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DEFENSE OF "VOLCANIC OROGENY" 1/

By

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INTRODUCTION

In a preliminary report, based on detailed observations in a few limited areas, this writer (1963) suggested that the structure of the Tucson Mountains west of the city of Tucson, Arizona, might be interpreted as the result of igneous action ("volcanic orogeny"). Other published contributions (1966a and b, 1967; Mayo and McCullough, 1964) have advanced this suggestion somewhat further, as have certain Master's theses (Greenstein, 1961; Bikerman, 1962; Assadi, 1964; Geiser, 1964, unfinished; Knight, 1967; McCoy, 1964). A history of geologic investigations in the Tucson Mountains has been published (Mayo, 1968).

The concept of "volcanic orogeny" has met with increasing opposition. Whatever the reasons for this, it seems that a defense is perhaps overdue. The arguments presented by certain critics require consideration, and it is thought that the general understanding of the problem of orogeny in the Tucson Mountains might be improved by discussion of some controversial issues. These are the reasons for this paper.

During preparation of this defense I have benefitted from the council of colleagues Paul E. Damon and Edgar J. McCullough, Jr., who of course are in no way responsible for my observations or conclusions.

SKETCH OF PRE-TERTIARY GEOLOGY

In the Tucson Mountains, formations belonging to the Paleozoic sequence are found apparently in place at only four known localities: Snyder Hill, the Sus Hills, the Twin Peaks and a small, unnamed hill north of the Twin Peaks (Damon, Bryant and Mayo, 1968, Pl. 1). However, Paleozoic limestone blocks, enclosed in latite, andesite, rhyolitic tuffisite, Amole Arkose and various rubbly mixtures, are widespread but are always found near igneous intrusions. The complex which includes these blocks was named the Tucson Mountain chaos (Kinnison, 1958, p. 28-30). Kinnison, who named the chaos and first proposed a sedimentary origin for it, has not been the most active critic of the "volcanic orogeny."

At Snyder Hill the Permian Concha Limestone and Rain Valley Formation are only gently warped. At the Twin Peaks, pre-Permian Paleozoic rocks are steeply tilted and may be strongly

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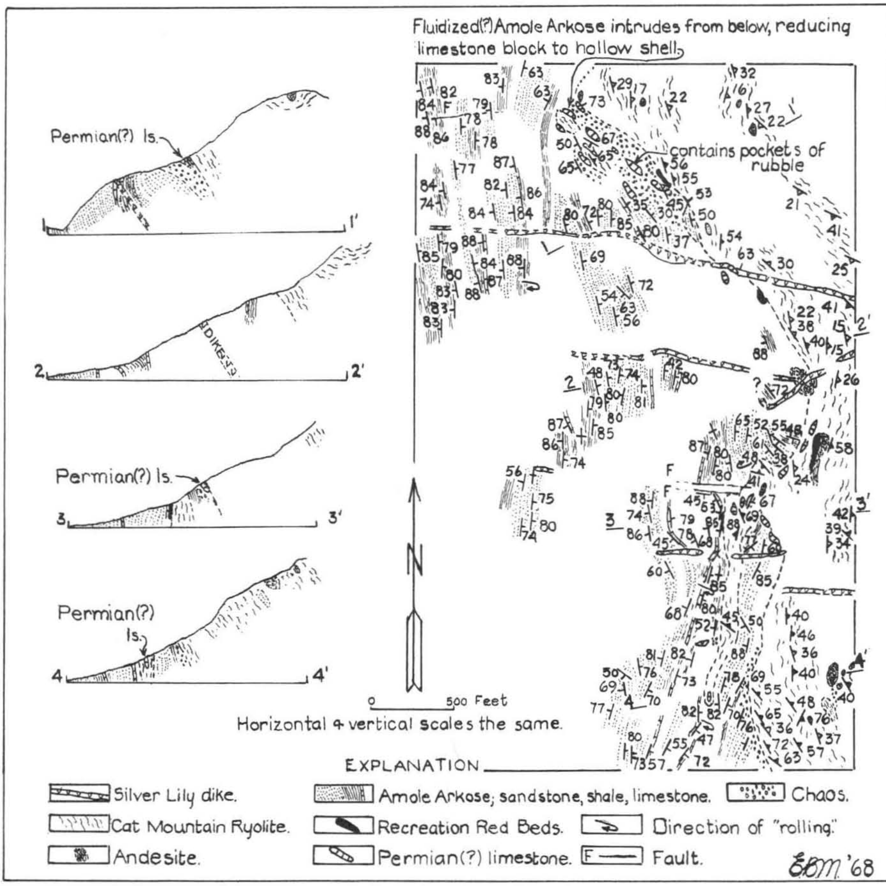

Figure 1.--Map and Cross Sections of an Area Along the Eastern Rampart of the Museum Embayment, East of Westward Ho Guest Ranch.

folded. There are limited exposures of Laramide (?) granite and older Precambrian Pinal Schist at this place. In the small hill to the north there is intense local deformation of Paleozoic limestones which suggests overthrusting or gliding. Paleozoic formations in the Sus Hills are intensely disturbed marginal to a large granitic intrusion. Thus, evidence of disturbances varies greatly in degree from place to place in the Paleozoic rocks, and the most impressive evidence is found where the old basement stands high and/or intrusive granite is exposed.

Although it can nowhere actually be demonstrated, it seems inevitable that the Paleozoic succession was formerly overlain by the Cretaceous volcanic rocks, Recreation Red Beds and Amole Arkose of Brown (1939). A recent radiometric date (Damon, 1967, p. 69-70) opens the possibility that the Red Beds may be Triassic, and this may apply also to the associated volcanic rocks. The age of the Amole Arkose is thought to be Lower Cretaceous. Because this age is of the greatest importance to the consideration of the tectonic history, it is unfortunate that a more definite assignment cannot be made. Hayes and Drewes (1968, p 56) tentatively correlate the Amole Arkose with Lower Cretaceous formations on the basis of lithology.

With few exceptions folds in the Recreation Red Beds and associated volcanic rocks are broad, gentle and dome-like. Locally the Amole Arkose is tightly folded, but in other places it is broadly warped. Fold axes mostly trend north-northwest. but there are important exceptions (Damon, Bryant and Mayo, 1968, Pl. 1). As in the Paleozoic section, so in the Mesozoic rocks, deformation varies remarkably from place to place. Further, the distrubance seems to be strongest near intrusive or extrusive centers (Mayo, 1966a) or marginal to domes in the Triassic (?) underlayer (e.g., Piedmontite Hills, idem., p. 10-11).

At least one steep-flanked fold was formed in the Red Beds as a result of emplacement, in Upper Jurassic time (Damon, 1967, p. 69-70; Mayo, 1961), of an intrusive andesite porphyry. The overall folding, however, which involves the Amole Arkose, must have taken place much later, perhaps near the end of the Upper Cretaceous. At about this time, but whether during or after the folding is not generally agreed, the Paleozoic and Mesozoic rocks were invaded by various magmas, now solidified as quartz diorite, andesite, quartz latite, granite and several rhyolites. Opinions differ as to whether the Tucson Mountain chaos was formed at the time of this igneous activity, or earlier. In any case the youngest dated Cretaceous formation, the early Maestrichtian or late Campanian Cat Mountain Rhyolite, intruded as tuffisite through the chaos and spread over it as ash flows (Fig. 3). Probably no significant folding of the sedimentary rocks took place after this event.

The Tucson Mountain problem includes the origin of the chaos, its relation to igneous action and to an inferred pre-Cat Mountain erosion surface (the Tucson surface). Let us consider the prevailing theories.

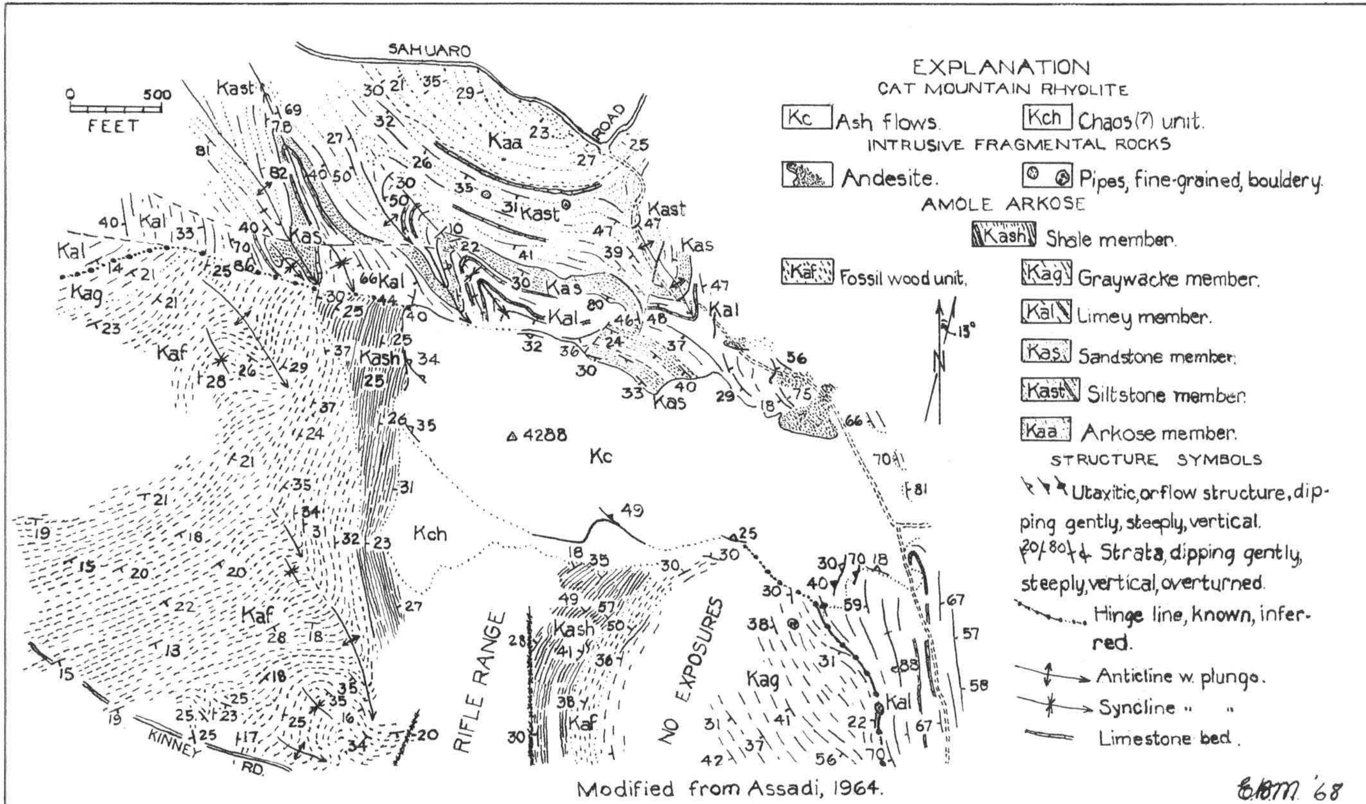

Figure 2.--Map of the Structure of the Amole Arkose Around Golden Gate Mountain. After S. M. Assadi, 1964.

TWO PRINCIPAL THEORIES

In my files there is a list of ten different explanations that have been offered for features like the Tucson Mountain chaos. Perhaps still other solutions will be added in future. At present, however, two theories seem to prevail.

According to the first of these the region underwent, in Upper Cretaceous time, an episode of intense compression during which the sedimentary strata were tightly folded. Then followed a time interval when a regional erosion surface was superimposed on the earlier-formed folds. After this surface was formed, upheaval re-established some feature of very great relief, perhaps a fault scarp. Erosional destruction of this uplift resulted in creation of a gigantic sedimentary breccia, the Tucson Mountain chaos, which was spread regionally over the previously-established unconformity.

A very recent version of this theory holds that two times of erosion intervened between the folding and emission of the Cat Mountain Rhyolite. During the first time the relief due to folding was eliminated; during the second the surface of the chaos was smoothed and the chaos was reduced to remnant patches. In view of the time required to accomplish these things the urgent need for age dates from the Amole Arkose can be appreciated.

As mentioned before, at some time during or after the folding, the sedimentary rocks were invaded by various magmas. This igneous activity culminated with extrusion of the Cat Mountain Rhyolite, which now rests on the chaos.

According to the second concept there was in Upper Cretaceous time, in the Tucson Mountains, no episode of intense, overall compression, resulting in tight folds. Instead, even during deposition of the Upper (?) Cretaceous Amole Arkose, there were premonitory upheavals and downsinkings announcing the beginning of emplacement of magma at depth (Mayo, 1966b). At this time some Amole strata could have been eroded from the highs and redeposited in the lows; local disconformities, such as should have resulted from this action, have been found. Subsequently, the intrusive activity increased and Amole deposition ended. The sedimentary strata were further uplifted, tilted and squeezed aside. Locally there is evidence (Mayo, 1966a, Fig. 3c, p. 19) that strata glided off the rising uplifts. Where magma gained the surface, the uplifted beds collapsed and subsided into those places from which support had been removed by the too rapid transfer of melt to the surface.

The observed folding of the sedimentary strata is held to be one result of the above-mentioned activity. Further, it is assumed that the rise of magma from depth and its possible spreading along Paleozoic "basement" strata broke these units into immense slabs. These slabs, and even some large pieces of the underlying Precambrian basement, together with disrupted masses of the overlying Mesozoic strata, were gradually upheaved. Aiding this upheaval was fluidization, engendered by the presence of gases and/or liquids, which attacked and reduced the slabs to lesser blocks and to rubble, and perhaps even disaggregated parts of the Mesozoic section. The resulting mixture of huge blocks and finer debris is the Tucson Mountain chaos. Remnants of the chaos are now found resting on, or included in, some of the intrusions, and the chaos is also found, tilted steeply inward,

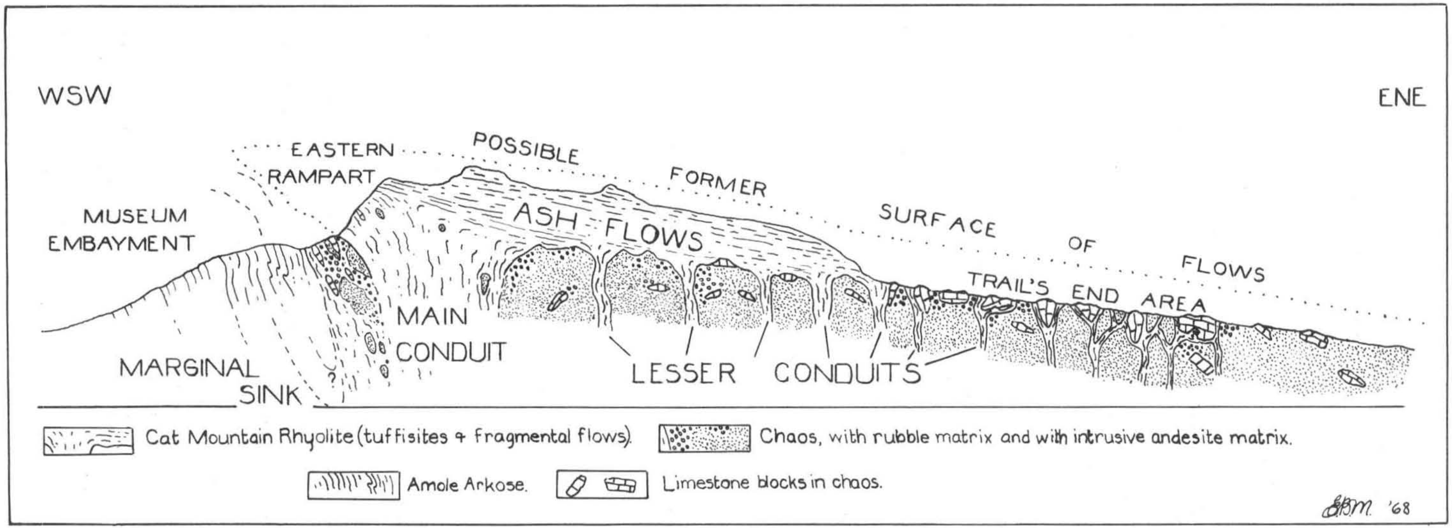

Figure 3.--Section Across the Tucson Mountains in the Trails' End Wash Area. Largely Hypothetical, but Incorporates Available Field Observations. Not to Scale.

marginal to places of extrusion (Fig. 3). During the above-mentioned activity, of course the normal processes of erosion and deposition were not suspended, so that local erosion surfaces might result, but the development of a regional unconformity is not necessary to the theory.

This second notion is the "volcanic orogeny."

The sedimentary theory, then, depends upon long-enduring erosion, great uplift, rock-fall and various other kinds of mass- and particle-transport, and deposition. The "volcanic orogeny" is a concept which involves the interplay of depositional processes and igneous action. To the sedimentary theory the igneous activity was incidental; to the "volcanic orogeny" it was vital.

The proponents of the sedimentary concept place special emphasis on the development of the regional Tucson surface prior to formation of the chaos and outpouring of the Cat Mountain Rhyolite. Among the localities where evidence is said to be exposed which proves the existence of such a surface, and the sedimentary origin of the chaos, the south slope of Cat Mountain, the west slope of Bren Mountain and Trail's End Wash on the east side of the range are repeatedly cited.

EXPOSURES ON CAT MOUNTAIN

This mountain is the type locality of the Cat Mountain Rhyolite of W. H. Brown (1939). In several steep gullies on the southern slope, north of Ajo Road, there are exposures which reveal to a very limited extent the relations between Amole Arkose, Tucson Mountain chaos and Cat Mountain Rhyolite. This is classic ground to defenders of the sedimentary theory.

I have made no detailed study of this area and have only visited the westernmost of the gullies on two field trips sponsored by the Arizona Geological Society. The second of these trips was in the Spring of 1964. As I recall it, the following is exposed in the west wall of the gully.

Just above the talus the Amole Arkose crops out. The bedding of the arkose strikes northwesterly and the dip component seen on the gully wall is steep northward, toward the mountain. Only a few feet at most is exposed of the contact between the arkose and a local, course basal conglomerate of the chaos. This contact is a plane, apparently sheared surface, that dips northward nearly 60 degrees toward and under the chaos. There is an angular discordance between arkose and chaos as must be expected if the exposed contact is a displacement other than a bedding fault. The members of the field party were told that this contact was indeed a local fault of no significance, and that the chaos actually rested on a flat or gently inclined surface.

Because no flat unconformity is to be seen here, it would appear reasonable to conclude that supporting evidence must be exposed in one or more of the nearby gullies. On inquiry, however, I was told that only at this very spot was any sort of contact actually visible between arkose and chaos. Of course it might be concluded that the contact is, in general, flat if its mapped or inferred trace is approximately parallel to the topographic contours. But this would not necessarily be a valid

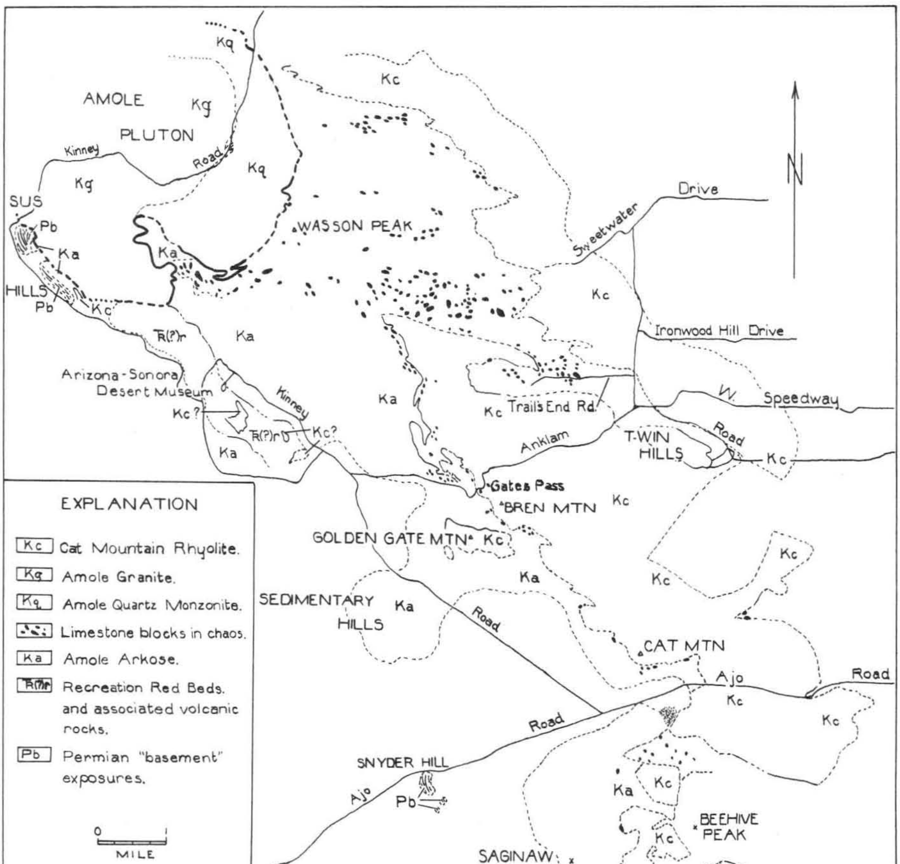

Figure 4.--Sketch of Some Features of the Pre-Tertiary Geology of Part of the Tucson Mountains. Compiled from Available Sources.

conclusion, because any steep surface could have just such a trace provided that its strike was approximately parallel to the present contours. It would follow, then, that even though the lower contact of the chaos may partly encircle a mountain, and even if two or more points having the same elevation can be located on this contact, there still would be no justification for assuming that the chaos rests on a flat surface. In form, this exotic unit could be an irregular funnel, cylinder, steep walled dome, or even a cone with external boundaries roughly parallel to the topographic contours. The observed steep inward dips would suggest the first of these. The close relation of structure and topography could be explained if the chaos-rhyolite sequence is more resistant to erosion than is the surrounding arkose. The topographic and structural relations at a volcanic plug rising above flat, weak sedimentary rocks illustrates the point.

Lacking any exposure of the inferred unconformity, the observer is forced to search for indirect evidence in the boulder conglomerate at the base of the chaos. These boulders are mostly sandstone, apparently derived from the Amole Arkose. It appeared to me that the longest axes in the clasts in this conglomerate were inclined northward, toward the mountain, at angles of 45 degrees or perhaps steeper. The same may be true of the huge blocks in the upper part of the chaos. If the above is correct, and it will have to be checked by a careful re-study of this and near-by gullies, then the assumption of a presently existing flat bottom to this deposit is ill-founded. The indications seem to be that the chaos rests on a steep surface which dips toward and under the Cat Mountain Rhyolite.

But what of the conglomerate itself? Boulder conglomerates are not usually deposited on slopes as steep as the one that appears to be indicated, therefore a flat surface must have existed here at the time that the conglomerate was deposited. This point, which seems to be the crux of the argument, will have to be conceded, but it is not accepted that the presence of this local body of conglomerate is proof of regional planation.

If, as previously stated, the processes of erosion and deposition were not suspended during the "volcanic orogeny," and if uplift and collapse took place at and near the sites of ash flow emission, then the conglomerate could have accumulated in a gradually developing marginal depression. As collapse continued, by down-warping and/or faulting, the conglomerate, and with it the overlying, blocky chaos, may have become tilted steeply inwards. This might have been the case regardless of whether the conglomerate was derived by erosion of a local uplift or was expelled from a fluidized pipe or dike. I suggest, pending detailed investigation, that some such marginal tilting operated here on the border of an eruptive center, and that the conglomerate was locally derived. Good evidence indicating that the above suggestion does not apply will be carefully considered, but unsupported assertions cannot be accepted.

BREN MOUNTAIN SECTION

At this place, on the western slope of Bren Mountain, south of Gates Pass (Fig. 4), Amole Arkose, Tucson Mountain chaos and Cat Mountain Rhyolite are again exposed in the usual sequence from bottom to top. Here the contact between arkose and chaos has not been seen and there is no basal conglomerate of the chaos.

During the 1964 visit of the Arizona Geological Society to this locality, it was agreed that the Amole-chaos contact could not be observed, but supporters of the sedimentary concept insisted that this surface, although concealed, had to be present, and that it was flat. At the time it seemed reasonable to suppose that the inferred contact could be approximately located by noting the distribution of outcrops which showed, on the one hand, well-stratified Amole Arkose, on the other a partially disaggregated or rubbly mass with many inclusions of foreign materials. But even more important than defining the position of this separating surface is to estimate its dip. At the time of the A. G. S. field trip two flat, oxide-coated fractures were found in what was then considered to be chaos. These fractures were pointed out as "proof" that the internal structure of the chaos is flat. The present writer could readily discern a steep planar structure in the chaos, but the very existence of this feature was vigorously denied. It might have been difficult to account for a steep planar arrangement in a body that was supposed to have been deposited on, and to still rest on, a flat surface.

Geologic mapping at 50 feet to the inch has been started here. This work is still in the beginning stages, but already some unexpected features have been found.

The area lies on the steep, northeast flank of a southeast-plunging anticline (Fig. 2) mapped by Assadi (1964). His geologic plan, made at 500 feet to the inch, shows this anticline to be a reasonably simple structure, but re-mapping of part of the northeast flank at a scale ten times that used by Assadi, reveals formidable complications. These are expressed as sudden, pronounced changes of strike as well as dip.

Associated with some of these abrupt disturbances are small, apparently intrusive masses of fragmental andesite, fine, even-grained andesite and Cat Mountain Rhyolite. In addition, several blocks of Recreation Red Beds and two of Paleozoic limestone have been mapped in the disturbed Amole Arkose. The field relations suggest that the complications of structure result at least in part from the forceful emplacement of the igneous materials and of the sedimentary rocks older than the Amole Arkose.

The best exposed of the Recreation Red Beds blocks may merit discussion. This big fragment is situated in a tiny ravine just below the trail southwest of the larger of the two known limestone masses and about one third of the distance from the foot of the Bren Mountain slope, below, to the base of the Rhyolite cliffs, above. The block is some 15 feet long and 7 feet wide in plan. Its vertical dimension is unknown. The longer horizontal axis trends N 75 W, athwart the general strike of stratification in the Amole Arkose, but within a few tens of feet of the red rock the Amole stratification bends abruptly to conform to the outline of the red inclusion.

This mass was partially excavated by a graduate student, Mr. R. C. Moores, II. Moores carefully cleaned and washed the excavated parts and photographed them in color. It seems that the red rock was once enclosed in a shell of Cat Mountain Rhyolite a foot or more thick, and that the entire structure was enwrapped conformably by the Amole stratification.

At present the best interpretation of the above data seems to be that the Cat Mountain Rhyolite, rising from depth, forced an included piece of Recreation Red Beds up into the

Amole Arkose. As Moores (1969) wrote: "It seems that here, at least, the Cat Mountain Rhyolite acted as both energizer and lubricant."

The larger of the two exposed limestone blocks also appears to rest in, not on, the Amole Arkose, some of which arches over one corner of the block. This limestone might once have been completely enclosed in the arkose (Mayo and McCullough, 1964, Fig. 2B, p. 83,84).

If these preliminary results can be accepted, then it will follow that the exotic blocks at this locality do not rest on an erosion surface, flat or otherwise. These are perhaps better regarded as foreign inclusions, in, not on, the Amole Arkose. If it is assumed that these inclusions represent huge clasts that slid into the basin of deposition during Amole sedimentation, then the presence of intimately associated structural disturbance and intrusive igneous material becomes a difficult problem.

The nature of the "matrix" of this chaos is surprising. So far, I have found little evidence of disaggregation or of the formation of rubbly mixtures. Although there are some local exceptions, in general the Amole, although much disturbed, has retained its coherence and its stratification. In fact, this stratification is the "steep planar structure" previously noticed in this part of the chaos.

From what was said above the outcome of any attempt to locate a contact between Amole Arkose and Tucson Mountain chaos at this locality can easily be predicted. There seems to be no such surface. "Chaos" at this place is simply disturbed Amole, pierced by numerous small intrusions, some of which are accompanied by exotic blocks.

Obviously, the chaos at this Bren Mountain locality is very different from that on the south slope of Cat Mountain. On Cat Mountain we may see the results of large scale upheaval, eruption and collapse, modified by contemporaneous erosion and deposition. At Bren Bountain we seem to see the exotic blocks "frozen" en route to the surface. Both of the localities appear to be marginal to major centers of eruption, and at neither place have I seen compelling evidence of the Tucson surface.

TRAIL'S END WASH

The above seems to be a convenient name for the big wash on the eastern side of the range, just north of Trail's End Road, near the Sahuaro School for Asthmatic Children, (Fig. 4). This locality seems to be situated well within, rather than marginal to, an area of eruption. Here the Amole Arkose has been reduced to isolated patches. The intervening spaces are occupied mostly by intrusive (and extrusive?) andesites of several textural varieties. These rocks in turn have been invaded by a plexus of pipes and curved, intersecting dikes. The pipe-like bodies consist of dacite, sperulitic rhyolite, Cat Mountain Rhyolite and flow-banded, aphanitic andesite (?). The network of curved dikes is Cat Mountain Rhyolite. The latest intrusion takes the form of large, irregular, quartz latite porphyry dikes (Silver Lily dikes, Brown, 1939).

Because Trail's End Wash has eroded some 10 to 25 feet into this complex, it can be seen that here again the limestone blocks are embedded in, not resting on, the intrusive rocks. Some of the limestones appear to be enwrapped in Amole Arkose or in sandstone of uncertain origin, but where exposures permit, a careful search reveals a selvage of Cat Mountain Rhyolite between limestone and arkose or sandstone. This relation recalls the similar one at the red block on Bren Mountain.

The limestones of the Trail's End area seem to be mostly Permian, but some may be older (McCoy, 1964, p. 17-20). Dr. Donald L. Bryant (personal communication) has informed me that fossils recovered from one of the blocks south of Trail's End Road, and perhaps a third of a mile east of the Sahuaro School, prove this limestone to be a piece from the Pennsylvanian-Permian Earp Formation.

Three large masses of the older Precambrian Pinal Schist have been found in the area. One of these is too poorly exposed to yield useful information. The strike of stratification in enclosing sandstone partially encircles the second one, as though the schist has been upheaved into yielding sediment. The third schist block was opened up, many years ago, by prospectors. In the bottom of the resulting pit a tuffaceous-appearing rock, probably Cat Mountain Rhyolite, underlies the schist and suggests how the basement block might have been emplaced.

Trail's End Wash was chosen by McCullough and me (1964) as one of the localities where the mechanism of emplacement of the exotic fragments seems especially clear. Steep flow structures in the enclosing andesite locally curve about some of the limestones. Further, the internal structure of certain limestones is domed, as though the rock has been forced upward by magma rising beneath. Other blocks are in part rubble, sparingly admixed with foreign materials. This condition suggests fluidization of shattered marginal portions of a block.

In the Spring of 1964 this area also was visited by members of the Arizona Geological Society. At that time four objections were made to the idea of emplacing the blocks by intrusive upheaval.

(1) The steep flow structure, mapped in the andesite "matrix" around some of the limestones does not exist. In fact,

(2) the andesite itself exists only as huge blocks in the chaos.

(3) Dome-like or arched structures in some of the limestone blocks, thought by Mayo and McCullough to have resulted from upwelling of underlying magma, were actually formed by the down-draping of the edges of the limestone due to erosional removal of support.

(4) In a near-by tributary wash, between two limestone masses, there was pointed out a clastic rock, resembling course-grained Amole Arkose, with abundant pebbles and cobbles of limestone. It was claimed that this peculiar mixture was proof of the sedimentary origin of the chaos.

In preparation for the visit to this locality by members of the Geological Society of America in April, 1968, these exposures were carefully remapped and the map area was somewhat extended. Places were found where the steep flow structure in the intrusive volcanics is so obvious as to preclude argument. No evidence at all was found which would suggest that the andesite exists as blocks comparable to the masses of limestone. However, as already mentioned, this volcanic rock is cut by a network of intrusive Cat Mountain Rhyolite, therefore, in this special sense, could be said to exist as blocks. Much of the andesite appears to have been intrusive, but some of it might have flowed out as lava. Examples were seen of the sagging of the margins of limestone masses due to erosional removal of support, but other arched limestones with andesite beneath them cannot be so explained.

When the Geological Society of America field party visited this area the first three objections, listed above, were not reiterated. Apparently it was accepted that some part at least of the volcanic "matrix" of the chaos is intrusive. This appeared to be progress, but the criticism took a new trend. All that the new work had accomplished was to show that the chaos had been invaded by various magmas, therefore the work was useless.

The above statement seems to imply that the chaos did once rest on the Tucson surface at this place, that all direct evidence has been destroyed, but that the reality of the surface is so firmly established that it cannot be affected either by evidence or by the lack of it. The critic next referred to the seemingly gentle surface, on which rest the Cat Mountain ash flows, as a remnant of the Tucson surface. This feature, which has still to be investigated, lies above, not below, the chaos. Further, if some of the andesite in the chaos is extrusive, then the surface under the ash flows may be a constructional feature. The Tucson surface should lie under the chaos and be an erosional feature. Perhaps the critic became confused.

But if direct evidence of the Tucson surface is not available at Trail's End Wash, maybe some indirect indication can be found. When the G. S. A. party arrived at the tributary wash where is exposed the coarse-grained sandstone with the limestone clasts the party was told that this material is the real matrix of the chaos. In other words this entire field of limestone blocks was once embedded in an extensive blanket of sand crowded with small, rounded limestone clasts. The limited exposure in this little wash could be all that remained of this sedimentary matrix after the magmatic invasion. If the sedimentary concept were an established fact, the above would be a reasonable interpretation. Before examining this spot in detail, let us digress.

Consider Fig. 1. The right-hand half of the figure is a map of an area along the Eastern Rampart (Mayo, 1966a, p. 23 et. seq.) of Cat Mountain Rhyolite cliffs east of Westward Ho Guest Ranch. The southeast corner of the map is the common corner of Sections 4, 3, 9 and 10, T 14 S, R 12 E.

In the top center of the map are shown two nearly parallel rows of limestone blocks embedded in a detrital matrix near the western border of the Cat Mountain Rhyolite. So striking is the mutual parallelism of the blocks, as well as the rows, that it is hard to escape the impression that all were formerly united in one, or perhaps two, enormous slabs. If this impression is valid, it would seem reasonable to infer that the former slab, or slabs, might have become segmented and partially disintegrated through attack by the active, abrasive matrix. The energy propelling the attack would have been furnished by the rhyolite. In support of this suggestion is the observation that near the blocks the matrix is especially rich in rounded, pebble-and cobble-sized limestone clasts. Also, as noted on the map, what appears to have been disaggregated Amole Arkose has attacked one of the blocks from below, reducing it to a shell. At another place a block has been shattered and at fracture intersections it contains pockets filled with limestone rubble.

The above observations suggest an alternative explanation for the coarse-grained sandstone with abundant limy clasts in the Trail's End area. Let us check this suggestion on the spot.

The above-mentioned mixture is restricted to a very small area, no more than 25 feet across, between limestone blocks. The coarse sandstone extends considerably farther, and a few small calcareous pebbles have been seen in it elsewhere, but the principal concentration of these clasts is found only in the very small space between the blocks. The sandstone has been intruded by masses of andesite and by small apophyses of Cat Mountain Rhyolite. Either of these intrusions could have activated the coarse sand, causing it to enter cracks in the limestone and to round off the resulting fragments. This result could have been predicted from observations along the Eastern Rampart. It hardly qualifies as indirect evidence of the Tucson surface.

It would seem, then, that in the three "classic" localities just discussed, evidence favoring the sedimentary theory, if not actually nil, is far from compelling. An attempt will now be made to discuss additional tectonic features in relation to the two principal bypotheses.

THE FOLDING

A critic of the "volcanic orogeny" wrote, in an unpublished report, that north-northwest-trending, "isoclinal" folds are ubiquitous in the Mesozoic sedimentary rocks throughout the Tucson Mountains. This condition was said to indicate an episode of compression (intense tectonism) which preceded establishment of the Tucson surface. Some observations which do not support the above conclusion were mentioned under 'sketch of pre-Tertiary geology' and pertinent literature was cited. The experience of gathering data for the structural map of the Museum Embayment (Mayo, 1966a, Pl. 1) convinced the present writer that intense compression, or crustal shortening, could scarcely begin to explain all of the characteristics of the folding. In addition to examples already cited, the structure of Golden Gate Mountain (Figs. 4, 2) may help to illustrate the inferred relation between folding and igneous action.

When the cross section through Golden Gate and Bren mountains was published (Mayo, 1963, Fig. 4, p. 70) the following statement was made (idem, p. 76): "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 section, almost completely walked out in the field, suggested a funnel in the Amole Arkose under Golden Gate Mountain; out of this funnel the Cat Mountain Rhyolite might have erupted.

Shortly after the above section appeared, S. M. Assadi mapped the structure of the arkose around the mountain. Unfortunately, a gap had to be left on the southwest because of the presence there of the rifle range. With this exception, the encircling structure was shown on a colored geologic map at the scale of 500 feet to the inch (Assadi, 1964, Pl. 1). Figure 2 of this paper is based on Assadi's map. His results seemed to confirm my earlier impression.

Seven units were recognized in the Amole Arkose by Assadi as indicated on Fig. 2. A curved, southwestwardly-concave "hingeline," probably a normal fault with downthrow southwest, completely separates the four lower units in the footwall from the three upper units in the hanging wall. In the hanging wall the fossil wood unit thins rapidly southeastward as though this unit had been "poured into" a subsiding basin, perhaps forming a delta. Assadi considered that at least part of the associated shale member was a more slowly-accumulated facies of the fossil wood member. At the time of this sedimentation there may have been active erosion on the footwall of the "hingeline" and there surely was active deposition on the hanging wall.

At some time while the Amole sediments were still relatively soft, the footwall, and perhaps also the hanging wall of the "hingeline" was uplifted. On the northeast side of the mountain, slump folds moved <u>up</u> the present inward dip away from the mountain. At one place (Fig. 2) a huge block appeared to have moved northeastward. Such reactions would seem to have been impossible had the dips of that time been in the same direction (southwest) as now.

Uplift at the site of the present Golden Gate Mountain could have been caused by the emplacement of magma beneath. The structure which eventually guided this melt to the surface may have been the "hingeline." Escape to the surface of various materials, including magma, should have promoted collapse. Thus the formerly outward dips were reversed, and perhaps a chaos was formed. If so, the Cat Mountain Rhyolite rose through and overwhelmed this chaos. Assadi mapped, on the southwest side of the mountain, below the Cat Mountain Rhyolite, what he terms "brecciated Amole." This broken-up material contains much tuff or tuffisite, therefore I have suggested (Fig. 2) that the mixture may be an initial chaos (?) unit of the rhyolite.

The above interpretation is essentially that of Assadi, and it seems reasonable. The structure shown on the map (Fig. 2) is obviously not a north-northwest trending, truncated, isoclinal syncline. Further, it seems awkward to explain such a peculiarly-shaped structure and such a tectonic history as a result of lateral compression.

If, in spite of the examples mentioned above, it is still considered that the evidence is inadequate which favors an origin of the folding through igneous action, then it would seem that the controversy can only be resolved by further field work. A careful re-mapping of the structure of the Amole Arkose partly around Bren Mountain might be useful. P. A. Geiser (1964) thought that the arkose formed a partial funnel around Bren Mountain. To map in detail every critical locality would require many years. The establishment of an acceptable theory of the folding, then, may be a matter of time and interest.

THE CHAOS AS A STRATIGRAPHIC UNIT

As mentioned under 'two principal theories,' a recent version of the sedimentary hypothesis postulates, besides the erosion surface at the base of the chaos, a second such surface on top of this unit. Also, it has been stated that the chaos is definitely a stratigraphic unit, always above the Amole Arkose and always below the Cat Mountain Rhyolite. There are places where no Amole Arkose can be found under the chaos, and places where no Cat Mountain Rhyolite rests on it, but let us ignore these exceptions.

The impression that the chaos is indeed a stratigraphic unit in the above sense is easily gained, but is misleading. A good place to demonstrate this is north of Golden Gate Mountain, along the Eastern Rampart of the Museum Embayment. Looking eastward from the floor of the embayment, the abrupt wall of Cat Mountain Rhyolite appears to rest on a gentle surface superimposed on the Amole Arkose. The chaos, which in fact separates arkose from rhyolite, is scarcely visible from the embayment floor. Viewed from the south, along the escarpment, Amole strata can be seen to dip some 70 degrees, or steeper, eastward, and it appears that the rhyolite, which overlooks the down-turned Amole, must indeed rest on a pronounced unconformity. This is certainly the conclusion to be reached from the distant views, but what is the actual case on the ground?

Consider again Fig. 1. Besides the map on the right-hand side, the left-hand side of the figure shows four sections across the rampart.

The sections reveal that the Cat Mountain Rhyolite does not rest on a gentle surface, eroded on the Amole Arkose. Instead arkose, chaos and rhyolite all dip steeply eastward. There is little discordance, if any, between these three units. This situation is somewhat like that found on Bren Mountain, yet the chaos does appear to rest on Amole Arkose and to underlie Cat Mountain Rhyolite.

One feature, however, makes this stratigraphic relation seem peculiar. As shown on the map (Fig. 1, right-hand side), apparently following a transverse zone of faults or fissures, the rhyolite extends westward across the chaos and has inserted itself, sill-like, along the steep stratification of the arkose. Several limestone blocks were found embedded in the tuffisite of this sill. This observation clearly supports the assumption that these calcareous masses were somehow brought up from depth.

Figure 3 is an attempt to represent in much generalized form what is known and inferred in a structure section across the Tucson Mountains in the Trail's End area. If field work currently in progress can be completed, a more accurate section will ultimately be available.

In the Trail's End area, besides numerous blocks, one steeply-dipping mass some 300 feet long of Amole Arkose, and one equally large and steep of Recreation Red Beds are known, but are not represented in Fig. 3. These two masses might be in place. If so, they would appear to be remnants of a Mesozoic sequence which was almost destroyed when the chaos was formed. It could also be argued that these masses are part of the floor on which the chaos was deposited. But this argument is disarmed by observations which reveal Paleozoic blocks resting in, not on, the arkose, and others that are at elevations lower than that of the supposed floor.

Where examined in detail it looks as though the chaos has risen through a collapsing Mesozoic sequence, and at a few places (e.g. Cat Mountain) may have undergone erosion and been deposited on the Mesozoic rocks. The chaos does not seem to be a stratigraphic unit in the usual sense.

AN ALTERNATIVE SOURCE FOR THE CHAOS BLOCKS (?)

Perhaps it can still be claimed that the Tucson Mountain chaos was deposited on an erosion surface, then was bulged upward, collapsed, was intruded, and was covered by ash flows. To me such an argument appears strained, but if a reasonable source could be indicated for the gigantic breccia, the sedimentary theory might acquire a firmer basis.

It has been suggested in an unpublished report that "the most likely site for such structurally and topographically high terrain is a north-northwest-trending zone which lies just west of the large Paleozoic outcrops at Snyder Hill in the south and the Picachos de Calera in the north." Figure 4 is a map that includes the sourthern part of this zone. Paleozoic (Permian) outcrops are indicated at Snyder Hill and the Sus Hills. The Picachos de Calera are several miles beyond the northwest corner of the map. Every limestone block of which I have record is shown in black.

In the north, near the Picachos de Calera, no limestones rest either on or in the Upper Cretaceous (?) deposits. Further, these deposits were not observed to be invaded on a large scale by intrusive volcanics. It may be that the Paleozoic exposures at the Picachos were lifted to their present position by the granite which crops out at the southern base of these hills.

It would seem (Fig. 4) that many of the chaos blocks could have been derived from the Sus Hills area. East of these hills the blocks are arranged in several nearly east-trending zones, as though they had been deposited in straight, parallel valleys. Such a rigidly parallel drainage seems improbable. Also, most of the Paleozoic exposures in the Sus Hills appear to be of the Pennsylvanian-Permian Earp Formation, only one block of which has so far been identified in the chaos to the east (Donald L. Bryant, personal communication). It is suggested that, as at the Picachos, so in the Sus Hills, the Paleozoic rocks were emplaced by the late Cretaceous granite.

In the broad gap between Snyder Hill and the Sus Hills there are no Paleozoic exposures. To the east much that may be chaos is overlain by the Cat Mountain Rhyolite, but the visible exotic blocks form a fringe along the southwest border of the rhyolite and some of them are embedded in the tuffisites or the ash flows themselves. The evidence suggests that these limestones were brought up from below, but could they possibly have been derived from a lofty scarp somewhere to the southwest?

Although direct evidence is lacking, suggestive observations can be made at two places. In the big wash at the south end of the Piedmontite Hills, at their southwestern corner, the Amole Arkose, resting unconformably on the red beds, dips 10 to 30 degrees away from the hills. Traversed down wash, these dips are seen to steepen as though the arkose were draped over the southwest flank of a box fold. The same structure can be seen in the first wash north of King Canyon, west of the Desert Museum. Although the contact is concealed at this place, there is no doubt that here again the Amole strata rest on the Recreation Red Beds and dip off them at moderate angles toward the southwest. Down-wash again, the dip of the arkose is seen to steepen. The westernmost measurement that I was able to make was 64 degrees southwest. These observations, while they do not preclude an uplift somewhere in the direction of dip, obviously do not indicate such a feature. Indeed, the existing data strongly suggest that the uplift was confined to the Tucson Mountains.

Could the exotic blocks in the southernmost part of the range have been derived from the vicinity of Snyder Hill? I know little of the geology south of Ajo Road, therefore approach this problem with uncertainty. Analogy with areas farther north would seem to make the question debatable. An impressive fact is the close association of the blocks with the Cat Mountain Rhyolite. Even the apparently isolated limestone, south of the junction of Ajo and Kinney roads and just north of the symbol Ka (Fig. 4) is closely associated with a rhyolite plug (Brown, 1939, colored geologic map) which could have lifted the block.

I am aware that the collapse of uplifts and their disappearance beneath the sea, or their burial beneath younger sediments, is well documented in the geologic literature. Accordingly, the lofty scarp from which the chaos blocks are assumed to have been derived might have collapsed and it could now lie buried beneath the alluvium of Altar Valley. Alternatively, the scarp might have been effaced by erosion since the dawn of the Tertiary. And yet, the rather considerable accumulated evidence from the Tucson Mountains does not seem to require the former presence of such a "lost Atlantis." At present it appears visionary and unnecessary to postulate such a source for the chaos blocks.

LACK OF ALTERATION OF THE LIMESTONE

At most places the limestone in the chaos is little altered. Boulders as much as six or eight feet through, and apparently completely marbleized, have been found in Trail's End Wash. As a rule, however, only a thin shell of incipient marbleization is present, or there may be a marginal bleached zone eight or ten inches thick. Commonly the edges of the blocks appear to have been shattered and partly rehealed. Evidence of silication appears to be lacking, except in the area north of the Museum Embayment.

If the blocks have been lifted from depth by intrusive magma it would seem that signs of contact metamorphism should be common. In fact, the surprising freshness of these huge fragments is perhaps the greatest obstacle to acceptance of intrusive emplacement. It is not necessary to suppose, however, that any of the blocks we see today were in contact with molten magma throughout their upward journey. That journey may have been relatively short and during much of it the limestone could have been shielded by rock which was finally converted to rubble.

North of the Museum Embayment some limestones, apparently completely enclosed in Amole Latite, seem to be quite unaltered except for incipient marbleization. Others in the same situation are largely silicated. Perhaps the silicated blocks were altered at depth before emplacement; possibly the metamorphosed masses once formed protecting rims around cores now represented by little altered blocks; or the silication may not result from contact with the magma alone but may depend upon the temperature, pressure, volume and composition of fluids which gain access to the limestone. Other factors, such as the purity or impurity of the included mass, may also play a part. In any case, the presence of nearly fresh blocks in the latite indicates that limestone can be in contact with magma, at least for a limited time, without becoming strongly altered. Accordingly, the surprising lack of silication in the limestones throughout most of the chaos may not be compelling evidence against emplacement by igneous action.

REGIONAL PATTERN OF BLOCKS

As already mentioned, the limestones in the northern part of the range (Fig. 4) are arranged in several parallel, northwest-trending zones, and they form a fringe along the southwest margin of the Cat Mountain Rhyolite. In this fringe many of the blocks are oriented parallel to the edge of the rhyolite, and beyond the northwest end of this border strip the orientation is continued into the nearly west-trending zone of blocks south of Wasson Peak. This pattern of crossing trends is distinct enough that it must mean something.

In the northernmost of the nearly west-trending zones, the individual blocks are so nearly parallel that it is easy to imagine them as remnants of several parallel, gigantic slabs. Dips are steeply northward, so the slabs may have been tilted northward and dismembered by the intrusive andesite. The same may apply to other block chains farther south, but in the nearly west-trending Sweetwater Drive swarm, the individual blocks are apparently disarranged. This condition may result, at least in part, from interference by the already-mentioned northwest trend, and perhaps by other trends. The "basement" limestone strata, forced upward by magma insertions, may have yielded on a pattern of intersecting fractures. Master fissures with nearly west trend seem to have determined the orientation of the belt as a whole, but within the swarm some slabs may have broken along northwest-trending fractures, to be lifted, tilted back, and dismembered. The same might have happened along fractures with other trends, such as northeast and north.

The vertical distribution of the blocks is of more than passing interest. In the vicinity of Wasson Peak the lowest exposed limestone, near Sweetwater Drive, is at an elevation of about 2,650 feet. The highest one, near the summit of Wasson Peak, is at nearly 4,300 feet. Thus the blocks are distributed throughout a vertical interval of more than 1600 feet. Moreover, they are fewer and smaller at the higher elevations, as though they were broken up and perhaps in part dispersed or assimilated en route. Quite possibly so thick a pile could accumulate by erosion of a lofty scarp, but if so, it is not easy to understand why the matrix is mostly igneous throughout (Amole Latite and andesite).

I would tentatively suggest, pending further information, that the pattern of block distribution (Fig. 4) was engendered by the rise of magma on a network of intersecting channels or fissures. In this network fissures with nearly west trend were dominant at many places, but fractures with other trends were locally important. I see no need to postulate an unknown source for these blocks. They appear to have been pried loose from the Paleozoic floor, tilted, lifted, dismembered and left as remnants, mostly in the intrusive volcanics but also in the Amole Arkose.

CONCLUSIONS

Many observations made in the Tucson Mountains during the past 12 years suggest the following.

(1) Evidence of the presence of the Tucson surface on the south slope of Cat Mountain is weak and inconclusive. Such a surface was inferred, not demonstrated, at that place.

(2) Detailed study now in progress on the west slope of Bren Mountain has so far failed to reveal the slightest evidence of a Tucson surface. In fact, the new observations appear to preclude such a feature.

(3) At Trail's End Wash, if the Tucson surface once existed, all direct evidence of it has been destroyed. Limestone clasts in coarse-grained sandstone, found only very near the big blocks, are evidence of attack by the activated sandstone on the blocks. They are not indirect evidence of a regional erosion surface.

(4) The intensity of folding and the trends of fold axes vary greatly from place to place, and the tightest folds are seen to be marginal to intrusions or to foci of eruption. Lateral compression does not appear to be a satisfactory explanation of this condition, but it might be explained as a result of upheaval, collapse and related gravitational adjustments.

(5) The Tucson Mountain chaos seems to have been derived from below, rather than from above. If this was the case, then the chaos is not a stratigraphic unit in the usual sense.

(6) A high source for the chaos blocks has been postulated along the western edge of the range, but Paleozoic formations represented in the chaos do not correspond to those now exposed in remnants of the postulated source. Further, the few available observations do not suggest a continuous structural and topographic high along this western margin.

(7) The lack of strong alteration of most of the limestone blocks is a serious, but perhaps not fatal, obstacle to acceptance of emplacement by igneous action. At some places the blocks are strongly silicated; other limestones, known to have been immersed in magma, are little altered.

(8) The regional arrangement of chaos blocks suggests control of emplacement by a network of intersecting fractures.

(9) There is still an immense amount of field work to be done. More structural data and more age dates are badly needed, and petrographic studies would be very helpful. With continued effort we might eventually understand this small, readily accessible mountain range. Such an understanding will not come about through repeated assertion. Dogmatic assertion is a poor substitute for detailed observations and measurements.

Finally, it should be realized that this paper is concerned with certain phenomena in the Tucson Mountains only. It seems reasonable to expect that the features found in these mountains will be repeated in some of the other ranges, but I have no knowledge of those more distant places.

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