Cretaceous rocks, or
      2) Paleozoic, Cretaceous, and Tertiary (Cat Mountain rhyolite) rocks

II. Sedimentary, representing
   A. Scree
   B. Mudflows
   C. Rockflows
   D. Rafting

III. Other
   A. Blocks from over-riding thrusts
   B. Residual conglomerate derived from eroded thrust plates
   C. Others?

Critical evidence to support these several opinions must be compatible with

1. Thickness of breccia, locally in excess of 200 to 300 feet
2. Distribution
3. Polymict composition (is Cat Mountain rhyolite present?)
4. Extreme size range (Quomodo?)
5. Nature of under- and overlying contacts
6. Nature of contacts within breccia between large boulders and matrix
7. Fracture pattern in overlying volcanics
8. Others?

Three areas will be visited: 1) south slope of Cat Mountain north of Ajo road; 2) west end of Sweetwater Drive; and 3) west slope of main ridge east of Golden Gate Mountain and south of Gates Pass.

The assistance of D. L. Bryant, R. H. Courtright, J. B. Kinnison, R. T. Moore, K. Richard, R. L. Whitney, and E. D. Wilson in the preparation of this field trip is gratefully acknowledged.

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With compliments, MB

ORIGIN OF THE CAT MOUNTAIN RHYOLITE[1/]

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INTRODUCTION

The main rock unit exposed in the southern half of the Tucson Mountains was named the Cat Mountain Rhyolite by Brown (1939). He considered it to be a series of rhyolite flows and mud flows which he assigned to the middle of Tertiary time. In later work (Kinnison, 1958; Taylor, 1959), a nuée ardente origin was assigned to the unit and it became classified a welded tuff. Kinnison (1959) described and mapped the chaotic megabreccia which underlies the Cat Mountain Rhyolite, naming it the Tucson Mountain Chaos and postulating a sedimentary-tectonic origin for the unit.

The current study suggests that the chaos is part of a volcanic sequence which includes the Cat Mountain Rhyolite, the lower portion of Brown's Safford Tuff in that area, and concludes with the spherulitic rhyolite intrusives. This sequence has been assigned to Maestrichtian (uppermost Cretaceous) time by K-Ar dating of Cat Mountain feldspars (Damon and Bikerman, 1963).

GENERAL PETROGRAPHY

The Cat Mountain Rhyolite is a welded tuff of ash-flow origin, following the usage of Smith (1960a). The main unit of the formation consists of at least two ash flows which can be distinguished on petrographic and radiochemical bases (Bikerman, 1962). The formation shows several vertical and horizontal changes in density and induration with the degree of welding. Using Smith's (1960b) definitions, zones of no welding and zones of partial to moderate welding as well as poorly developed granophyric zones are found, although they are somewhat obscured by later alteration.

The general rock type is a rhyolite-to-quartz latite containing phenocrysts of quartz, K-spar, altered plagioclase, and magnetite. Hornblende and biotite are rare to absent in all sections studied. The quartz shows characteristic embayment in all zones studied. The nonwelded zones have a matrix containing nearly undeformed glass shards and pumice fragments. This is seen particularly well in the distal end of a small ash flow exposed just south of Ajo Road and Quarry Hill (see also Kinnison, 1958). In the more indurated samples the matrix is generally brown or orange in color, sometimes nearly opaque and

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1/ Contribution No. 83, Program in Geochronology, University of Arizona, Tucson.

is composed of devitrified or altered glass and small pumice shards. The color is caused by the presence of hematite, either disseminated or in small discrete specks.

In the chaos portion of the sequence, the groundmass where observed was a devitrified altered glass having no recognizable individual glass shards. In both the chaos matrix and in the welded zones above the chaos, a pervasive calcite alteration on feldspars, particularly the plagioclases, was found. The main petrographic difference between the chaos and overlying ash flows is in the xenolith content of the various units. The chaos contains a variety of sizes of xenolithic material ranging from large blocks of Amole Arkose and Paleozoic limestones to millimeter-sized arkose and andesite inclusions. In thin section the foreign material makes up 30 to 40 percent of the rock. In contrast, the ash flows contain fewer and smaller xenoliths, and the upper unit is cleaner than the lower. Furthermore, the overlying Safford Tuff contains considerably fewer xenoliths, and the spherulitic rhyolite nearly none. In all cases the xenoliths are of the same arkose or andesite composition with rare carbonates present. This variation is important in the development of the following vulcanologic theory.

VULCANOLOGY

First, a review of modern thinking on pyroclastic volcanics may be of value to the reader. Early work considered acidic extrusive sheets as true liquid flows or as interbedded liquid flows, mud flows, and ash falls. Observations on the nuée ardente eruptions at Mount Pelee and La Sourfriere in 1902, 1903, and later, combined with studies of the Katmai eruption (Fenner, 1923) and those of Vesuvius and various volcanoes in Japan and the East Indies, brought about a change of thinking toward a particulate gas-flow origin for these rocks.

The importance of a gaseous suspension of liquid droplets and solid magmatic (and xenolithic) particles was emphasized in work by Gilbert (1938) and Reynolds (1954), among many others. Marshall (1935) defined the term "ignimbrite" for deposits formed by a nuée ardente mechanism. Lately the differences between the small observed nuée ardente eruptions and the large-scale eruptions that produce ignimbrites or ash flows (Smith, 1960a) have been emphasized. Papers by Smith (1960a and b), Ross and Smith (1961), van Bemmelen (1961), and Fisher (1960), among others, have established criteria for classification and identification of these units.

For example, the Cat Mountain Rhyolite, having an estimated area of nearly 30 square miles and an average thickness of 400 feet or so (an approximate volume of 10 cubic kilometers), would fall into the fissure- and multiple-vent source class. This class is thought to be associated with important subsidence structures (Smith, 1960a, fig. 3). It would furthermore be characterized as an ignimbritic eruption (high gas content and high viscosity magma) by van Bemmelen (1961).

Observations in the Tucson Mountains do not support the existence of cratering or caldera collapse. Possibly Mackin's (1960) ideas, that subsidence in the basins accompanied the ignimbrites, are applicable here.

The chaos unit is a pyroclastic flow breccia (Fisher, 1960) of probable true nuée ardente-type origin. A further application of the concepts of fluidization as originally applied to geology by Reynolds (1954) is being made by Mayo (1963) to explain the chaos unit and related problems in the Tucson Mountains.

THE CAT MOUNTAIN VOLCANIC HISTORY

The postulated sequence of events for the Cat Mountain formation began with rising magma stoping its way slowly up through the basement complex, the Paleozoic limestones, and the Mesozoic arkoses and andesites. This material rose rapidly enough so that the stoped fragments did not have a chance to be assimilated into the magma and yet sufficiently slowly to allow silica replacement of parts of the limestone blocks. The upper front of the rising magma was cooled and its gas content increased by the presence of the included material. It probably was a partially molten, gas-rich mass when it pushed up through the pre-existing surface in several fissures (or possibly vents). On reaching the surface, the material erupted with sufficient force to spread large blocks of the competent limestone quite far from the sources (fig. 1A). The temperature of emplacement was below that needed to produce welding. This origin explains the "cooling rims" around some of the longer xenolithic blocks, as well as explaining the tuffaceous matrix and general appearance and distribution of the unit. However, the presence of rounded conglomerate zones (Kinnison, 1959) suggests interspersed times of erosion on the newly formed volcanic piles between successive pulses of eruption; or perhaps the rounded cobbles are the results of entrainment in the gas phase of the rising magma and subsequent dumping. The number of pulses of nuee activity has not been determined as yet. Part of the problem in determining the number of pulses lies in the dual nature of a nuee ardente. A nuée ardente consists of a lower avalanche portion containing the bulk of the solid material which closely follows the existing depressions in the terrain (the "ladu"), and an upper freely moving cloud (nuage) whose deposits closely resemble an ash or tuff fall, or the nonwelded portions of an ash flow. This upper part produces thin, easily eroded ash zones.

The main series of ash-flow eruptions followed the nuée ardente deposits, using the same orifices in some cases and new ones in others (fig. 1B). There were at least two main ash flows, separated by some short time interval. This separation is indicated by the fact that the two main welded zones are divided by a partially welded tuff phase. If there had been only one eruption, or if insufficient time for cooling had elapsed between the two, then the whole formation would have been but a single cooling unit (Smith, 1960a). If the time interval was long, then the unwelded upper portion of the lower flow would have been eroded and the lower portion of the second flow would have a chilled contact on some sort of relief. The actual contact between flows is not a well-marked line but rather a transition from a fairly clean, partly welded tuff to a slightly more xenolithic, equally welded unit. This situation is due to two factors: the first is the continuation of vapor-phase crystallization from the lower welded unit into the fresh ash, and the second is the baking and surface mixing of the contact by the upper flow.

The lower flow is less competent and less welded than the upper and hence probably was emplaced at a lower temperature. Furthermore, it contains a greater proportion of its total bulk in xenoliths than the upper flow. The xenolithic content of both flows decreases slightly towards the tops of the flows, probably as a result of gravity working on the blocks in the fluidized suspension.

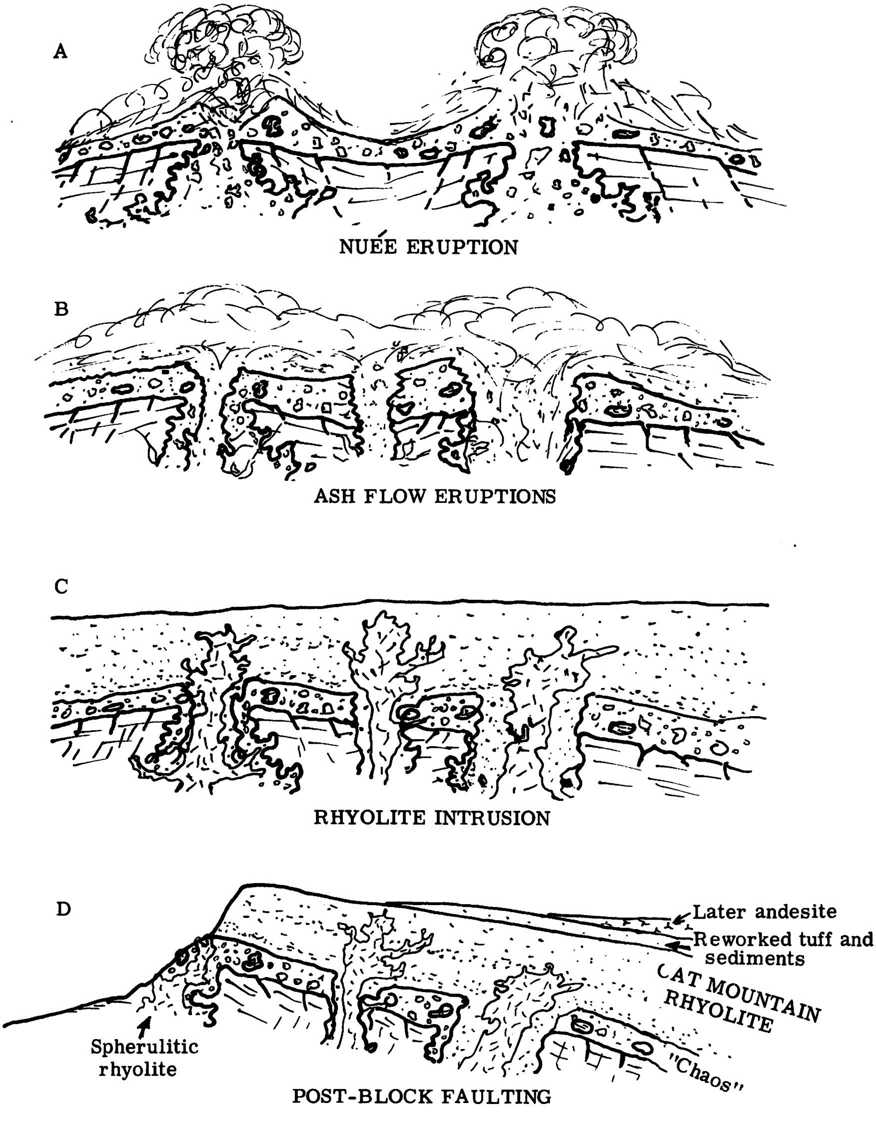
A
NUÉE ERUPTION
B
ASH FLOW ERUPTIONS
C
RHYOLITE INTRUSION
D
Later andesite
Reworked tuff and sediments
CAT MOUNTAIN RHYOLITE
"Chaos"
Spherulitic rhyolite
POST-BLOCK FAULTING

FIGURE 1

Starting with the unwelded tuff at the base, the rock passes through a zone of partial welding (using the definitions of Smith, 1960b) into a fairly well-developed zone of dense welding. None of the Cat Mountain units show the extreme welding of the vitrophyre zone, as was shown to the author in the Superior Dacite (D. W. Peterson, 1961, Arizona Geological Society field trip). From the zone of dense welding, the upward progression through the zone of crystallization to the nonwelded top is masked by the upper flow. Weathered-out, flattened pumice shards in the moderately welded zones give these zones a characteristic streaked appearance. This contrasts with the highly jointed welded phases which present a somewhat more homogeneous appearance, and which weather into near-vertical cliffs rather than into the rounded hills formed on the softer material. Radiometric analyses (Bikerman, 1962) give additional proof of the differences in the zones, as the welded zones have an average potassium content in the whole rock of about 4 percent, while the nonwelded zones have a higher potassium content ranging from 4.4 to 5.8 percent.

The second or upper flow presents characteristics similar to the lower one, showing a stratification from the partially welded interflow material through densely welded material into a nonwelded tuff capping. This soft tuff is not preserved on top of the western escarpment but is found in the lower reaches of the eastern dip slope, as in the Twin Hills area, where it shows evidence of water reworking in its upper parts. Brown (1939) mapped this tuffaceous phase as part of his extensive Safford Tuff unit. However, recent K-Ar dating of biotite from the Safford Formation (renamed by Kinnison, 1958) in the northern portion of the range gives a date of 25.2 million years (Damon and Bikerman, 1963), or Oligocene-Miocene. It is now proposed that the "Safford" name be restricted to the mid-Cenozoic rocks, while the Maestrichian tuffs be included in the Cat Mountain Rhyolite and a new name be given to the sediments previously included in the Safford formation in the Twin Hills region.

The final action of this volcanic cycle was the intrusion of gas-free, comparatively clean remnant magma through the old vents and through some new planes of weakness formed by structural adjustment to produce the spherulitic rhyolite (fig. 1C). This unit is interpreted as having a similar relationship to the Cat Mountain sequence as did the famous spine at Pelée to the Pelean eruptions.

Examination of outcrops of the spherulitic rhyolite shows that this intrusive usually outcrops in areas of thickest chaos unit, or near the postulated vents, and that it intruded with sufficient heat and force to weld the chaos around it while disrupting any bedding previously present. An estimation of importance of this intrusion in forming the steep dip angles on the range relative to the importance of the more general dislocation caused by the major structural changes associated with the block faulting (fig. 1D) is not undertaken here.

SUMMARY

From the original highly xenolithic chaos member of nuée ardente origin through the progressively cleaner ash flows and to the almost xenolith-free spherulitic rhyolite, the entire Cat Mountain sequence is considered to be caused by evolution of a single magma.

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with the writer's compliments

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.

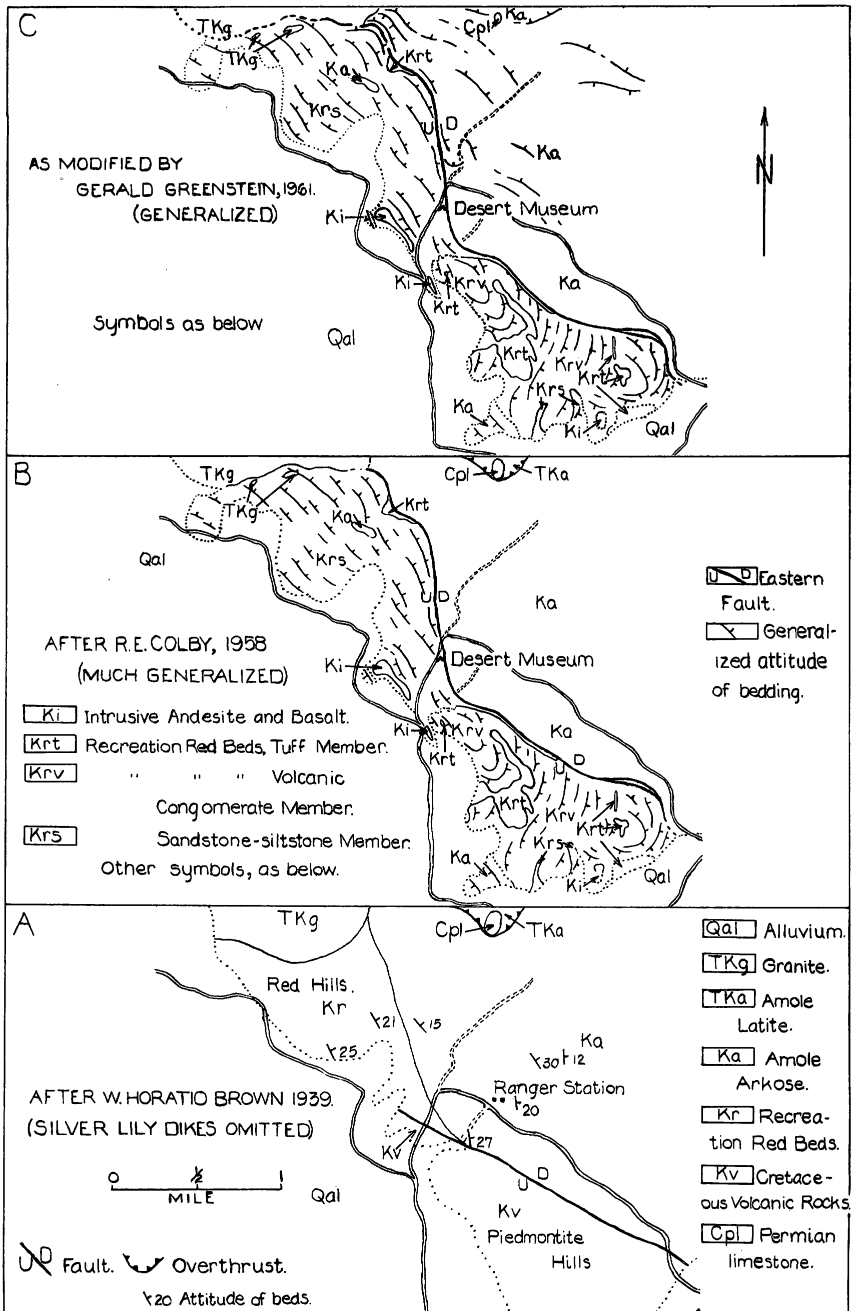

FIGURE 1.- REVISIONS OF GEOLOGY- PIEDMONTITE HILLS - RED HILLS

E.B.M. '63

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 <u>without transport</u>. The abrasive action and extreme mobility of a gas-solid <u>fluidized system</u> 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 <u>tuffisierung</u> (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.

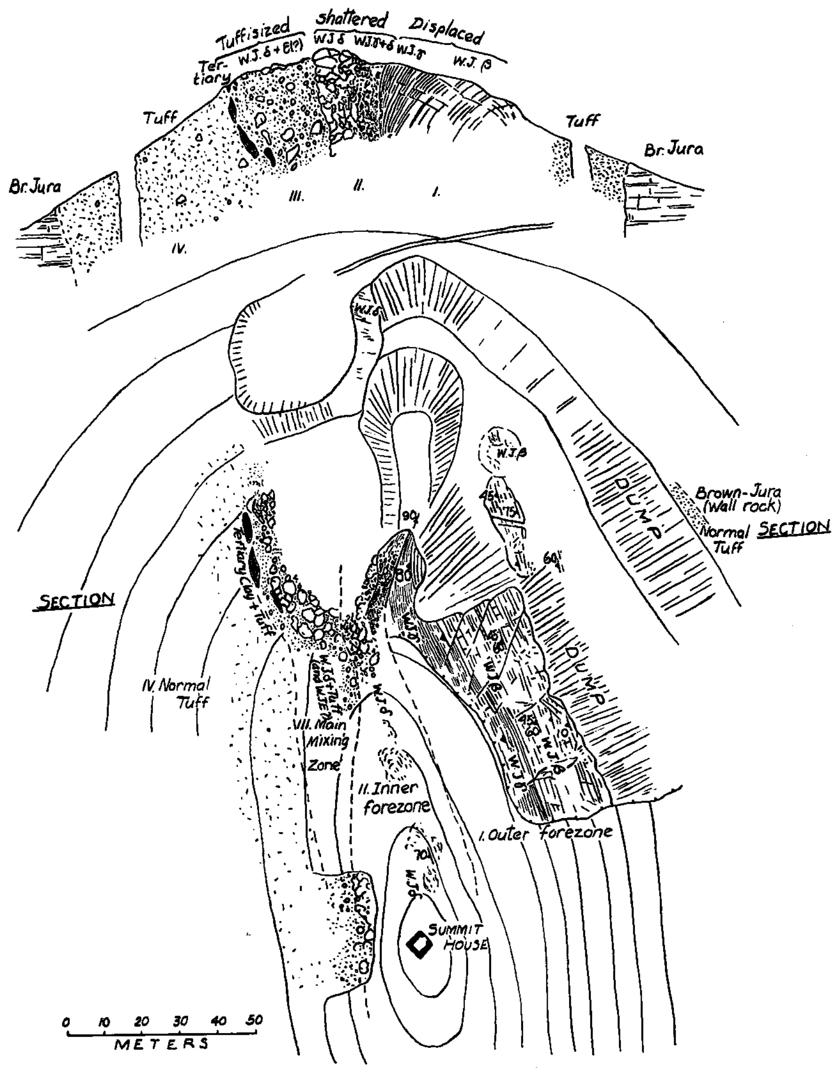

FIGURE 2 - SKETCH MAP AND CROSS SECTION OF THE AICHELBERG IN THE SWABIAN ALB, GERMANY

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 vari-colored 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

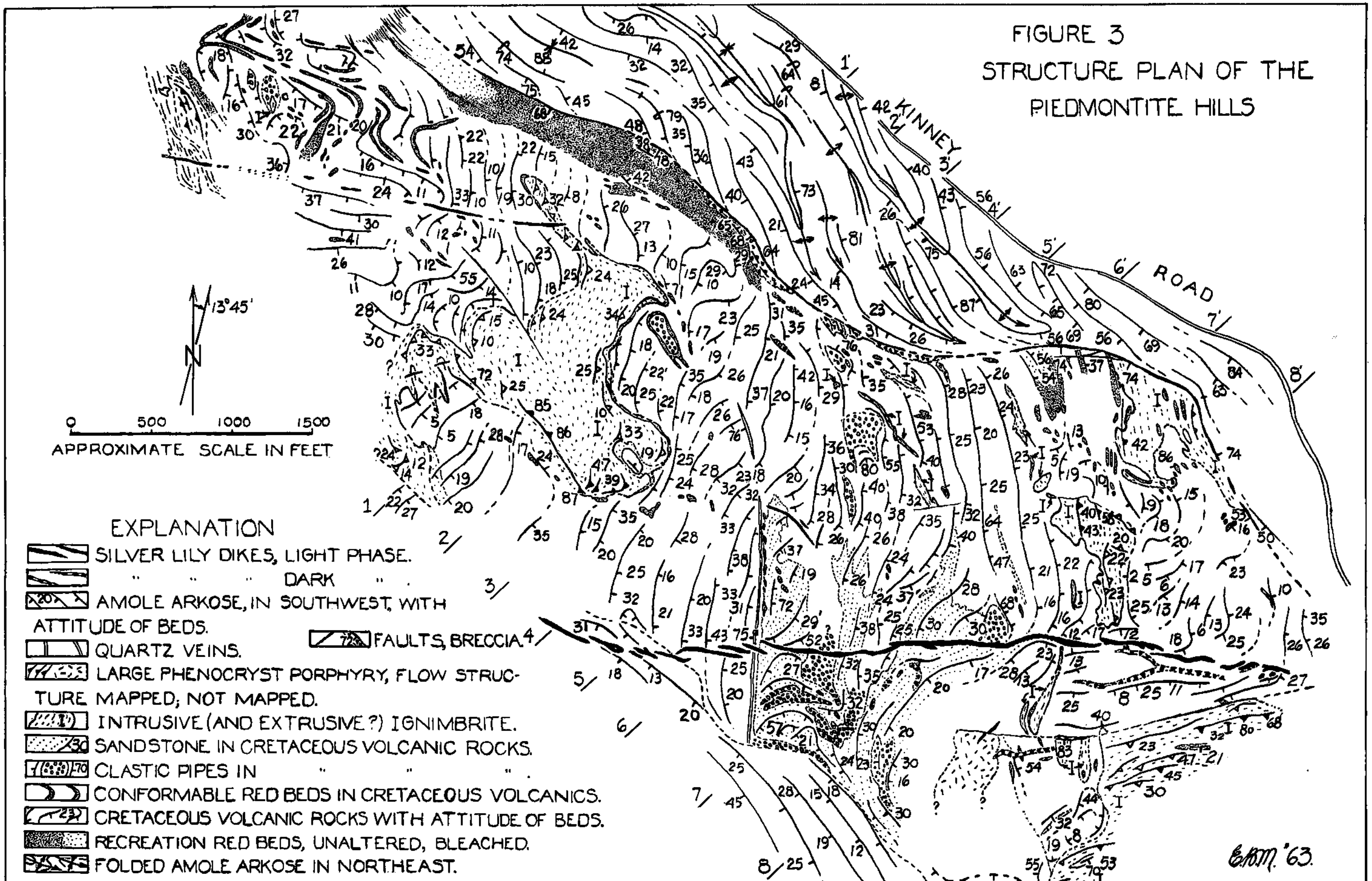

FIGURE 3
STRUCTURE PLAN OF THE PIEDMONTITE HILLS

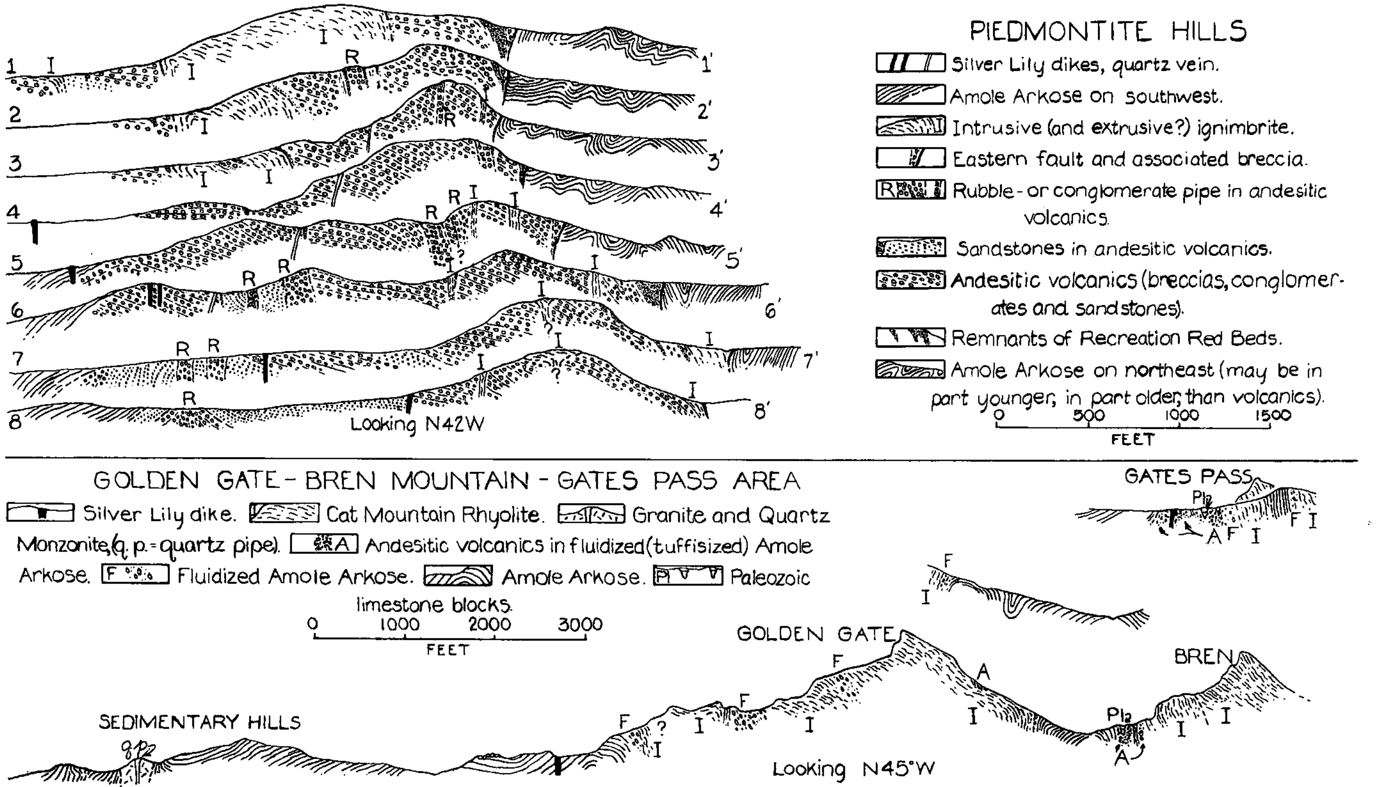

FIGURE 4-STRUCTURE SECTIONS

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^{o}, 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^{o}, 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.

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