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PROGRESS REPORT ON THE MOGOLLON PLATEAU VOLCANIC PROVINCE, SOUTHWESTERN NEW MEXICO: NO. 2*

by

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INTRODUCTION

In 1968 we published the first progress report on our efforts to unravel the geology of the Mogollon Plateau volcanic province. In this article we will briefly review our present knowledge, stressing progress since 1968. The contributions of Merritt J. Aldrich, Edmond Deal, Ronald Fodor, Glenn A. Krimsky, Douglas H. Krohn, and Eugene I. Smith, present or former graduate students at the University of New Mexico, are gratefully acknowledged. Much new information has been made available by members of the U.S. Geological Survey, which is evaluating potential mineralization of wilderness and primitive areas; the work of James C. Ratté, David L. Gaskill, George Erickson, Helmuth Wedow, and Gordon P. Eaton has been especially significant. Cooperation with Paul E. Damon, University of Arizona and Michael Bikerman, University of Pittsburgh has resulted in invaluable K-Ar radiometric dates and with David Strangway, University of Toronto, has gone a long way toward establishing a record of mid-Tertiary magnetic reversals.

VOLCANIC STRATIGRAPHY

The outline given in 1968 is essentially undamaged, but many details have been added. Only a broad outline can be given here; unit-by-unit description would fill a bulletin-size publication.

The volcanic rocks included on the Geologic Map of New Mexico (Dane and Bachman, 1965) as Datil Formation actually consist of at least three major eruptive cycles, each consisting of mappable units from different centers. In general, each cycle proceeds from andesitic flows to quartz latite and rhyolite lava flows and pyroclastic rocks, especially ash-flow tuffs, to dark-colored rocks ranging in composition from high-alkali, high-silica basalt (basaltic andesite) to quartz latite. There are many complications to this sequence and capping basaltic andcsite of one cycle may be identical with, or indistinguishable from, the basal andesites of the next. Until a better terminology evolves, rocks coeval with the first cycle, which includes the type section of the original Datil Formation of Winchester (1920) in the Bear Mountains, Socorro County, will be called Datil (restricted sense) and all three cycles Datil (broad sense).

*UNM Contribution to Planetary Geology No. 11.

VOLUME OF VOLCANIC ROCKS

Volume of the entire Datil (broad sense) is of the order of 10^4 km', over an area of about 18,000 km^2 (7,000 $miles^2$). If subsurface parts of the volcanic complex are considered the value may be as much as one order of magnitude greater.

AGES OF VOLCANIC ROCKS

The radiometric K-Ar ages of the three cycles can now be established at 29-38+ m.y., 23-27.5 m.y., and about 20.6-22.4 m.y., respectively. The main phase of Basin and Range faulting occurred between 20 m.y. and 6 m.y. and was accompanied by basaltic volcanism. Rhyolite ash occurs interbedded in Gila Conglomerate, sediments shed from rising fault blocks, and some of it seems pyroclastic rather than epiclastic, but its sources are unknown. Details of radiometric age dates are available in Elston, Bikerman and Damon (1968) and Elston and Damon (1970).

VOLCANIC SUBPROVINCES AND THEIR STRUCTURAL CONTROL

The volcanic rocks of the Mogollon Plateau are sharply divided into eastern and western subprovinces by a line that can be projected northward from the Santa Rita-Hanover axis (Fig. 3). The Santa Rita-Hanover axis is a Cretaceous structural high that controls, or is controlled by, the Santa Rita stock, the Wimsattville Basin, and the Hanover-Fierro stock. On the southern face of the Pinos Altos Mountains the reason can be seen. The Hanover-Fierro stock was a topographic barrier during eruption of the Kneeling Nun and Tadpole Ridge Quartz Latites, more or less contemporaneous members of the first Datil (broad sense) cycle that erupted from sources, respectively, to the southwest and northeast. They butted up against the bar-

rier, but did not override it. Intravolcanic gravels appear to be gravels shed by the barrier. Whether the dividing line between the eastern and western provinces is the northward subsurface continuation of the Santa Rita-Hanover axis is a matter of highest practical importance. The Santa Rita-Hanover area is the most richly mineralized district yet discovered in New Mexico. A possible extension of its controlling structure under volcanic cover for tens of kms is an exciting but unproved possibility. Merritt J. Aldrich and Douglas H. Krohn are investigating the problem by geologic and geophysical techniques respectively. Preliminary results are sufficiently encouraging to justify continuation of the work.

Whatever the nature of the barrier that divides the eastern and western volcanic subprovinces, it continues north to about Beaverhead. West of Pelona Mountain and on both sides of the San Augustin Plains rocks of the two subprovinces intermingle. Isopachs on, and fluidal textures of, a porphyritic andesite mapped by Stearns (1962) as Tda,, indicate northward thickening and movement toward the San Augustin Plains. In other words, there is evidence of a topographic low at the approximate site of the San Augustin Plains as early as mid-Tertiary time, long before the Quaternary age assigned to the border faults and most of the sedimentary fill of the present plain. Similarly, the Santa Rita-Hanover axis shows that north-trending structures existed in Late Cretaceous time, long before the onset of north-trending Basin and Range faulting of the Black Range and Rio Grande trough to the east.

GEOLOGIC STRUCTURE

The interpretation of the Mogollon Plateau as a ring-dike complex at a moderate erosion level, given in our 1968 article and earlier by Elston (1965 a and b) remains unchanged: (1) a roughly circular mountainous rim with a triangular, or deltoid, mountain system attached to the southeastern end, (2) an outer graben system surrounding the rim, (3) an inner basin drained by headwaters of the three forks of the Gila River (Fig. 1) and (4) a central peak, Black Mountain, a stratovolcano of basaltic andesite with summit caldera, formed at the end of the third volcanic cycle.

Recent work by Ratté and others (1969) has resurrected the possibility of a second fault-controlled mountainous rim, outside the graben system. This thought first occurred to one of us (Elston) in 1965 when the Mogollon Plateau was described as having a diameter of 90 miles (150 km). This figure included the Big Burro, Pinos Altos, Cuchillo, San Mateo, Magdalena, Gallina, and Datil Mountains. Lack of evidence for any structural connection of these ranges with the rest of the Mogollon Plateau relegated this idea into limbo and reduced the size of the Mogollon Plateau to 75 miles (125 km). However, Ratté and others mapped an arcuate fault system concentric with the west side of the Mogollon Plateau in the Blue Mountain Primitive Area near the New Mexico-Arizona line. Their discovery has raised again the problem of the actual extent of the province.

The polygonal-to-arcuate outline of the Mogollon Plateau within the graben system is controlled by a system of faults, and modified by intrusive-extrusive complexes of flow-banded rhyolite and pumiceous tuff. The flow-banded rhyolite bodies constitute the ring-dike complex. Where they erupted to the surface, thick but fairly local flows formed under a breccia carapace. Intrusion seems to have caused arching of the mountainous rim of the Mogollon Plateau. Where preserved, the rim is an asymmetrical anticline which dips steeply outward and gently inward toward the inner basin (Figs. 3, 4). Figure 3 does not give a true picture of the outcrop areas of arcuate intrusions because they are covered by younger rocks over large areas. Each of the three major volcanic cycles contributed flow-banded rhyolites which in general become younger toward the interior of the Mogollon Plateau.

Our latest work has thrown new light on the role of flow-banded rhyolites: structurally, there appear to be two major types: (1) those that form the framework of the entire structure, and (2) those that surround individual cauldrons (Rhodes, 1970). Examples of the first, or framework type are, in the first cycle the Mimbres Peak Rhyolite (Fig. 2, col. VI), and in the second cycle, the Fanney Rhyolite (Fig. 2, col. IV), and possibly the Taylor Creek Rhyolite (Fig. 2, col. VII), and a pre-Taylor Creek rhyolite, as yet unnamed, that occurs in the eastern circumference of the structure. No flow-banded rhyolite in the framework of the Mogollon Plateau has yet been identified as belonging to the third cycle but there are a number of undated rocks of this type, especially in the northeastern quarter. The second, or cauldron, type occurs around the periphery and in the central domes of ash-flow cauldrons and chemically resembles the ash-flow tuffs which erupted from the cauldrons. They are described in the discussion of individual eruptive centers.

The distinction between the two types is not always clear. The Fanney Rhyolite, a framework unit, also forms part of the rim of the Bursum cauldron. The Jerky Mountain Rhyolite (Fig. 2, cols. II and III, Fig. 3) rims the eastern side of the source cauldron of the Bloodgood Canyon Rhyolite, which it resembles chemically and mineralogically but it also forms the framework of the northern margin of the Mogollon Plateau (Fig. 3). Evidently, fractures that control either the overall framework or individual cauldrons locally were conduits for either or both types of rhyolite. The Jerky Mountain Rhyolite forms a tongue between Willow Creek and Black Mountain and trends westerly across the western side of the inner basin and could, possibly, be an elongated and off-center resurgent dome for the entire Mogollon Plateau (B in Fig. 3). If it is, in fact, part of a resurgent dome, the graben within it could be a sector graben.

In general, the flow-banded rhyolites surrounding cauldrons contain more phenocrysts than those that form the outer framework. Chemical and structural affinity to a known ash-flow sheet is their chief characteristic. The relationship of the crystal-rich Taylor Creek Rhyolite to the ash-flow tuffs has not yet been established.

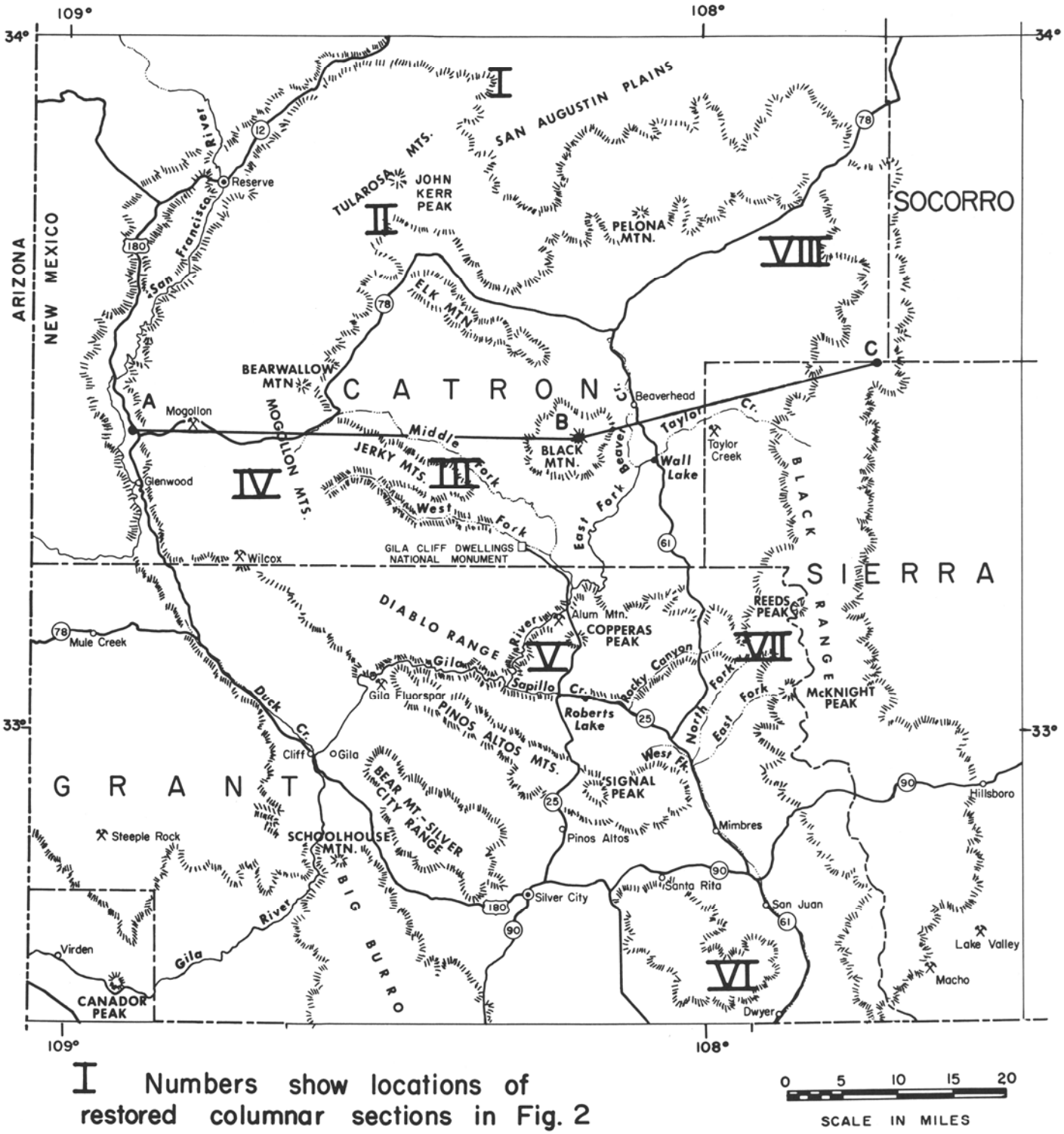


FIGURE 1.
Index map of the Mogollon Plateau volcano-tectonic complex.

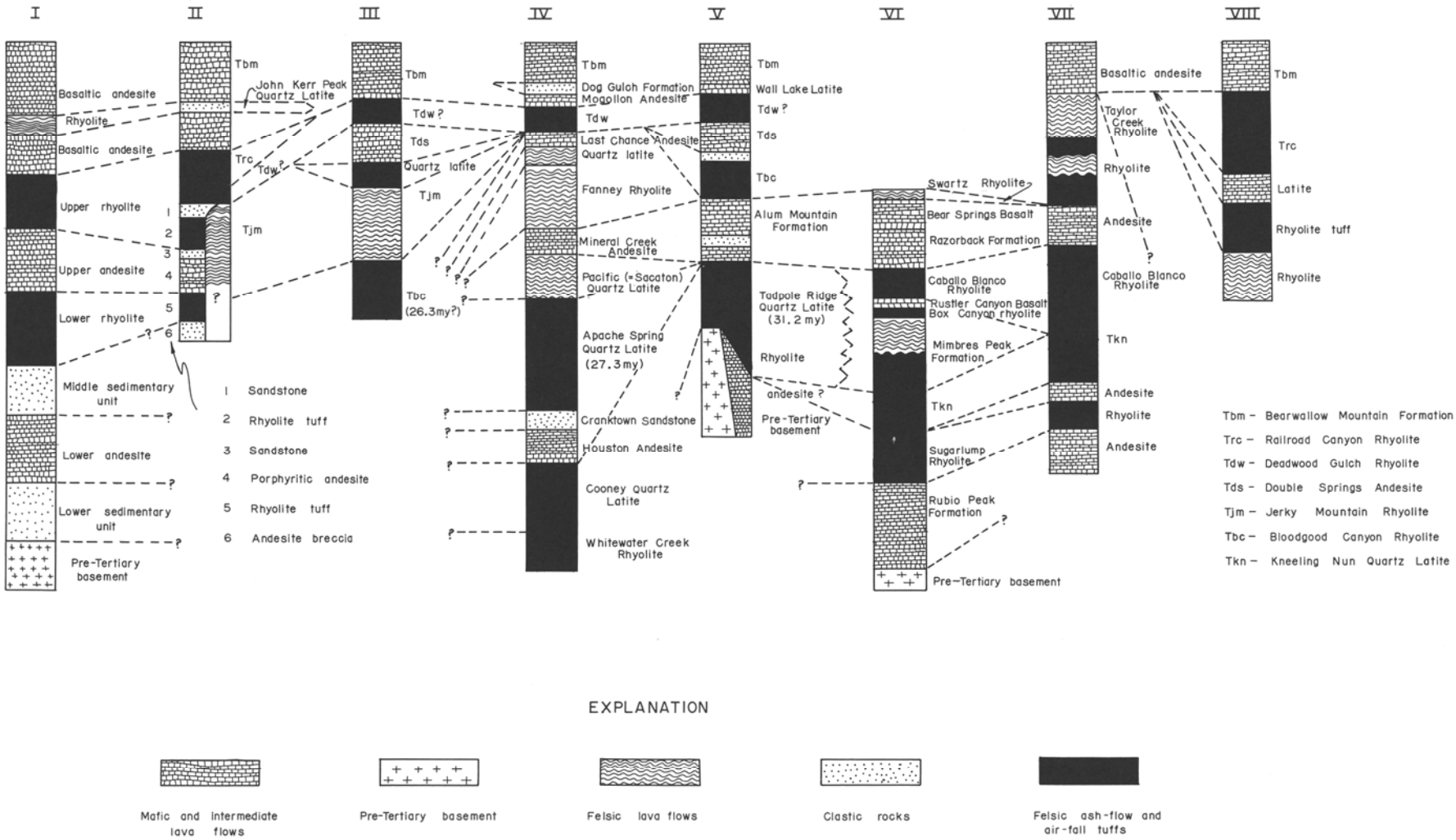


FIGURE 2.

Stratigraphic Correlation Chart of Tertiary Volcanic Rocks in the Mogollon Plateau Volcanic Province. Sources of Data: Column I—Stearns (1962); Column II—R. C. Rhodes and E. I. Smith (unpublished data); Column III—P. J. Coney (unpublished data), W. E. Elston (unpublished data); Column IV—Ferguson (1927), Rhodes (1970); Column V—W. E. Elston (unpublished data); Column VI—Elston (1957); Column VII—W. E. Elston (unpublished data), Erickson and Wedow (in press); Column VIII—W. E. Elston (unpublished data), R. V. Fodor (unpublished data).

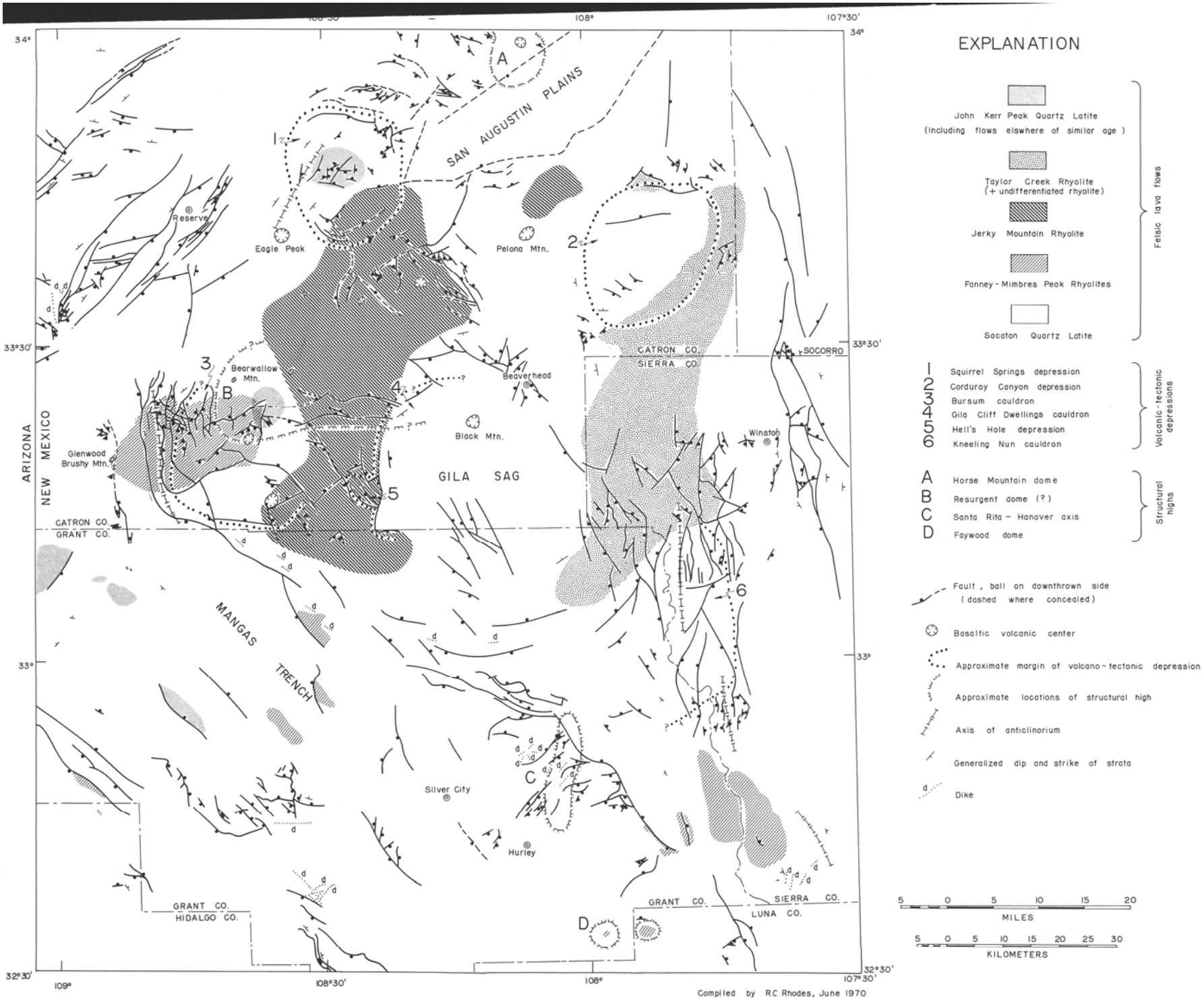


FIGURE 3.
Preliminary Volcano-Tectonic Map of the Mogollon Plateau Volcano-Tectonic Province.

SECONDARY ERUPTIVE CENTERS

According to the interpretation given here, the Mogollon Plateau is a master structure of volcano-tectonic origin. Presumably, upwelling magma of the framework rhyolite caused arching of the rim, and withdrawal of magma from below caused sagging of the inner basin and, possibly, subsidence of the outer graben. Most of the volcanic rocks, by volume, however, came from secondary vents superimposed on the main structures. They range in size from cinder cones a few hundred meters across to 25 km ash-flow cauldrons.

First Datil Cycle.—For rocks of the first Datil (broad sense) cycle, a major ash-flow vent, the source of the Kneeling Nun Quartz Latite, was discovered in the southern part of the Black Range by Kuellmer (1954). Recently, Erickson and Wedow (in press) extended the source cauldron of the Kneeling Nun Quartz Latite farther to the north. Its actual rim is not well-defined because much of it appears to have been eroded off the escarpment of the Black Range to the east and covered by younger rocks to the west. Great masses of flow-banded rhyolite in the northern part of the Lake Valley quadrangle (Jicha, 1954) and the northeastern corner of the Dwyer quadrangle (Elston, 1957) may form the southern cauldron wall. This possibility is supported by the sporadic distribution of the Kneeling Nun to the south. The flow-banded rhyolites were assigned to the Mimbres Peak Formation as one of the framework rhyolites. Actually, the rocks designated as Mimbres Peak Formation in this area are far thicker and more complicated than at the type section, west of the Mimbres Valley. They include crystal-rich as well as crystal-poor varieties; thicknesses are as great as 3,000 feet (1,000 m) and dips up to 70° have been measured in waterlaid pumiceous tuff. Clearly this area needs more detailed work.

Second Datil Cycle.—The Black Range appears to be the source area of at least some of the ash-flow tuffs of the first Datil (broad sense) in the southeastern part of the Mogollon Plateau, east of the Santa Rita-Hanover axis. The Caballo Blanco Rhyolite increases in thickness and number of cooling units toward the Kneeling Nun vent zone.

The Datil (restricted sense) of the type section is still illdefined. Winchester's type section is incomplete. The most detailed published description of a section close to the type locality is that of Givens (1957), who accepted the basal Spears Member and median Hell's Mesa Member of Tonkin (1957) and divided the Hell's Mesa Member into eight units. He disputed (p. 18) the *nueé* ardente origin of units of the Hell's Mesa Member and therefore failed to recognize that his Units 3, 4, and 5 were zones of a single cooling unit. His work, of course, was done prior to the publication of the classic paper on zones of ash-flow tuffs by Smith (1960), but other workers in the region were aware of many of the problems summarized by Smith.

Another problem introduced by Givens' subdivision of the Hell's Mesa Member is the inclusion of a basaltic andesite (Unit 6) and a white-to-pink, single feldspar, biotite-poor, ash-flow tuff above the basaltic andesite (Unit 7) that may not belong to the Datil (restricted sense) at all. Also, he missed a purplish-pink crystal-poor ash-flow tuff directly below the basaltic andesite. The upper ash-flow tuffs of Givens' section resemble those of the third, or possibly second, cycle of the Datil (broad sense), while the lower ones are typical of first-cycle rock. In other words, the problem of defining the enigmatic term Datil Formation (or Group) is compounded by the fact that no source is known, that the type-section is incomplete, and that the upper part of the more complete section of Givens (1957) may contain rocks much younger than the lower part. Thickness and degree of welding of the lower part of Givens' Hell's Mesa Member increase toward the Magdalena-San Mateo Mountain region, and that is where the source probably is located. This was confirmed by a study of flow directions by Krimsky (1969) and by the fact that a great swarm of dikes and faults focuses on the same area. Weber (1963) recognized that the Magdalena and San Mateo Mountains had the characteristics of vent zones.

West of the type area of the Datil (restricted sense) on the western end of the San Augustin Plains, Stearns (1962) mapped rocks that appear to be an extension of the Spears and lower part of the Hell's Mesa Member as, respectively, Tda_1 and $Tdrp_1$. In the southwestern part of his area some $Tdrp_1$ looks different from the rest and may be related to the Squirrel Springs depression (Fig. 3, feature 5, see below for description). Currently, Edmond G. Deal, University of New Mexico, is restudying the entire problem of the type Datil and its sources, and so are Charles E. Chapin and students from N.M.I.M.T.

Another ash-flow tuff section of the first eruptive cycle (Datil, restricted sense), the Tadpole Ridge Quartz Latite, occurs in the Pinos Altos Mountains, west of the Santa Rita-Hanover axis. It resembles the undated Cooney Quartz Latite of the Mogollon mining district (Ferguson, 1927) and one of us (Rhodes) has come close to connecting the two sections in the field. Tadpole Ridge and Cooney Quartz Latites, the Whitewater Creek Rhyolite beneath the Cooney and the andesites above it (Fig. 2, cols. IV and V) all have fluidal textures indicating movement from an unknown center to the southwest. The center could be buried under younger rocks or, possibly, the complicated area around Schoolhouse Mountain at the northern end of the Big Burro Mountains, described by Wargo (1959), could be part of it. So far it has not been possible to correlate rocks of the Schoolhouse Mountain area with those of the Mogollon Plateau with any degree of continuity.

The distribution of the andesites beneath the main ash-flow tuffs of the first volcanic cycle is a topic in its own right and is discussed in another article by Elston in this guidebook. The dark-colored "basaltic andesite" above the main rhyolite sequence has at least two known centers: a caldera near Copperas Peak and a basaltic vent marked by bombs on the west side of the Mimbres Valley, a few miles south of San Juan.

In our 1968 report we mentioned two cauldrons that are part of the second Datil (broad sense) cycle: the Bursum cauldron (Fig. 3, No. 3) and the Gila Cliff Dwellings cauldron (Fig. 3, No. 4). The Bursum cauldron is the source of the Apache Spring Quartz Latite ash-flow tuff; the mineralogically similar Pacific Quartz Latite of Ferguson (1927), almost certainly identical with the Sacaton Quartz Latite of our 1968 report, crops out in an are around its

western margin. It is the oldest known map unit that follows the arcuate outline of the west side of the Mogollon Plateau; the associated Apache Spring Quartz Latite has been dated at about 27.3 m.y. In our 1968 report we mentioned that the Apache Spring is essentially confined to its cauldron. Since then, doubt has been cast on the few suspected outliers. In particular, a rock of somewhat similar appearance has been found in the Blue Mountain Primitive Area near the Arizona-New Mexico line, above a moonstone-bearing, ash-flow tuff dated by Paul E. Damon (quoted by Ratté and others, 1969) at 24.9 ±0.7. m.y. It thickens westward toward the White Mountains of Arizona; it is possible that its distal end extended eastward into the Mogollon Plateau. At present, therefore, the Apache Spring Quartz Latite is known only in its source cauldron with any degree of certainty; there it is at least 800 m (2,500 feet) thick. The Gila Cliff Dwellings cauldron is the source of the Bloodgood Canyon Rhyolite ash-flow tuff; the flow-banded Jerky Mountain Rhyolite forms its western margin (Fig. 2, col. III). The Bloodgood Canyon Rhyolite (called Moonstone Tuff by Wargo, 1959) was described in our 1968 report as a sheet that "spilled copiously out of its source cauldron." In another publication in the same year, one of us (Elston, 1968) cited two disparate K-Ar dates : 26.3 ±0.8 and 23.2 ±0.7 years, and concluded that "It is therefore not yet clear whether all rocks tentatively included in this formation did, in fact, originate from a common source in a single eruptive cycle spanning several million years. Since then a profusion of new dates of moonstone-bearing, single-feldspar rhyolites has added confusion: the 24.9 ±0.7 m.y. date previously cited from Ratté and others (1969), and a 22.8 ±0.7 m.y. date from a rock in Railroad Canyon, on State Highway 78 northwest of Beaverhead (Elston and Damon, 1970). The rock in Railroad Canyon definitely is stratigraphically higher than the Bloodgood Canyon Rhyolite; its position above the Deadwood Gulch Rhyolite near Coyote Peak, west of Pelona Mountain, places it in the third volcanic cycle. Unfortunately, the Bloodgood Canyon Rhyolite in the source cauldron has not yet been dated; the 26.3 ±0.8 m.y. moonstone-bearing tuff in the Schoolhouse Mountain area can be traced to the cauldron via intermediate outcrops in the Silver City and Pinos Altos ranges. The existence of at least two moonstone-bearing tuffs in the northern and northwestern parts of the Mogollon Plateau seems established, but there may well be four or more. In our earlier report we correlated a moonstone-bearing, ash-flow tuff near the settlement of Blue in the Blue Mountain Primitive area with Bloodgood Canyon Rhyolite; the radiometric age of 24.9 ±0.7 m.y. reported by Ratté and others (1969) is just within the limit of one standard deviation from Wargo's date of 26.3 ±0.8 m.y. We also tentatively correlated the unit mapped by Stearns as $Tdrp_2$ with Bloodgood Canyon, but the radiometric age of 23.2 ±0.7 m.y. of a rock near Reserve makes this doubtful. We now are uncertain whether $Tdrp_2$ represents rhyolite from an unkown center, Railroad Canyon, Bloodgood Canyon, or a mixture of all of them and perhaps more. To confuse matters further, Ratté and others (1969) described the cauldron fill of the newly-discovered Red Mountain caldera in Arizona as "virtually identical" in appearance to the ash-flow tuff at Blue, although they concluded from trace-element compositions that the units were probably not the same. Krimsky (1969) concluded the same from flow-direction studies, but he recognized that his data were somewhat ambiguous. Unfortunately, all of the units have reverse remanent magnetism. The petrologic reason for the proliferation of moonstone-bearing tuffs and the difficulties in distinguishing between them is fairly simple: no matter what the composition of the source magma might have been, all differentiation trends lead to the same residuum, provided that Ca is low (which it is) and physical conditions of the magma chamber about the same.

At present the actual distribution of the Bloodgood Canyon Rhyolite outside the source cauldron remains unknown; as far as we can judge, it spread to the south and west and possibly elsewhere.

In 1968 we knew little about the second volcanic cycle east of the Santa Rita-Hanover axis. The tin-bearing Taylor Creek Rhyolite has now been dated at 24.0 ±0.5 m.y. near the end of the second cycle. The relationship of this phenocryst-rich arcuate complex of domes, linear vents, flows, and breccias to the Gila Cliff Dwellings cauldron or to the source area of the underlying moonstone-bearing, ash-flow tuffs (2 in Fig. 3) remains unknown. The great mass of crystal-poor, flow-banded "framework" rhyolite, traced from the junction of State Highway 61 and Rocky Canyon to the Taylor Creek area remains undated; it is older that both the Taylor Creek Rhyolite and the underlying ash-flow tuffs and not related to any known cauldron.

South of the Mogollon Plateau the single dome complex of Swartz Rhyolite (Elston, 1957) remains the sole representative of the second volcanic cycle in the Mimbres Valley. The Red Mountain caldera of Ratté and others adds another small (about 5 km) cauldron to the list of known vents of the second volcanic cycle. No vent for the andesitic or basaltic rocks of the second cycle has yet been identified. In the Mogollon area they seem to have flowed from the southwest.

Third Datil Cycle.—The stratigraphy of the third volcanic cycle is slowly being unravelled, but the vents are still in doubt. The basal sediments and the Deadwood Gulch Rhyolite, a pumiceous poorly welded ash-flow and ash-fall tuff characterized by poor welding, low phenocryst content, and weak normal remanent magnetism, remains the most widespread stratigraphic marker horizon west of the Santa Rita-Hanover axis and its northern extension. It has been traced from its type locality at Mogollon eastward to Beaverhead and south to the junction of the West and Middle Forks of the Gila River. Lithologically similar rock occurs as far west as the Arizona line near State Highway 78. It unconformably overlaps a number of older rocks. A radiometric age of 21.7 ±0.7 m.y. has been reported for a sample collected near Beaverhead.

In spite of its wide extent, the source or sources of the Deadwood Gulch Rhyolite remain unknown. The area of maximum thickness is about 1000 feet (300 m) in the Mogollon Range and also farther east in the Hell's Hole depression (Fig. 3, feature 5). The underlying quartz latite is about equally thick in the Hell's Hole depression (Rhodes, 1970) . This quartz latite has not been definitely identified

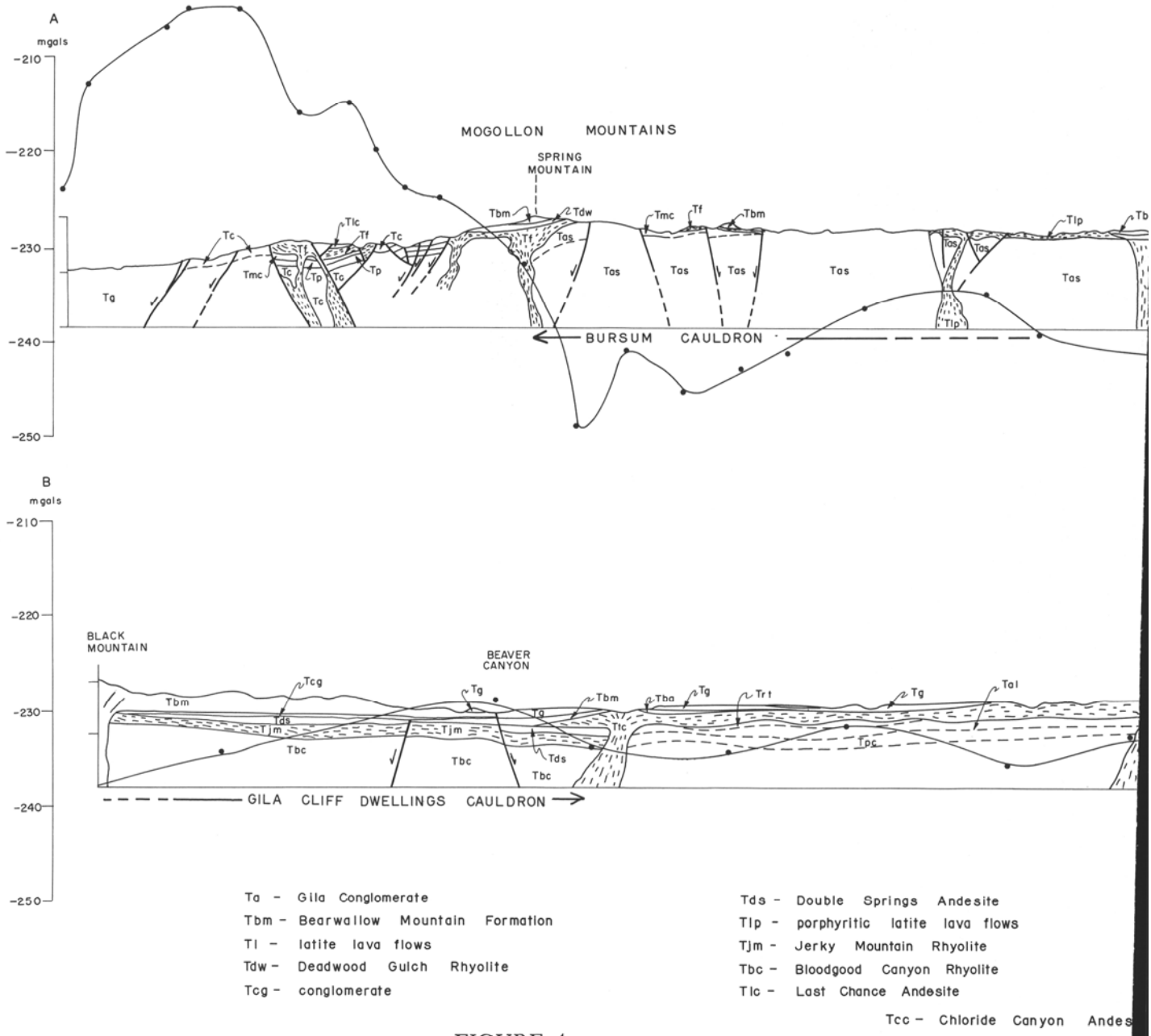
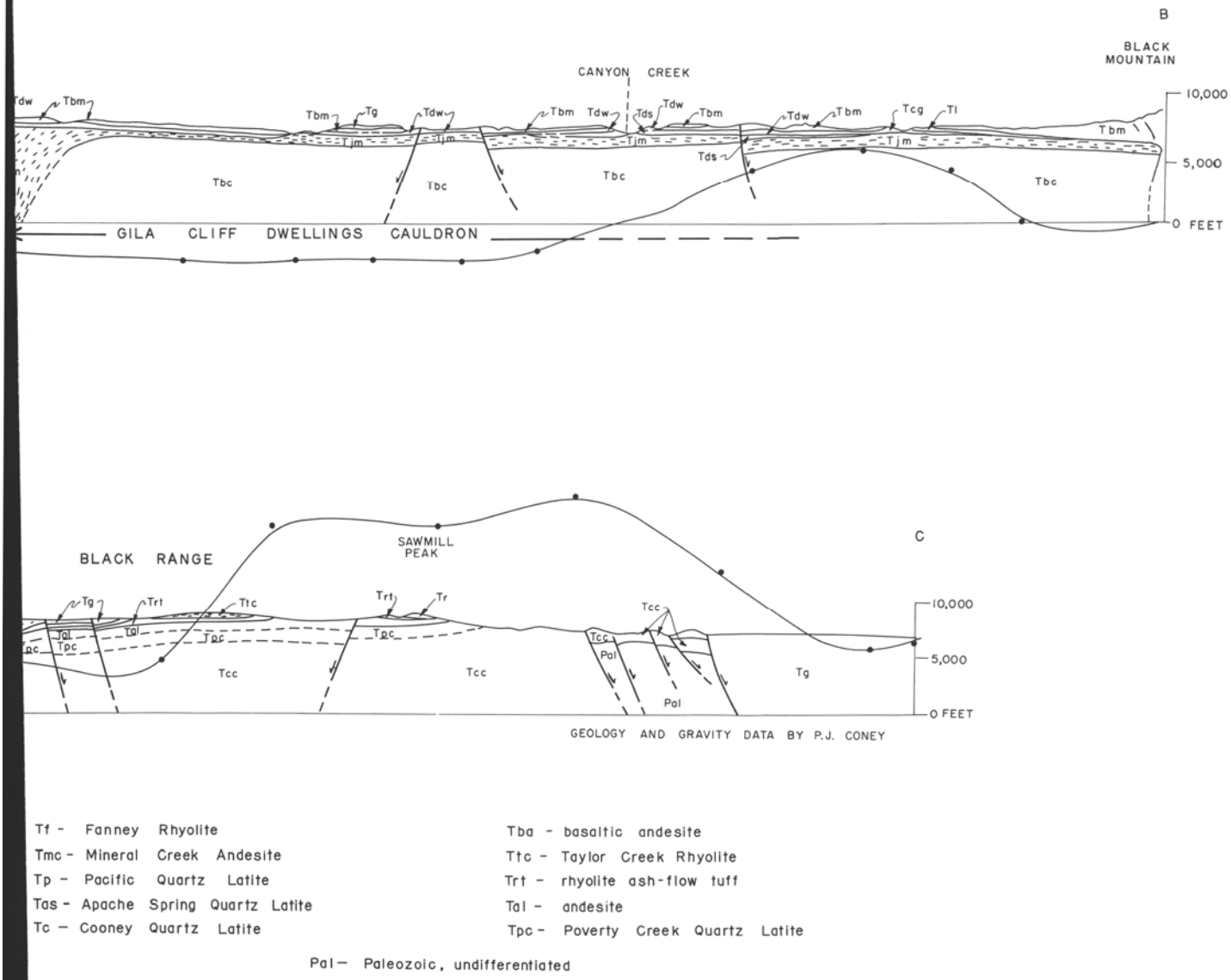


FIGURE 4.
Geologic Cross-section and Gravity Profile Across The Mogollon Plateau, Alon

far from the Hell's Hole depression; possibly the ash-flow tuff which caps Shelley Peak, south of Mogollon Creek, is an outlier. Its absolute age and assignment to the third volcanic cycle are uncertain. Hell's Hole is at the junction of the Bursum and Gila Cliff Dwellings cauldrons, undoubtedly a much-fractured area favorable for the eruption of later rocks. As yet, however, there is no direct evidence that it is a vent zone and not merely a filled-in topographic depression.

Another possible source cauldron is the Squirrel Springs depression (Fig. 2, col. I and II, fig. 3, No. 1) recently mapped by one of us (Rhodes) and Eugene I. Smith. It has many characteristics of a cauldron: polygonal marginal fractures, pronounced negative gravity anomaly according to work by Douglas H. Krohn, and a central dome complex of John Kerr Peak Quartz Latite (new name). The domes were mapped in detail by Smith (1970), who also determined the age of the John Kerr Peak Quartz Latite as 21.4 ±1.1 m.y. by the fission-track method. Unfortunately most of the Squirrel Springs depression is flooded by later basaltic andcsite of the Bearwallow Mountain Formation, and it is not known which ash-flow tuff, if any, erupted from it. Possible candidates are the 23.2 m.y. moonstone-bearing, ash-flow tuff sequence traceable from the Tularosa Mountains toward Blue River in Arizona, some rocks mapped as Railroad Canyon Rhyolite ash-flow tuff, some of the rocks



Tf - Fanney Rhyolite
Tmc - Mineral Creek Andesite
Tp - Pacific Quartz Latite
Tas - Apache Spring Quartz Latite
Tc - Cooney Quartz Latite
Tba - basaltic andesite
Ttc - Taylor Creek Rhyolite
Trt - rhyolite ash-flow tuff
Tal - andesite
Tpc - Poverty Creek Quartz Latite
Pal - Paleozoic, undifferentiated

ne ABC in Figure 1. Note: No Terrain Corrections Made on Gravity Data.

designated by Stearns as $Tdrp_1$ in the western side of his map area, and the Deadwood Gulch Rhyolite. Even the stratigraphic correlations shown in Figure 2, columns I and II are tentative. For example, we found a boulder of what appears to be John Kerr Peak Quartz Latite in the Deadwood Gulch Rhyolite near Coyote Peak. If this identification is correct, the Deadwood Gulch Rhyolite is unlikely to be older than John Kerr Peak Quartz Latite, as shown in Figure 2, column 2.

The source of the Railroad Canyon Rhyolite (22.8 ±0.7 m.y. and stratigraphically above the Deadwood Gulch Rhyolite, 21.7 ±0.7 m.y.) is equally uncertain. It reaches its maximum thickness of about 500 feet (150 m) around a roughly circular shallow topographic and structural depression northeast of Beaverhead (Fig. 3, No. 2). Flow directions measured by one of us (Rhodes) and Krimsky (1969) radiate from the depression, which seems to be rimmed by small faults. As yet, however, there is no direct geologic or geophysical evidence that it is a cauldron at all. Ronald V. Fodor, University of New Mexico, is currently working on the problem. Other possible sources for the Railroad Canyon Rhyolitc, as well as for older ash-flow tuffs in the northern end of the Black Range (including the units shown on the eastern end of the structure section in Fig. 4) are in the San Mateo-Magdalena Mountain area.

The Railroad Canyon Rhyolite thins westward from the

shallow depression northeast of Beaverhead. Rocks of similar Ethology and age (23.2 ±0.7 m.y.) over 100 in thick crop out in Tularosa Canyon between the Squirrel Spring depression and Reserve. This section continues westward to just east of Luna. If one placed a constraint of one standard variation on probable K-Ar ages, the true age of the Railroad Canyon Rhyolite would be in the overlap of its age, 22.8 ±0.7 m.y., and that of the underlying Deadwood Gulch Rhyolite, 21.7 ±0.7 years, i.e., 22.1-22.4 m.y. This would place it beyond the age of the rocks of Tularosa Canyon, for which an age of 23.2 ±0.7 m.y. was reported from the upper member but for which no source is known aside from, possibly, the Squirrel Springs depression.

The reason for the confusion caused by the multiplicity of moonstone-bearing tuffs has already been discussed.

While our knowledge of sources for the rhyolites of the third Datil (broad sense) cycle remains unsatisfactory, a number of centers for post-rhyolitc basaltic andesites have been mapped. They include some of the highest mountains on the northern and western rim of the Mogollon Plateau: Luera Peak, Pelona Mountain, O-Bar-O Mountain, Eagle Peak, a small center south of Eagle Peak called the Sheepherder's Baseball Park, Bearwallow Mountain, the side of Willow Mountain drained by Willow Creek, and Mogollon Baldy. Some of the peaks on the Black Range look similar, but no work has yet been done there. On the south side, Brushy Mountain is a possible center. Black Mountain, the peak in the center of the inner basin, is an eruptive center and so are a number of smaller features in the graben zone west of Black Mountain and on Elk Mountain.

Considering their age, around 21 m.y., the basaltic centers have remarkably well preserved details of morphology and internal structures. This is probably the result of the porosity of vesicular and fragmental basalt; rain water seeps into pore spaces, and runoff does not form sheet wash or channels. In contrast to basaltic centers, rhyolite domes erode rapidly once their breccia carapaces are worn off and rarely show signs of primary topography.

Black Mountain and Willow Mountain have calderas, offset from their present crests, filled with andesite. The central caldera or crater of Eagle Peak was intruded by a large plug of platy spherulitic latite, which now forms the highest part of Eagle Peak. Pelona Mountain, O-Bar-O Mountain, and a peak on the western end of Elk Mountain aligned in a WSW trend, are almost identical: olivine basaltic andesite flows dip gently outward from a cratered cone, black scoria and bombs are scattered at the top. The crater is filled with steeply inward-dipping, crudely bedded vent agglomerate of scoria and bomb fragments oxidized to bright red. The vent agglomerate, in turn, is intruded by a somewhat asymmetrical dome of flow-banded, porphyritic, augite-hornblende-biotite latite. While the topography of the basaltic andesite cones is well preserved, the younger porphyritic latite domes in their craters are deeply eroded. The clip of flow bands permits reconstruction of their original shape. These domes, designated Pelona Mountain Formation by Elston (1968), together with the John Kerr Peak dome complex, constitute the last known eruptive phase of the third Datil (broad sense) cycle.

Post-Datil Volcanic Centers—Basalt is interbedded with Gila Conglomerate at several horizons, and at least two small cinder cones are known, one in the Silver City Range and the other east of the Mimbres Valley about 10 miles southeast of San Lorenzo. The age of the Gila Conglomerate of the Mimbres-Sapillo drainage can be bracketed by two whole-rock K-Ar dates: the basaltic andesite of the spillway at Roberts Lake, two thin flows just above the base of the Gila, has an age of 20.6 ±0.5 m.y.; an olivine basalt that caps mesa tops near the village of Mimbres is 6.3 ±0.4 m.y. old. The lower basaltic andesite is faulted and tilted; the upper basalt has dips that need not be much higher than the slope over which it flowed. In effect, these two units bracket not only the Gila Conglomerate but the main stage of Basin and Range faulting.

A low area around Mule Creek, on both sides of State Highway 78, is surrounded by rhyolite domes associated with flows and pumice which intertongue with the lower part of the Gila Conglomerate. The rhyolite is younger than the main basaltic andesite of the area, which probably correlates with the Bearwallow Mountain Formation. A whole-rock K-Ar date for obsidian "Apache tears" of 18.6 m.y. (Weber and Bassett, 1963) is consistent with field relations, in spite of the unreliability of whole-rock dates of glasses. One of us (Rhodes) is investigating the possibility that the low area around Mule Creek could be a post-Datil cauldron. Rhyolite ash-fall tuff is common in the lower part of the Gila Conglomerate.

SUMMARY OF STRUCTURAL EVOLUTION

In spite of the maze of detail that can be added to our 1968 report, the conclusions on structural evolution remain essentially unchanged. The unconformities between the three "Datils" remain. Evidence for the structural unity of the Mogollon Plateau has been strengthened by the tentative recognition of "framework" and "cauldron" rhyolites, by gravity work by one of us (Coney) and by Douglas H. Krohn, and by the aeromagnetic survey by Eaton (1970) .

The Datil (restricted sense) cycle of volcanism (29-38 m.y.) formed the basement on which the Mogollon Plateau was built. One major vent zone, that of the Kneeling Nun Quartz Latite, coincides with part of the eastern side of the Mogollon Plateau; aside from this no major vents of this age have yet been found within the "framework" rhyolites. The Mogollon Plateau as a topographic feature began to form during the second cycle, with the rise of "framework" rhyolites, which include all units shown on Figure 3 except the first-cycle Mimbres Peak Rhyolite and third-cycle John Kerr Peak Quartz Latite. Major ash-flow cauldrons and smaller andesitic centers formed on the inner side of the mountainous rim. This was followed by bevelling, eruption of third cycle rhyolites from centers not yet established but possibly located, in part, on the outer rim. Subsidence of the inner basin, rises of the rim, and subsidence of the outer graben were renewed and continued until about 6 m.y. ago. Great stratovolcanoes of basaltic andesite and related rocks erupted on the rim at the end of the third volcanic cycle, enhancing its height. Another stratovolcano erupted in the center of the inner basin, which was largely flooded by basaltic andesite. A number of small

cinder cones erupted along fracture zones on the basin floor.

The volcanic cycles became progressively shorter and more localized. The first lasted about 10 m.y., beginning at about 38 m.y. ago, the second cycle 5 m.y., and the third about 2 m.y. Basin and Range faulting began about 20 m.y. ago. In the Sapillo-Mimbrcs Valley it had essentially ceased 6 m.y. ago; elsewhere it continues to the present time. Throughout its history, the Mogollon Plateau shed vast amounts of debris in all directions, which has led to a highly confused terminology of Tertiary elastic rocks throughout the region. Many structures show evidence of repeated rejuvenation. Some Basin and Range faults are reactivated Laramide faults. Distribution of volcanic rocks shows a depression near the site of the present-day San Augustin Plains as early as the first volcanic cycle. The Santa Rita-Hanover axis and its northern extension dates back to the Cretaceous but is parallel to the late Tertiary Rio Grande trough.

Time has not permitted analysis of the aeromagnetic maps of Eaton (1970), but even a cursory glance shows the extreme complexity of patterns on the rim of the Mogollon Plateau compared with the surrounding country and inner basin.

One of us (Coney) began a gravity survey in 1968; it is being continued by Douglas H. Krohn, University of New Mexico, and by personnel of the U.S. Geological Survey. It not only confirmed the negative anomaly mentioned in our 1968 report but added an important detail: traverses (such as the E-W traverse in Fig. 4, by Coney) show no important departure from regional values until the first "framework" rhyolite, i.e., the outer part of the postulated ring-dike complex, is reached. Then there is a rapid drop of tens of milligals (up to 60 milligals on data to which Bouguer and free-air corrections, but no terrain corrections, have been applied). Low values continue across the inner basin. This pattern bears no obvious relationship to surface structures and known differences in rock density. Obvious low-density areas, like the gravel-filled Glenwood graben and cauldrons of porous, low-density, ash-flow tuffs, give negative anomalies below 10 milligals, about an order of magnitude less than the anomaly of the structure as a whole. The conclusion is that the negative gravity anomaly within the framework of arcuate flow-banded rhyolite intrusions is not the result of a shallow body of low-density rock, such as pumice or gravel. Rather, the entire Mogollon Plateau is the surface expression of a large pluton, deeply rooted in the crust and upper mantle, having but little density contrast with surrounding rocks. Structural and petrologic reasons for considering the Mogollon Plateau rocks to be largely derived from the mantle were given in our 1968 article and by Elston (1969).

PETROLOGY

In previous publications we referred to the entire volcanic rock suite as calc-alkalic. The alkali-lime index of all available chemical analyses falls slightly on the calc-alkalic side of the boundary between the calc-alkalic and alkali-calcic classes of Peacock (1931). As petrologic work progressed, a more complicated picture emerged. One of us (Elston, 1957) maintained a long time ago that the andesite-rhyolite association and the dark "basaltic andesite" (actually tholeiitic andesitcs to rhyolites) association were not consanguineous. This conclusion, from both petrologic and field evidence, was difficult to prove, because (1) analyses were few, (2) there are statistical weaknesses in accepted systems of petrologic classification, and (3) there are no highly felsic end members in the basaltic andesite association and no mafic end members in the andesite-rhyolite association.

Reevaluation of new chemical analyses, especially by Rhodes (1970) has thrown new light on petrochemistry: (1) the basaltic andesite association follows calc-alkalic trends. (2) The andesite-rhyolite association follows distinctly more alkalic trends. (3) The rhyolitic sequence of the second Datil (broad sense) is more alkalic than the first, and the third more alkalic than the second. (4) Within each cycle successive major ash-flow tuff sheets became more alkalic. (5) The high-calcium, two-feldspar ash-flow tuffs, mostly quartz latites, are zoned; Ca, Ca/Na, and Na/K increase upward and SiO_2, K, and total alkalis increase downward. Mineralogically this change is reflected by an upward decrease in quartz and plagioclase/sanidine, and upward increases in Na in sanicline and Ca in plagioclase. Biotite is ubiquitous, but amphibole and pyroxene appear toward the top. This sequence, documented locally by Giles (1967) as well as Rhodes (1970) has been found elsewhere and interpreted as eruption of a zoned magma chamber, the uppermost felsic parts erupting first. (6) Low Ca, high-SiO_2 rhyolite ash-flow sheets show little or no significant differentiation; their composition is already near the thermal trough of the system SiO_2-$NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O of Tuttle and Bowen (1958). This explains the proliferation of "moonstone tuffs", i.e., single-feldspar, sanidine cryptoperthite-quartz rhyolites. (7) As a workinig hypothesis, "framework" rhyolites that outline the Mogollon Plateau volcano-tectonic complex arc direct differentiates of the deepseated parent magma, which ascended through master fractures. "Cauldron" rhyolites are chemically similar to the mean of the ash-flow tuffs within the cauldrons and probably represent defluidized residues of the source magma of the ash-flow tuffs. As Giles (1967) and other workers have shown, field evidence and thermodynamic equilibrium indicate a shallow source for the cauldrons. They appear to be surface expressions of shallow secondary magma chambers in the upper crust, at a depth of a few km.

A similar conclusion was reached by Branch (1966) for the Triassic volcanic rocks of Oueensland. Branch's terminology is somewhat different from that employed here (Branch used cauldron as a synonym for "volcano-tectonic depression"). (8) The timing of volcanism is not related to any known orogeny, nor is the Mogollon Plateau controlled by any known crustal structure.

ECONOMIC GEOLOGY

The article by Elston (this Guidebook) covers the application of our work to ore deposits. Briefly, structural highs (culminations) on the rim of the volcano-tectonic frame-

work tend to be mineralized and altered. Margins of cauldrons locally arc sites for alteration. The question of the Santa Rita-Hanover axis has already been discussed.

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