



## *Mid-Tertiary magmatism in southeastern Arizona*

M. Shafiqullah, P. E. Damon, D. J. Lynch, P. H. Kuck, and W. A. Rehrig  
1978, pp. 231-241. <https://doi.org/10.56577/FFC-29.231>

*in:*  
*Land of Cochise (Southeastern Arizona)*, Callender, J. F.; Wilt, J.; Clemons, R. E.; James, H. L.; [eds.], New Mexico Geological Society 29<sup>th</sup> Annual Fall Field Conference Guidebook, 348 p. <https://doi.org/10.56577/FFC-29>

---

*This is one of many related papers that were included in the 1978 NMGS Fall Field Conference Guidebook.*

---

## **Annual NMGS Fall Field Conference Guidebooks**

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual [Fall Field Conference](#) that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

### **Free Downloads**

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

### **Copyright Information**

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

*This page is intentionally left blank to maintain order of facing pages.*

# MID-TERTIARY MAGMATISM IN SOUTHEASTERN ARIZONA\*

M. SHAFIQULLAH, P. E. DAMON, D. J. LYNCH and P. H. KUCK

Laboratory of Isotope Geochemistry  
Department of Geosciences  
University of Arizona  
Tucson, Arizona

and

W. A. REH RIG  
Continental Oil Co.  
Denver, Colorado

## INTRODUCTION

Southeastern Arizona is characterized by subparallel north-northwest trending mountain ranges, 5 to 30 km wide, separated by valley floors or alluviated basins. The area lies within the mountain region of the southern Basin and Range province (fig. 1). The Mesozoic and Cenozoic geology of the area is characterized by superimposed deformation, complex structural relationships and localized zones of mineralization. Moreover, it is difficult to distinguish between the effects of different tectonic episodes. Fortunately, the deformational episodes were accompanied by igneous activity, making possible radiometric dating of Tertiary fossil-poor continental deposits. Some of the complex structural-lithologic relationships are partially exposed in fault-controlled, tilted mountain blocks, while others are buried under an extensive cover of Cenozoic sedimentary rocks in the alluviated basins. Margins of the basins and the pediments have become the focus of mineral exploration because most of the exposed deposits have already been found.

This paper deals with the chronology of post-Eocene volcanism and tectonism in southeastern Arizona from 111° 30'W longitude to its eastern border, and from 32° 31' N latitude south to the international border (fig. 2). Some of this data has already appeared in progress reports or other reports of limited circulation. K-Ar ages for 26 samples are listed in Table 1. To facilitate interlaboratory comparison, previously reported K-Ar ages have been recalculated using constants recommended by Steiger and Jager (1977). However, the analytical uncertainties associated with the previously reported samples have not been modified. Our work reassigns geologic ages to several units formerly correlated only by lithologic similarity.

## EPISODES OF TECTONISM

The Basin and Range disturbance, responsible for the formation of the modern landscape of Arizona, is the latest in a series of tectonic episodes that have deformed the region since before the beginning of the Cenozoic era. During the Laramide orogeny, northeast-southwestward directed compression caused folding, thrust faulting and basement uplift (Drewes, 1976, 1978; Davis, 1978). Intermediate to silicic volcanism and plutonism accompanied compression. Many Laramide plutons contain significant disseminated copper-molybdenum mineralization.

The region was quiescent from the end of the Laramide orogeny, 50 m.y. ago, until the beginning of the Oligocene,

about 38 m.y. ago (Damon and Mauger, 1966; Livingston and others, 1968; Damon, 1968; Epis and Chapin, 1975; Gilluly, 1956; Hayes, 1970). Detritus from eroded "Laramide" mountains formed the lower members of the Pantano Formation and other early to middle Oligocene, coarse-grained, clastic deposits found throughout the region.

Since the beginning of the Oligocene, the region has been subjected to three episodes or stages of tectonism (Shafiquallah and others, 1976a; Damon and others, 1978). The first stage, a period of heating and crustal melting, lasted throughout Oligocene time and was characterized by intermediate to silicic volcanism, emplacement of granitic plutons and evolving cauldron complexes. The third stage, the Basin and Range disturbance, encompasses the last 12 m.y., during which thin, brittle crust was rifted. This stage is also characterized by mantle-related basaltic volcanism. Stage 2 covers the 12 m.y. transition between the magmatism of Stage 1 and rifting of Stage 3.

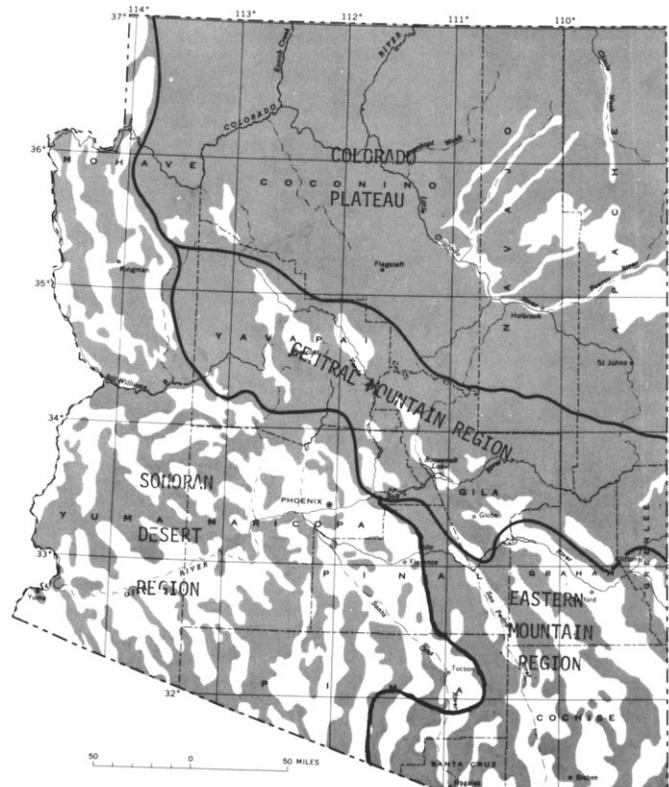


Figure 1. Physiography of Arizona. Mountains and basins are represented by darker and lighter shades, respectively.

\*Contribution No. 816. Department of Geosciences, University of Arizona.

Stage 1 magmatic activity progressed from small eruptions of intermediate composition lavas to massive effusions of rhyolitic ash-flow tuffs over hundreds of square kilometers. Much of southeastern Arizona was blanketed with such flows from eruptive centers in the Chiricahua Mountains (Marjaniemi, 1968), the Tucson-Roskrige mountains (Bikerman, 1968; Eastwood, 1970), the Galiuro Mountains (Creasey and Krieger, 1978) and the Santa Rita Mountains (Drewes, 1972). In the Chiricahua Mountains alone, about 400 km<sup>3</sup> of rhyolitic lavas and ash-flow tuffs were erupted from either cauldron complexes, fissure systems or isolated vents. The Turkey Creek caldera in the Chiricahua Mountains is the best exposed and

SHAFIQULLAH, DAMON, LYNCH, KUCK and REHRIG described of these complexes (Marjaniemi, 1968). This caldera is about 20 km in diameter and contains a sub-volcanic pluton. Coarse-grained, granitic plutons were intruded at many places in southeastern Arizona either before or simultaneously with eruption of ash-flow tuffs. In addition, gneissic core complexes such as the Tortolita-Santa Catalina-Rincon mountains were created or reactivated (Damon and others, 1963; Mauger and others, 1968; Creasey and others, 1977). During Stage 1, the crust was heated in some areas with possible attendant melting and extension. This crustal extension is evidenced by north to north-northwest trending dikes, veins and plutons (Rehrig and Heidrick, 1976) and the inception of low-angle,

Table 1. K-Ar data for mid-Tertiary samples from southeastern Arizona

Sample No.	Sample description and location	Percent K	Radiogenic argon-40 (x 10 <sup>-12</sup> mole/g)	Percent atmospheric argon-40	Age in m.y.
1. RM-2-64	Plagioclase, Turkey Track andesite porphyry, Twin Buttes, Sierrita Mountains, Pima Co. This andesite flow shows pillow structure and a scoriaceous, oxidized surface. The flow is contained within the Helmet Fanglomerate beds, a Pantano equivalent. Lat 31° 57.1' N, Long 111° 04.5' W.	0.70	38.4	56.0	31.37 ± 1.20
2. PED-7-65	Biotite, Pantano tuff, Pantano Wash area, about 1.2 km ENE of Cienega Gap railroad bridge, at an elevation of 1,049 m, Davidson Canyon, Pima Co., Lat 32° 01.4' N, Long 110° 38.1' W.	7.4	388.8 383.6	40.0 27.2	29.47 ± 0.90
3. UAKA-77-61	Whole rock, alkali basalt from the Cloudburst type section. Lower sequence of basic volcanics, upper section of fanglomerates. The section overlies Oracle Granite. The sample was collected approximately 100 m above the unconformity. Cloudburst Wash, Oracle quad., Pinal Co. Lat 32° 42.08' N, Long 110° 45.20' W.	1.49 <sub>1</sub>	73.05 74.38	32.5 31.4	28.30 ± 0.63
4. PED-11-70	Sanidine, biotite-quartz ash-flow tuff interbedded with tilted, imbricated gravels composed primarily of volcanics and Paleozoic rocks. Blake's Spring, Lyle Canyon area, San Ignacio del Babocomari, Cochise Co. Lat 31° 37.27' N, Long 110° 25.27' W.	8.25	401.26	9.2	27.84 ± 0.68
5. UAKA-77-66	Biotite, tuff from Montana Pk. Formation, Montana Pk., Ruby quad., Pima Co. Lat 31° 26.06' N, Long 111° 13.08' W.	6.69 <sub>0</sub>	327.16 328.56	26.6 27.3	27.20 ± 0.60
6. PED-3-69	Plagioclase, Turkey Track Porphyry, overlying the Mineta formation at an elevation of 1,177 m, Mineta Ridge, Redington quad., Pima Co. Lat 32° 20.25' N, Long 110° 29.83' W.	1.17	55.0	79.5	26.92 ± 2.40
7. PED-10-70	Sanidine, unwelded ash-flow tuff within a sequence containing red arkose. The sequence is overlain by thinly bedded, fresh water limestone about 0.48 km east of PED-9-70, San Ignacio del Babocomari Float, Babocomari River, Ft. Huachuca quad., Cochise Co. Lat 31° 38.03' N, Long 110° 26.70' W.	6.25	291.50	10.6	26.71 ± 0.65
8. UAKA-77-62	Whole rock, dacite tuff from the uppermost of the volcanics exposed in the Dobbs Buttes, Viopuli region, Cocoraque quad., Pima Co. Lat 32° 03.05' N, Long 111° 26.08' W.	2.60 <sub>0</sub>	117.4 117.8 115.4	6.3 6.1 7.6	25.65 ± 0.54
9. PED-40-63	Plagioclase, Turkey Track Porphyry intercalated in Pantano beds, where bridge crosses Cienega Creek gap on old Highway 80, elevation 1,024 m, Pima Co. Lat 32° 01.20' N, Long 110° 38.70' W.	0.88	38.33	71.6	24.93 ± 2.60
10. PED-9-70	Whole rock basalt intercalated in a bedded, reddish, arkosic sandstone. San Ignacio del Babocomari Float, Ft. Huachuca quad., Cochise Co. Lat 31° 37.98' N, Long 110° 27.17' W.	1.49	64.62	66.7	24.85 ± 0.97
11. JKP-2-68	Whole rock, basaltic andesite, near bench mark 5177, Cerro Colorado Mountains, Pima Co. Lat 31° 42.82' N, Long 111° 14.9' W.	1.90	79.1	54.5	23.85 ± 0.80

Sample No.	Sample description and location	Percent K	Radiogenic argon-40 ( $\times 10^{-12}$ mole/g)	Percent atmospheric argon-40	Age in m.y.
12. UAKA-76-113	Whole rock, andesite from Nipper Fm. Sample was collected 2.3 road miles on the road to Portal from Onion Saddle. The unit consists of pebble conglomerate, fissile black shales and more massively bedded shales. The shales contain abundant gastropods and fossil wood associated with chert pebbles, Chiricahua Mountains, Cochise Co. Lat 31° 54.3' N, Long 109° 14.5' W.	1.86 <sub>3</sub>	103.6 105.2 101.8	13.3 11.5 15.0	31.77 ± 0.66
13. DM-2-68	Sanidine, rhyolite tuff, grey-pink, poorly-welded. Faraway Ranch Fm., member 3 of lower rhyolite, upper part of the unit, west side of Erickson Ridge, Chiricahua National Monument, Cochise Co. Lat 31° 59.40' N, Long 109° 22.00' W.	8.66	448.3	11.4	29.61 ± 1.69
14. DM-5-67	Sanidine, basal Weatherby Canyon ignimbrite south of Eagle Nest Peak at about 1,500 m elevation (Marjaniemi, 1969). Peloncillo Mountains, Hidalgo Co., New Mexico. Lat 32° 00.12' N, Long 108° 56.80' W.	6.72	316.2	1.7	26.94 ± 0.82
15. DM-6-67	Biotite, basal Eagle Cliffs, rhyolite member, about 0.6 km up NNW trending canyon off Cake Creek, Cave Creek Fm., Chiricahua Mountains, Cochise Co. Lat 31° 53.18' N, Long 109° 11.02' W.	7.20 7.04 7.20	323.2 323.2 343.0	36.4 41.6 34.3	26.42 ± 0.65
16. DM-3-68	Biotite, porphyritic rhyolite dike intrusive into monzonite, in moat volcanics, around resurgent dome of Turkey Creek caldera, Chiricahua Mountains, Cochise Co. Lat 31° 52.87' N, Long 109° 24.25' W.	7.48	331.8	32.3	25.40 ± 0.73
17. DM-1-68	Sanidine, upper part of lower rhyolite, Horseshoe Canyon, 23 m above bottom of Pothole Canyon, Chiricahua Mountains, Cochise Co. Lat 31° 46.03' N, Long 109° 10.38' W.	7.47	325.3	8.7	25.11 ± 1.18
18. UAKA-73-15	Biotite, medium-grained quartz monzonite, Swisshelm stock which intrudes Cretaceous sedimentary rocks, Swisshelm Mountains, Cochise Co. Lat 31° 41.25' N, Long 109° 33.25' W.	7.17	387.6	37.8	30.91 ± 0.77
19. UAKA-73-12	Biotite, from a buff to grey, fine-grained, hypidiomorphic granular granodiorite to quartz diorite. The granodiorite stock intrudes a series of volcanics in the Pat Hills, Dos Cabezas quad., Cochise Co. Lat 32° 00.58' N, Long 109° 37.5' W.	6.90	361.4	33.7	29.96 ± 0.74
20. PED-8-69	Biotite, Jhus Canyon pluton, at an elevation of 1,680 m, in Jhus Canyon, Portal quad., Chiricahua Mountains, Cochise Co. Lat 31° 58.03' N, Long 109° 14.53' W.	7.25	375.0	19.2	29.59 ± 0.90
21. UAKA-73-13	Biotite, granite from Circle I Hills. The granite is intrusive into Precambrian(?) schist, Willcox quad., Cochise Co. Lat 32° 21.35' N, Long 109° 50.31' W.	7.00 <sub>5</sub>	345.3 349.1 355.0	51.0 39.3 38.3	28.43 ± 0.62
22. UAKA-72-67	Biotite, granodiorite, from bedrock beneath large boulders in the canyon bottom SE of Rockfellow Dome, Pearce quad., Cochise Co. Lat 31° 55.23' N, Long 109° 58.10' W.	7.21	294.4	46.3	23.40 ± 0.60
23. UAKA-75-105a	Whole rock, andesite dike, same as UAKA-75-105.	3.44	189.0 189.0 188.7	6.7 6.8 6.4	31.43 ± 0.68
24. UAKA-75-105	Sericite, veinlets in an andesite dike within the Las Guijas alkasite. Attendant quartz veins contain zinc-tungsten mineralization, Las Guijas Mine, Las Guijas Mountains, Arivaca quad., Pima Co. Lat 31° 39.43' N, Long 111° 22.75' W.	9.21	488.1 480.1	12.8 13.4	30.03 ± 0.65
25. UAKA-76-33	Whole rock, basaltic andesite from A Mountain (Sentinel Peak), Tucson Mountains, Pima Co. Lat 32° 12.62' N, Long 110° 59.5' W.	2.63 <sub>9</sub>	112.41 110.55	13.27 13.59	24.20 ± 0.52
26. UAKA-76-31	Whole rock, basaltic andesite from Tumamoc Hill, Tucson Mountains, Pima Co. Uppermost unit of the Tumamoc Hill basaltic andesite sequence. Lat 32° 12.77' N, Long 111° 03.35' W.	2.67 <sub>3</sub>	109.20 111.62	11.25 10.66	23.67 ± 0.51

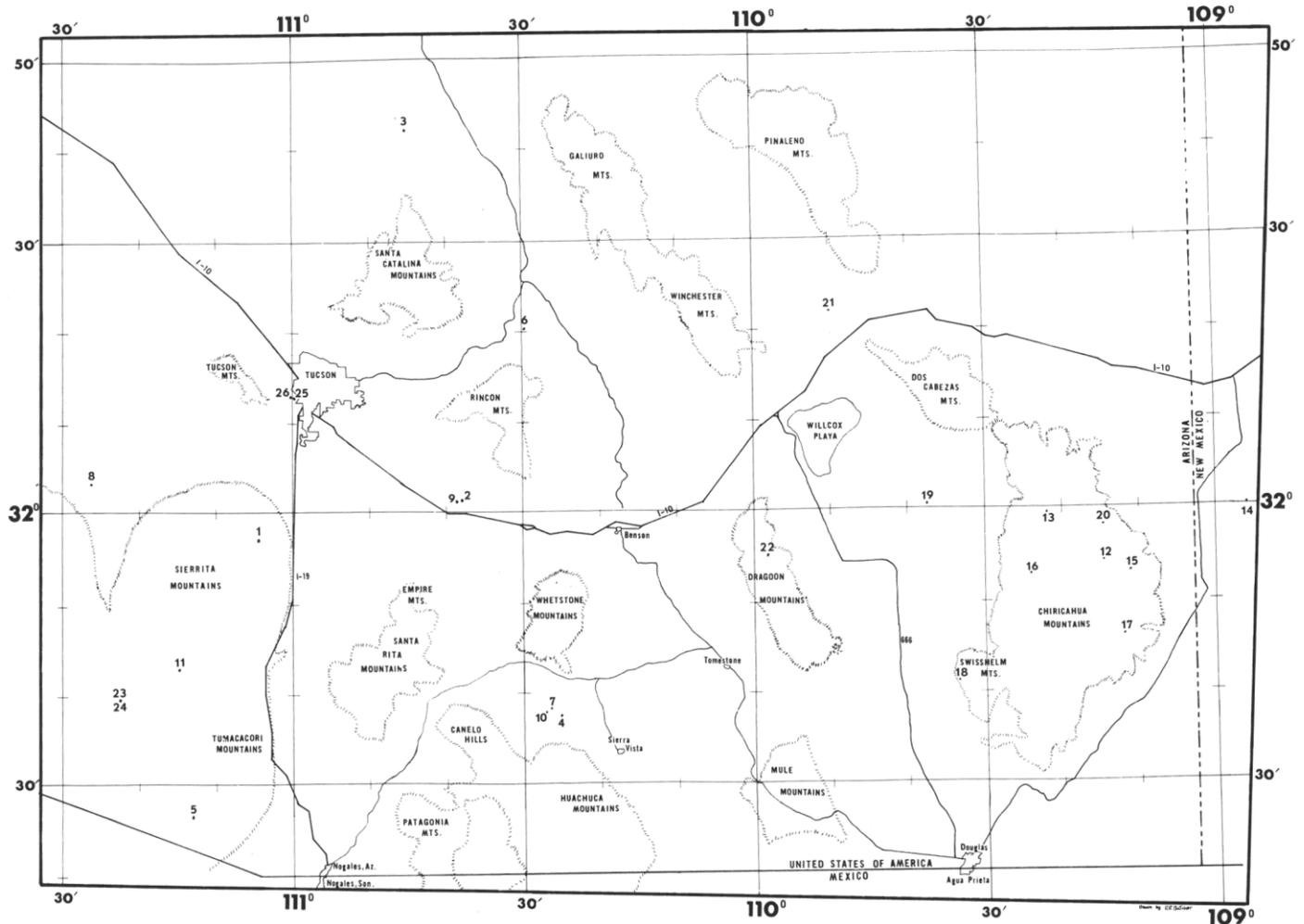


Figure 2. Sample location and index map. Numbers 1 to 26 indicate location of samples listed in Table 1 and referenced in text.

normal faulting of a similar trend. Other structural adjustments during this stage were primarily local, such as the collapse of calderas and the rise of resurgent domes.

Calc-alkaline rhyolite, andesite and doreite (high-potassium basaltic andesite) lavas of Stage 1 will be referred to as the primary RAD clan. Initial strontium isotope ratios for the members of this clan cover a relatively small range suggesting a common parent. The initial ratios of 0.7069 to 0.7096 (fig. 3) are probably too high for these rocks to have been derived and fractionated solely from primitive mantle material (Damon, 1971; Damon and Shafiqullah, 1976). At the same time, the values are too low, and some volcanics are too basic to suggest anatexis of Precambrian sialic basement rocks. In contrast, the totally unrelated Stage 3 basalts have primitive mantle ratios of 0.704 or less, although a few Stage 1 and Stage 2 silica-rich alkali olivine basalts have initial ratios up to 0.7066.

Erosion of Stage 1 uplifts and lava flows added detrital material to coarse-grained sediments already accumulating in broad Stage 1 basins. The poor sorting in these sediments and the angular to subrounded aspect of their larger clasts indicate that the detritus was deposited close to its source. RAD clan lava flows were erupted as the detritus accumulated, adding to the basin fill, and providing useful marker beds for radiometric dating.

The culmination of the massive Stage 1 rhyolite effusions occurred between 30 and 24 m.y. ago (fig. 4). However, felsic lavas continued to erupt sporadically until about 12 m.y. ago, with their composition becoming less silicic with time. During

this transition period, ultra-potassic trachytes (Shafiqullah and others, 1976b) of a secondary RAD clan were erupted at Picacho Peak and other places in southern and central Arizona.

The tectonic styles changed along with the chemical composition of the extrusive rocks. In some localities, horizontal lava flows were tilted to steep attitudes during both Stage 1 and 2 by what appears to be local "thin-skin rotation" in the upper crust. By the end of the transition period, 12 m.y. ago, extension had been established and precursors of the modern basins had formed. In fact, an angular unconformity is found locally throughout southern Arizona between steeply tilted, early Stage 2 rocks, and more nearly horizontal, younger late Stage 2 and Stage 3 rocks (Damon and others, 1973; Eberly and Stanley, 1978). Evidence suggests that much of the crustal extension took place prior to Stage 3, and that crustal rotation was essentially complete 15 m.y. ago.

Only alkali-olivine basalts were erupted during Stage 3. These basalts apparently came from the mantle through cold and brittle crust without significant contamination, forming the San Bernardino and other volcanic fields (Damon, 1971; Lynch, this guidebook). The tectonics of Stage 3 consisted of nearly vertical fault movements with the creation and filling of intermontane basins. The continuity of this stage to the present is clearly established by Holocene fault scarps found in

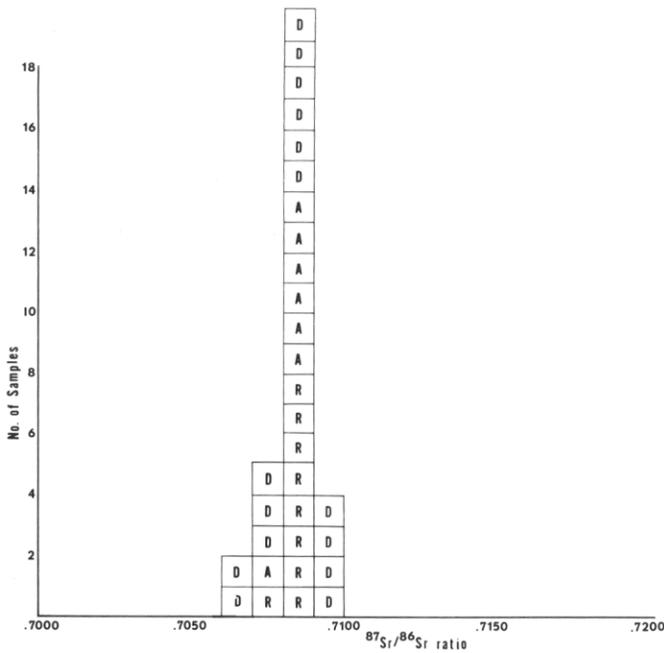


Figure 3.  $^{87}\text{Sr}/^{86}\text{Sr}$  initial ratios for some Oligocene and lower Miocene volcanic rocks (40 to 20 m.y. old) occurring between  $31^{\circ} 30' \text{ N}$  to  $33^{\circ} 30' \text{ N}$  latitude, and  $110^{\circ}$  to  $112^{\circ}$  longitude. Data from Laboratory of Isotope Geochemistry, University of Arizona. R=rhyolite, A=andesite and D=doreite (i.e., potassic basaltic andesite).

some basins. One example is the 5-m scarp formed by the 1887 earthquake on the east side of San Bernardino Valley (Aguillera, 1888; Sumner, 1977).

The transition from silicic to basaltic volcanism during Stage 2 probably represents slow solidification of lower crustal materials (Damon, 1971). Stage 2 was also a time of volcanism in the central mountain and Sonoran Desert regions as shown in Figure 4. Note also the sharp peak of late Stage 1 volcanism (silicic to intermediate rocks) in southeastern Arizona. The Colorado Plateau also has a small late Stage 1 peak of volcanism. In the Sonoran Desert and central mountain regions, the peaks of silicic volcanism are broad and encompass late Stage 1 and early Stage 2, implying that the silicic to intermediate volcanics decrease in age westward. Basaltic volcanism is minor in the eastern mountain region except in the San Bernardino volcanic field. The basalts are widespread along the margin of the Colorado Plateau with the central mountain region, especially in the San Francisco volcanic field around Flagstaff, and in the White Mountains volcanic field of east-central Arizona. Basaltic volcanism also appears to increase volumetrically and becomes younger towards the north, from the Sonoran Desert region to the Colorado Plateau (fig. 4). Stage 3 lavas of the Colorado Plateau and its margins represent the only true bimodal, "fundamentally basaltic" (Lipman and others, 1971) volcanic rocks in the region.

### CORRELATION OF MID-TERTIARY SEDIMENTARY AND VOLCANIC ROCKS

Detritus, eroded from the mountains prior to and during Stage 1, was deposited in local closed basins and was thus limited in areal extent. As the sediments were studied in each locality, they were given separate names. The Helmet Fan glomerate of Cooper (1960), the Mineta Beds of Chew (1962)

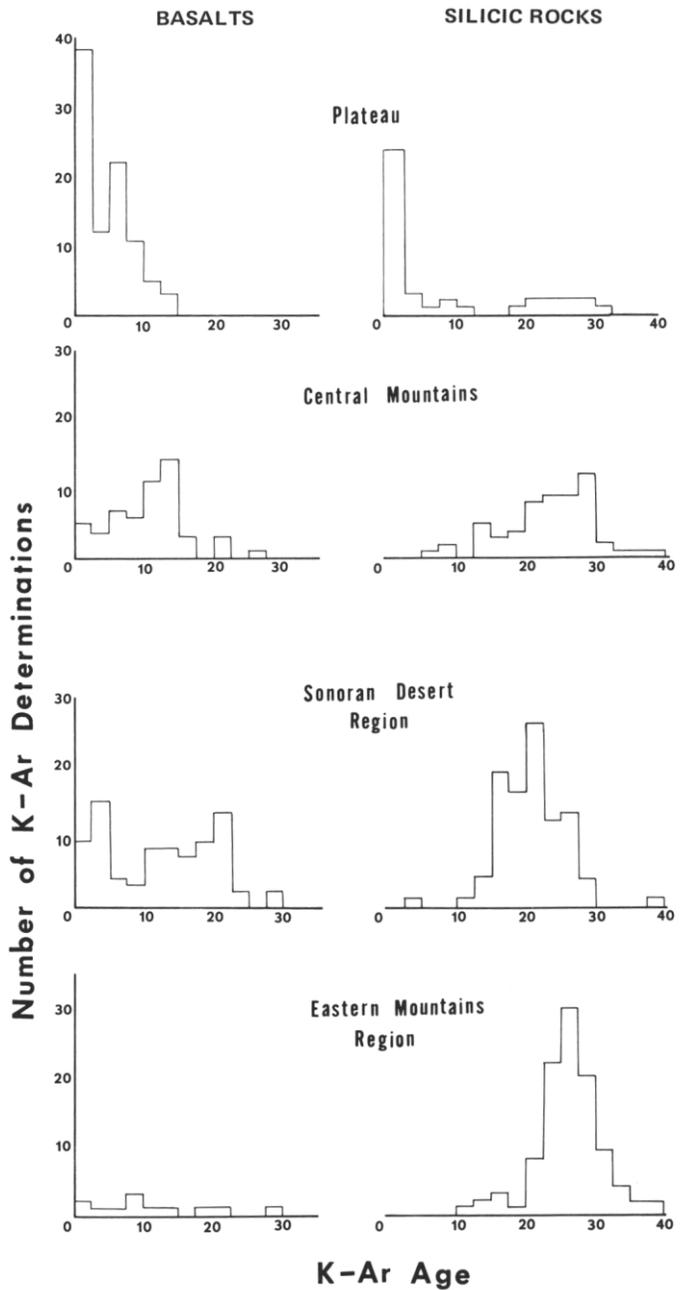


Figure 4. Histograms showing K-Ar ages of volcanic rocks from various physiographic regions of Arizona. Histograms based on both published data from literature and unpublished data from Laboratory of Isotope Geochemistry. Data for samples from the Arizona Strip are not included in the histograms.

and Clay (1970), the Cloudburst Formation (Creasey, 1965a, 1967; Heindl, 1963) and the Locomotive Fonglomerate (Lukanuski and others, 1975), have long been recognized as being equivalent to the Pantano Formation described by Brennan (1962), Finnell (1970) and Moore and others (1941).

Eldred Wilson (as cited in Cooper, 1961) noted the widespread occurrence of a distinctive andesite porphyry having large plagioclase phenocrysts which is interbedded with the Pantano Formation and equivalent gravels. Wilson called this andesite the "Turkey Track Porphyry." The distinctive petro-

graphic characteristics and chemistry of this andesite (Halva, 1961; Mielke, 1965) suggest penecontemporaneous eruption over large areas of southeastern Arizona. For this reason, Cooper (1961) suggested that the Turkey Track Porphyry is a good marker unit for the late Oligocene. In the type section of the Pantano Formation, there is a  $29.9 \pm 0.9$  m.y. old latite tuff (Table 1, no. 2) and  $24.9 \pm 2.6$  m.y. old flow of Turkey Track Porphyry (no. 9). The Helmet Fanglomerate exposed on the east side of the Sierrita Mountains contains a Turkey Track Porphyry flow with an apparent age of  $31.4 \pm 1.2$  m.y. (rio. 1).

Bikerman and Damon (1966), Damon and Bikerman (1964), Marvin and others (1973) and Marvin and others (this guidebook) have reported Oligocene radiometric ages for flows and tuffs in the Pantano Formation and its equivalents. The extreme lithologic variability encountered within these isolated units indicates that discontinuous basins received sediments from continually changing source areas. Lithologic types vary from algal limestones to coarse fanglomerates containing some clasts exceeding 2 m in diameter (Grimm, 1978; Clay, 1970; Enlows, 1955; Pashley, 1966).

The Mineta Formation (Clay, 1970; Chew, 1962) is a sequence of conglomerate, sandstone, siltstone and limestone found on the eastern flank of the Rincon Mountains. These beds and the underlying Paleozoic and Mesozoic strata dip steeply to the northeast. Tilting of the strata took place prior to extrusion of the Turkey Track Porphyry flows that overlie the Mineta beds. The absence of gneissic clasts within the Mineta beds suggest that the gneisses were not exposed to erosion before the extrusion of  $26.9 \pm 2.4$  m.y. old lavas (no. 6). The basal conglomerate grades to limestone, the upper half of which contains evaporites and siltstones.

Gravel units of the Babocomari Ranch area north of Sierra Vista were assigned to the Pantano Formation because of their lithologic similarities (Vice, 1973; Hayes and Raup, 1968). Three K-Ar ages (nos. 4, 7, and 10) from volcanics intercalated in the gravels range from  $24.9 \pm 1.0$  to  $27.8 \pm 0.7$  m.y. in age, confirming their correlation with the Pantano Formation. An ash flow (Marvin and others, 1973) in Pantano-like gravels, north of the Huachuca Mountains at the Babocomari River, is  $38.9 \pm 1.5$  m.y. old. A 10 m.y. hiatus apparently exists between this intercalated tuff and the overlying Blake's Spring ash-flow tuff of Vice (1973). Bikerman and Damon (1966) noted a similar 11 m.y. hiatus between the Rillito andesite ( $39.4 \pm 1.3$  m.y.) and the Upper andesite ( $28.5 \pm 1.9$  m.y.) in the northern Tucson Mountains. A rhyolitic ash flow (sanidine:  $37.6 \pm 1.7$  m.y.; biotite:  $33.6 \pm 2.6$  m.y.) at Davidson Canyon (Damon and Bikerman, 1964) also appears to be a basal Pantano equivalent.

Basalt flows near the top of poorly indurated, Pantano-like gravels at the northern end of the Tortolita Mountains have K-Ar ages of approximately 21 m.y. Thus, deposition of the Pantano sequence took place over a nearly 20 m.y. time span in the intermontane basins. The Stage 1 basin fill includes thousands of meters of semi-consolidated, variably-sized clastics with some shales, limestones and evaporites. The sequences can be correlated to some extent on the basis of lithologic characteristics, presence of igneous clasts and types of deformation, but they may have different source areas and environments of deposition. The presence of limestones and evaporites indicate lacustrine deposition under arid conditions (see Scarborough and Peirce, this guidebook).

## SHAFIQULLAH, DAMON, LYNCH, KUCK and REHRIG *Reassessment of Lithologic Correlations*

Several coarse clastic units in the region previously thought to be Cretaceous are found to be Pantano equivalent. One of these units is the Montana Peak Formation (Webb and Coryell, 1954) which overlies the Oro Blanco Conglomerate (Fowler, 1938) at Montana Peak northwest of Nogales. The formation consists of andesitic agglomerates, breccias, conglomerates and tuffs with numerous ash layers (Nelson, 1968). The volcanics grade from an andesite near the base of Montana Peak, to a rhyolite at the summit. The Montana Peak Formation has been correlated with Mesozoic rocks (Wilson and others, 1969) such as the Cat Mountain Rhyolite of the Tucson Mountains (Taylor, 1959), the Salero Formation of the Santa Rita Mountains and the Demetrie Wash Volcanics of the Sierrita Mountains (Knight, 1970). Webb and Coryell (1954) considered the formation to be late Cenozoic in age. The biotite from a tuff (no. 5) immediately below the summit rhyolite is  $27.2 \pm 0.6$  m.y. old, confirming the mid-Tertiary age of the formation.

The Cloudburst Formation in the San Manuel-Kalamazoo area of the Black Hills is overlain unconformably by the San Manuel Formation, and overlies both Precambrian Oracle Granite and a Laramide quartz monzonite porphyry. In Cloudburst Wash, more than 1,500 m of the Cloudburst Formation rests in apparent sedimentary contact upon the Oracle Granite. The formation consists of interbedded gravels and volcanic flows ranging in composition from basalt at the base to latite near the top. Heindl (1963) considered the Cloudburst Formation to be a Pantano equivalent, while Creasey (1965a, 1967) suggested that it may be late Cretaceous to early Tertiary in age. The  $28.3 \pm 0.6$  m.y. age of the basalt (no. 3) confirms the Cloudburst Formation as mid-Tertiary.

The nearly cylindrical San Manuel-Kalamazoo porphyry copper orebody has been diagonally offset by the San Manuel fault (Lowell, 1968; Lowell and Guilbert, 1970). The fault has also displaced the overlying Cloudburst Formation. This post 28 m.y. fault movement may have occurred as the result of the uplift and doming of the Rincon-Santa Catalina-Tortolita gneissic core complex and could be contemporaneous with movement along the San Xavier fault (Cooper, 1960, 1973; Creasey and Kistler, 1962; Shafiqullah and Langlois, this guidebook). The gold, silver and lead mineralization in the Mammoth-St. Anthony mine is associated with oxidized veins in rhyodacite or rhyolite bodies that intrude the Cloudburst Formation, and is therefore much younger than the 65 m.y. old San Manuel-Kalamazoo copper deposit (Creasey, 1965b, 1967).

The Nipper Formation of Enlows (1955) in the Chiricahua Mountains has traditionally been assigned to the Cretaceous because of its similarity to Bisbee Group rocks. The lower members of this formation are conglomeratic with some rather large clasts (up to 3 m in diameter). The upper units of the Nipper near Onion Saddle are well sorted, fine-grained, fissile shales and limestones interbedded with coarser-grained sandstones. The shales contain intercalated andesitic lava flows. The age of one andesitic flow collected along the Portal to Onion Saddle road is  $32.4 \pm 0.7$  m.y. old (no. 12), indicating that the upper part of the Nipper Formation is Oligocene in age and equivalent to the Pantano Formation. This age is corroborated by a  $28.6 \pm 1.2$  m.y. fission track age on the Nipper Formation at Round Valley, 6 km northwest of Portal (Drewes, pers. commun.).

The poorly fossiliferous Glance Conglomerate is recognized in the Canelo Hills, as well as the Huachuca, Winchester, Whetstone, Mustang, Mule, Empire, Santa Rita and Little Dragoon mountains (Ransome, 1904; Hayes and Drewes, 1968; Hayes, 1970; Sabins, 1957; Schafroth, 1968). On the basis of structural and stratigraphic evidence, the Glance Conglomerate in its type locality is Cretaceous in age. The highly variable thickness and clast lithology of the Glance presumably reflects conditions of local relief and differences in source rock types (Hayes, 1970; Bilodeau, this guidebook). In the northern part of the Huachuca Mountains, a clastic unit correlated with the Glance Conglomerate has been divided into three units. The lower and upper conglomerates are separated by a volcanic unit composed of rhyodacitic lavas and flow breccias. These volcanics, which appear to be flows intercalated into this unit (Scarborough, pers. commun.), yield mid-Tertiary K-Ar ages (Dockweiler, M.S. thesis in prep.). Limestone and other clasts in this conglomerate do not show any evidence of reheating. Hayes and Raup (1968) have suggested that some of the igneous bodies in the area are Tertiary dikes or sills. Poorly consolidated conglomerate in both the Huachuca and Whetstone Mountains and the Canelo Hills exhibit similarities with the Pantano conglomerates (Scarborough, pers. commun.). Because of these similarities between the Cretaceous Glance Conglomerate and various indurated mid-Tertiary conglomerates, one should use the term "Glance" with discretion.

The reassignment of several stratigraphic units from the Cretaceous and Paleocene to the mid-Tertiary confirms the presence of an Eocene erosional surface in southeastern Arizona. This erosional surface was recognized earlier by Epis and Chapin (1975) and Gilluly (1956), and correlates with the late Eocene magma gap of Damon and Mauger (1966) and Damon (1971), and the Laramide magma gap of Coney and Reynolds (1977). Renewed magmatic activity during the Oligocene was accompanied by rapid erosion of mountain ranges and accumulation of coarse clastic deposits, like the Pantano beds, in local shallow basins.

#### *Volcanics of the Chiricahua Mountains*

The Faraway Ranch Formation, which unconformably overlies the Nipper Formation in the northern part of the Chiricahua Mountains, consists of nine units which range from immature, coarse, clastic sediments to volcanic flows of doreite, basaltic andesite, andesite, latite and rhyolite (Fernandez and Enlows, 1966). Ages of  $29.6 \pm 1.9$  m.y. (no. 13) for unit 3 and  $28.3 \pm 2.0$  m.y. for unit 7 (Marjaniemi, 1968) show that this formation is also a Pantano equivalent. Unconformities exist between some of the units of the Faraway Ranch Formation, implying that the area was tectonically active during deposition of the beds. The rhyodacite ash-flow tuffs of the Faraway Ranch Formation were the predecessors of a thick, younger blanket of rhyolites. Enlows (1955) observed that the Faraway Ranch Formation was the youngest rock unit cut by the northwest-trending Apache Pass fault. The latest movement along the Apache Pass fault postdates the  $28.3 \pm 2.0$  m.y. old Faraway Ranch Formation.

Thick rhyolitic welded tuffs of the Cave Creek and Rhyolite Canyon Formations were erupted onto an erosional surface on the Faraway Ranch Formation and older rocks. The Weatherby Canyon ignimbrite (Gillerman, 1968) in the Peloncillo Mountains of New Mexico is petrographically similar to the Rhyolite

Canyon tuff and has been dated at  $26.9 \pm 1.7$  m.y. (no. 14). This ignimbrite is contemporaneous with the  $26.4 \pm 0.7$  m.y. old Cave Creek rhyodacite (no. 15) but slightly older than the Rhyolite Canyon Formation.

Ages of the members of the Rhyolite Canyon Formation range from  $25.6 \pm 0.8$  to  $24.7 \pm 0.7$  m.y. (Marjaniemi, 1968). Samples 16 and 17 described in Table 1 have ages that also fall within this range. Sample 16, a  $25.4 \pm 0.7$  m.y. old, porphyritic rhyolite dike, transects the Turkey Creek subvolcanic pluton and forms part of the subvolcanic laccolith (Drewes and Williams, 1973) or resurgent dome (Marjaniemi, 1970) in the Turkey Creek caldera. The different units of the Rhyolite Canyon Formation are so close together in age that the relationship between the intrusion of the resurgent dome and the eruption of the ash-flow tuffs cannot be precisely determined. Faults radial to the subvolcanic pluton or the resurgent dome have disrupted both the rhyolites and the older country rocks (Marjaniemi, 1969).

The spectacular cliffs and spires of the Chiricahua National Monument are features eroded from thick rhyolite ash-flow tuff layers of Rhyolite Canyon Formation. Marjaniemi (1968) estimated that  $400 \text{ km}^3$  of rhyolite were erupted to cover an area of  $1,600 \text{ km}^2$ . He identified one possible eruptive center at Turkey Creek on the west side of the range and suggested that several others were present. It should be noted that eruption of these thick and widespread rhyolite ash-flow tuffs (Faraway Ranch and Rhyolite Canyon formations) in eastern Cochise County was contemporaneous with the deposition of coarse-grained clastic units (Pantano beds).

#### *Volcanics of the Tucson Mountains*

The Sentinel Peak-Tumamoc Hill area has been an unofficial type section for the Oligocene-Miocene boundary in southeastern Arizona. These volcanics, reported by Damon and Bikerman (1964), help define the late Eocene magma gap as well as the angular unconformity between the Laramide and mid-Tertiary volcanic rocks. They also demonstrate the contemporaneity of the climax of RAD volcanism with the updoming of the Santa Catalina-Rincon-Tortolita gneissic complexes (Bikerman and Damon, 1966). However, Bikerman and Damon found the age of the youngest doreite flow on Tumamoc Hill to be significantly reduced ( $19.8 \pm 3.0$  m.y.) relative to its equivalent on Sentinel Peak. The doreite contains vugs filled with secondary calcite and quartz, which may explain the unusually large error in this age. The youngest doreite conformably overlies an alluvial unit on Tumamoc Hill and unconformably overlies a tuffaceous unit at Sentinel Peak (Phillips, 1976). Because of the significance and accessibility of this locality, the youngest doreite lavas on both Sentinel Peak and Tumamoc Hill were recollected and reanalyzed. The resulting ages,  $23.7 \pm 0.5$  m.y. (no. 26) and  $24.2 \pm 0.5$  m.y. (no. 25) respectively, are identical within experimental error. The extrusion of the lavas on the west side of Santa Cruz Valley is apparently contemporaneous with the uplift and cooling of the gneissic domes on the northeast side of the valley.

The volcanic-sedimentary sequence in the Del Bac Hills, about 12 km to the south, is similar to that at Tumamoc Hill. Percious (1968) reported  $24.2 \pm 1.0$  and  $25.4 \pm 0.7$  m.y. ages for two of the younger flows in the Del Bac Hills. The youngest basaltic andesite from Cerro Colorado Peak, 55 km southwest of the Del Bac Hills, is dated at  $23.8 \pm 0.9$  m.y. (no. 11).

Mid-Tertiary lavas are also present in several mountain ranges west of Tucson. For example, a  $25.7 \pm 0.5$  m.y. old lava flow (no. 8) caps Martina Peak at Dobbs Buttes, 4.8 km southeast of Viopuli, and overlies the Laramide Bell Mountain Volcanics.

### MID-TERTIARY PLUTONISM

The plutons of Stage 1 fall into 3 general classes. One class is associated with metamorphic core complexes and may have been the source of heat responsible for formation of the complexes. Pre-Oligocene plutons adjacent to the complexes may have been heated enough to partially or completely reset their K-Ar clocks. A second class of plutons is associated with resurgent domes in the centers of calderas. The third class consists of small stocks that are not associated with either cataclastic deformation or cauldron complexes and are generally finer-grained than the other two types.

The Leatherwood Quartz Diorite of the Santa Catalina Mountains (Damon and others, 1963; Livingston and others, 1967; Mauger and others, 1968; Creasey and others, 1977) is a pre-Oligocene pluton that was reset during the mid-Tertiary magmatic period. The Catalina Granite and Happy Valley Granodiorite (Drewes, 1971) are other examples of plutons associated with a metamorphic core complex. The fine-grained monzonite pluton (no. 16,  $25.4 \pm 0.7$  m.y.) found in the central dome of the Turkey Creek caldera (Marjaniemi, 1969) and the Jhus Canyon monzonite (no. 20,  $29.6 \pm 0.9$  m.y.), which is possibly related to the Faraway Ranch Formation (Damon and others, 1970) (no. 13,  $29.6 \pm 1.6$  m.y.), are two examples of subvolcanic plutons. Other subvolcanic plutons may exist in southeastern Arizona but have not yet been documented or exposed by erosional processes.

The Pat Hills, the Circle I Hills, the Swisshelm and the Stronghold stocks are examples of the third class of plutons. The Pat Hills granodiorite ( $30.0 \pm 0.7$  m.y., no. 19) south of Dos Cabezas Peaks intrudes both a  $33.7 \pm 1.5$  m.y. andesite (Marvin and Cole, 1978) and a sequence of dacite flows and tuffs (Ettinger, 1962). The Circle I Hills granite ( $28.3 \pm 0.7$  m.y., no. 21), north of Willcox, is on strike with the western ridge of the Dos Cabezas Mountains. The granite intrudes Precambrian schist and is partly covered by Tertiary volcanics. The medium-grained Swisshelm quartz monzonite ( $30.9 \pm 0.8$  m.y., no. 18) intrudes both Paleozoic and Mesozoic sediments. All three mid-Tertiary plutons were previously considered to be of Laramide age on the basis of lithology, texture and inadequate stratigraphic data. Damon and Bikerman (1964) reported a  $22 \pm 3$  m.y. age on a granodiorite phase of the Cochise Stronghold pluton in the Dragoon Mountains. Marvin and others (this guidebook) also reported  $24.1 \pm 2.0$  and  $27 \pm 2$  m.y. ages for the quartz monzonite phase of the pluton. A recollected sample of the granodiorite (no. 22) phase of the pluton has an age of  $23.4 \pm 0.6$  m.y.

### MID-TERTIARY MINERALIZATION

Although mid-Tertiary deposits are widespread through the North American Cordillera, only a few sub-economic deposits are known in southeastern Arizona. At least three types of mid-Tertiary ore deposits are recognized in the area:

1. Vein deposits containing galena, sphalerite, chalcocite and occasionally wolframite. Two examples of this type are the Las Guijas mine, northwest of Arivaca, and the St. Anthony mine, southwest of Mammoth. Sericite associated with wolframite-rich quartz veins and sulfide-rich andesite dike rock

is  $31.4 \pm 0.7$  m.y. old (no. 23). The early hypogene mineralization at Mammoth-St. Anthony mine is presumably penecontemporaneous with intrusion of rhyolite and rhyodacite bodies into the  $28.3 \pm 0.6$  (no. 3) Cloudburst Formation. The St. Anthony mine produced over 300,000 ounces of gold, one million ounces of silver and 40,000 tons of lead.

2. Limestone replacement deposits such as the one associated with the Cochise Stronghold granite ( $23.4 \pm 0.6$  m.y., no. 22) at the Abril mine in the Dragoon Mountains (Perry, 1964).

3. Mid-Tertiary plutons with disseminated sulfides. For example, the Jhus Canyon quartz monzonite ( $29.6 \pm 0.9$  m.y., no. 20) in the Chiricahua Mountains contains sub-economic amounts of chalcocite and molybdenite (Chakarun, 1973). Replacement deposits are also present in Paleozoic strata adjacent to the Jhus Canyon stock (Brittain, 1954).

Supergene enrichment of Laramide copper ores occurred during Eocene time. A blanket of Stage 1 lavas then protected porphyry copper deposits from erosion during the Oligocene and Miocene. Thus, mid-Tertiary volcanism played an important role in the preservation of porphyry copper deposits being mined today (Livingston and others, 1968). Other economic deposits may exist in the region, but are buried under Stage 1 volcanics and have not been exposed by erosion. Elston and others (1976) have shown that many of the mid-Tertiary, Cu-Pb-Zn deposits in southwestern New Mexico are associated with 43 to 29 m.y. old resurgent cauldrons which produced flows of andesites and felsic tuffs, while molybdenum-tungsten mineralization is associated with 32 to 21 m.y. old alkali rhyolite volcanoes.

### GENESIS OF MID-TERTIARY MAGMAS

Massive amounts of Stage 1 silicic and intermediate volcanic rocks were extruded in southeastern Arizona between 40 and 20 m.y. ago. Christiansen and Lipman (1972) proposed a model which was the first plate tectonic evolutionary scheme for Tertiary magmatism in the western United States. This model defined a transition between talc-alkaline volcanism and "fundamentally basaltic" volcanism which apparently occurred during Stage 1. Their "fundamentally basaltic" rock composition lies near the talc-alkalic and alkali-calcic boundary on a Peacock diagram. In Arizona, a significant petrographic, chemical and isotopic transition from the RAD (rhyolite-andesite-doreite) clan to basaltic volcanism occurred during Stage 2.

Lipman and others (1971) suggested that the massive, mid-Tertiary, silicic rocks were derived from the subducted Farallon plate. The strong relationship between potash and silica (Dickinson and Hatherton, 1967; Hatherton and Dickinson, 1968; and Dickinson, 1975) indicates a depth to the Benioff Zone for southeastern Arizona of about 200 to 300 km (Keith, 1978). However, a dearth of basaltic rocks and uniformly high strontium initial ratios also indicate that the mid-Tertiary RAD magmas were not derived directly from a primitive mantle source. The model of Lipman and others (1971) has several petrologic limitations (Wyllie and others, 1976). Trace elements, such as Rb and Y, of the RAD clan (Steven Rooke, pers. commun.) do not fall within the range of the trace elements found in any partial melts of subducted oceanic lithosphere, as calculated by Gill (1974). The RAD clan evolutionary model is compatible with the plate tectonic mechanism of Coney and Reynolds (1977). Apparently, Laramide

and mid-Tertiary arc-type magmatic tectonic episodes are related to rapid changes in the subduction process. Laramide orogeny resulted from rapid convergence, and hence a decrease in the angle or slope of the subducting Farallon plate (Coney and Reynolds, 1977; Damon, 1968). During Stage 1 time, convergence of the plates evidently ceased and the subducting Farallon plate probably collapsed, resulting in upwelling of the asthenosphere (Damon, 1971). The RAD clan model is consistent with the partial melting of basal crustal rocks in the presence of water (Damon and Shafiqullah, 1976; Damon and others, in preparation). At a later time, more extensive melting and subsequent fractional crystallization produced the secondary RAD clan, ranging in composition from doreite to ultra-potassic trachyte (Shafiqullah and others, 1976).

### CONCLUSIONS

Geologic evolution of southeastern Arizona during the Cenozoic has been complicated by episodes of deformation and by deposition of continental sedimentary deposits without diagnostic guide fossils. Prior to the application of radiometric dating, lithologic similarities were the only criteria available for assigning ages to many rock units. Unfortunately, some formations of both Cretaceous and mid-Tertiary ages have similar lithologic characteristics so that some perfectly reasonable but incorrect age assignments have been made in the past. New data show that several stratigraphic units previously thought to be Cretaceous are mid-Tertiary equivalents of the 40 to 21 m.y. old Pantano Formation.

We recognize three overlapping stages of magmatic-tectonic activity which occurred during the last 38 m.y. Stage 1 (38 to 24 m.y. ago) was characterized by the accumulation and deformation of sedimentary sequences, crustal melting, the widespread extrusion of intermediate to silicic volcanics and the intrusion of plutons. The Stage 1 volcanic rocks range in composition from rhyolite to doreite; the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the members of this sequence fall within a narrow range, suggesting consanguinity. Stage 2 represents a transition from silicic to basaltic volcanism during a time of complex tectonism. This stage also involved a shift from thin skin rotation of the crust to continental rifting. Stage 3, the Basin and Range disturbance, is still in progress and is characterized primarily by basaltic volcanism.

### ACKNOWLEDGMENTS

This research was supported by both National Science Foundation Grant EAR76-02590 to Dr. P. E. Damon, and the State of Arizona. We are indebted to P. J. Coney, H. Drewes, S. B. Keith, F. Koutz, H. W. Peirce and P. Anderson for their enlightening and helpful discussions. J. P. Jenney, D. W. Marjaniemi and R. L. Mauger dated a number of samples while at the Laboratory of Isotope Geochemistry. We have drawn upon their data from earlier reports of limited distribution. Special thanks to M. Peyton-Severson for editorial work; we would also like to thank R. B. Scarborough, R. R. Butcher, G. Paden, L. Gonzales, S. Harralson and M. Hescox for their help in various phases of this research.

### REFERENCES

- Aguillera, J. G., 1888, Fenomenos seismicos del 3 de Mayo de 1887: Anales del Ministerio de Fomento de la Republica Mexicana, v. 10.
- Bikerman, M., and Damon, P. E., 1966, K-Ar chronology of the Tucson Mountains, Pima County, Arizona: Geol. Soc. America Bull., v. 77, p. 1225-1234.
- Bikerman, M., 1968, The geology of the Roskrige Mountains: Ariz. Geol. Soc. Guidebook III, p. 183-191.
- Brennan, D. J., 1962, Tertiary sedimentary rocks and structures of the Cienega gap area, Pima County, Arizona: Ariz. Geol. Soc. Digest, v. 5, p. 45-57.
- Brittain, R. L., 1954, Geology and ore deposits of the western portion of the Hilltop Mine area, Cochise County, Arizona [Ph.D. dissertation]: Tucson, Univ. of Ariz., 97 p.
- Chakarun, J. D., 1973, Geology, mineralization, and alteration of the Jhus Canyon area, Cochise County, Arizona [Ph.D. dissertation]: Tucson, Univ. of Ariz., 89 p.
- Chew, R. T., 1962, The Mineta Formation, a middle Tertiary unit in southeastern Arizona: Ariz. Geol. Soc. Digest, v. 5, p. 35-43.
- Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States, part II. Late Cenozoic: Phil. Trans. Roy. Soc., London, v. 271 A, p. 249-284.
- Clay, D. W., 1970, Stratigraphy and petrology of the Mineta Formation in Pima and eastern Cochise Counties, Arizona [Ph.D. dissertation]: Tucson, Univ. of Ariz., 184 p.
- Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff Zones: Nature, v. 270, p. 403-406.
- Cooper, J. R., 1960, Some geologic features of the Pima mining district, Pima County, Arizona: U.S. Geol. Survey Bull. 1112-C, p. 63-103.
- Cooper, J. R., 1961, Turkey Track porphyry—a possible guide for correlation of Miocene rocks in southeastern Arizona: Ariz. Geol. Soc. Digest, v. 4, p. 17-33.
- Cooper, J. R., 1973, Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona: U.S. Geol. Survey Misc. Inv. Map 1-745.
- Creasey, S. C., and Kistler, R. W., 1962, Age of some copper-bearing porphyries and other igneous rocks in southeastern Arizona: U.S. Geol. Survey Prof. Paper 450-D, p. D1-D5.
- Creasey, S. C., 1965a, Geology of the San Manuel area, Pinal County, Arizona: U.S. Geol. Survey Prof. Paper 471, 61 p.
- Creasey, S. C., 1965b, Isotopic age of fresh and altered igneous rocks associated with copper deposits, southeastern Arizona [abs.]: Geol. Soc. America, Abs. with Programs, Ann. Mtg., p. 38.
- Creasey, S. C., 1967, General geology of the Mammoth quadrangle, Pinal County, Arizona: Geol. Survey Bull. 1218, 94 p.
- Creasey, S. C., Banks, N. G., Ashley, R. P., and Theodore, T. G., 1977, Middle Tertiary plutonism in the Santa Catalina and Tortolita Mountains, Arizona: J. Res., U.S. Geol. Survey, v. 5, p. 705-717.
- Creasey, S. C., and Krieger, M. H., 1978, Galiuro volcanics, Pinal, Graham, and Cochise Counties, Arizona: J. Res., U.S. Geol. Survey, v. 6, p. 115-131.
- Damon, P. E., Erickson, R. C., and Livingston, D. E., 1963, K-Ar dating of Basin and Range uplift, Catalina Mountains, Arizona: in Nuclear Geophysics, Nat'l. Acad. Sci.-Nat'l. Research Council Pub. 1075, p. 113-121.
- Damon, P. E., and Bikerman, M., 1964, Potassium-argon dating of post-Laramide plutonic and volcanic rocks within the Basin and Range Province of southeastern Arizona and adjacent areas: Ariz. Geol. Soc. Digest, v. 7, p. 63-78.
- Damon, P. E., and Mauger, R. L., 1966, Epeirogeny-orogeny viewed from the Basin and Range Province: Soc. Min. Eng. Trans., v. 235, p. 99-112.
- Damon, P. E., 1968, Application of the potassium-argon method to the dating of igneous and metamorphic rocks within the Basin and Ranges of the Southwest: Ariz. Geol. Soc. Guidebook III, p. 7-22.
- Damon, P. E., and others, 1970, Correlation and chronology of ore deposits and volcanic rocks: University of Arizona, Tucson, Geochronology Lab. Ann. Prog. Rept. C00-689-130 to U.S. Atomic Energy Comm.
- Damon, P. E., 1971, The relationship between late Cenozoic volcanism and tectonism and orogenic-epirogenic periodicity: in Conf. on The Late Cenozoic Glacial Ages, Turekian, K. K. (ed.), New York, John Wiley, p. 15-35.
- Damon, P. E., Shafiqullah, M., and Lynch, D. J., 1973, Geochronology of block faulting and basin subsidence in Arizona [abs.]: Geol. Soc. America, Abs. with Programs, v. 5, p. 590.
- Damon, P. E., and Shafiqullah, M., 1976, Genesis of the mid-Tertiary magma series of the Basin and Range Province [abs.]: J. Ariz. Acad. Sci., v. 11, p. 84.
- Damon, P. E., Shafiqullah, M., and Lynch, D. J., 1978, Late Cenozoic landscape developments in the Basin and Range Province of Arizona

- in Smiley, T. L., Pewe, T. L., Nations, J. D., Schafer, J. P. (eds.), *Landscapes of Arizona: The Geological Story* (in press).
- Davis, G. H., 1975, Gravity induced folding of a gneiss dome complex, Rincon Mountains, Arizona: *Geol. Soc. America Bull.*, v. 86, p. 979-990.
- Davis, G. H., 1978, Laramide folding and faulting in southeastern Arizona: submitted for publication, *Am. J. Sci.*
- Dickinson, W. R., and Hatherton, T., 1967, Andesite volcanism and seismicity around the Pacific: *Science*, v. 157, p. 801.
- Dickinson, W. R., 1975, Potash-depth (K-h) relations in continental margin and intraoceanic magmatic arcs: *Geology*, v. 3, p. 53-56.
- Drewes, H., 1971, Mesozoic stratigraphy of the Santa Rita Mountains, southeast of Tucson, Arizona: *U.S. Geol. Survey Prof. Paper 658-C*, 81 p.
- Drewes, H., 1972, Cenozoic rocks of the Santa Rita Mountains southeast of Tucson, Arizona: *U.S. Geol. Survey Prof. Paper 746*, 66 p.
- Drewes, H., 1976, Laramide tectonics from Paradise to Hells Gate, southeastern Arizona: *Ariz. Geol. Soc. Digest*, v. 10, p. 151-167.
- Drewes, H., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: *Geol. Soc. America Bull.*, v. 89, p. 641-657.
- Drewes, H., and Williams, F. E., 1973, Mineral resources of the Chiricahua Wilderness Area, Cochise County, Arizona: *U.S. Geol. Survey Bull.* 1385-A, 53 p.
- Eastwood, R. L., 1970, A geochemical petrological study of mid-Tertiary volcanism in parts of Pima and Pinal Counties, Arizona [Ph.D. dissertation] : Tucson, Univ. of Ariz., 212 p.
- Eberly, L. D., and Stanley, T. B., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: *Geol. Soc. America Bull.*, v. 89, p. 921-940.
- Elston, W. E., Rhodes, R. C., and Erb, E. E., 1976, Control of mineralization by mid-Tertiary volcanic centers, southwestern New Mexico: *New Mexico Geol. Soc. Spec. Pub.* 5, p. 125-130.
- Enlows, H. E., 1955, Welded tuffs of Chiricahua National Monument, Arizona: *Geol. Soc. America Bull.*, v. 66, p. 1215-1246.
- Epis, R. C., and Chapin, C. E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the northern Rocky Mountains: *Geol. Soc. America Memoir* 144, p. 45-74.
- Ettinger, L. J., 1962, Geology of the Pat Hills, Cochise County Arizona [M.S. thesis] : Tucson, Univ. of Ariz., 47 p.
- Fernandez, L. A. Jr., and Enlows, H. E., 1966, Petrography of the Faraway Ranch formation, Chiricahua National Monument, Arizona: *Geol. Soc. America Bull.*, v. 77, p. 1017-1030.
- Finnell, T. L., 1970, Pantano formation in Changes in Stratigraphic nomenclature by the U.S. Geological Survey, 1968: *U.S. Geol. Survey Bull.* 1294-A, p. A35-A36.
- Fowler, G. M., 1938, Montana Mine, Ruby: Some Arizona Ore Deposits: *Ariz. Bur. Mines Bull.* 145, p. 119-124.
- Gill, J. B., 1974, Role of underthrust oceanic crust in the genesis of a Fijian talc-alkaline suite: *Contr. Mineral. and Petrol.*, v. 43, p. 29-45.
- Gillerman, E., 1968, Weatherby Canyon ignimbrite: *Ariz. Geol. Soc. Guidebook III*, p. 223-227.
- Gilluly, J., 1956, General Geology of central Cochise County, Arizona: *U.S. Geol. Survey Prof. Paper* 287, 169 p.
- Grimm, J. P., 1978, Cenozoic pisolitic limestones of Pima and Cochise counties, Arizona [M.S. thesis] : Tucson, Univ. of Ariz., 71 p.
- Halva, C. J., 1961, A geochemical investigation of basalts in southern Arizona [M.S. thesis] : Tucson, Univ. of Ariz., 88 p.
- Hatherton, T., and Dickinson, W. R., 1968, Andesite volcanism and seismicity in New Zealand: *J. Geophys. Res.*, v. 73, p. 4615-4619.
- Hayes, P. T., and Drewes, H., 1968, Mesozoic sedimentary and volcanic rocks of southeastern Arizona: *Ariz. Geol. Soc. Guidebook III*, p. 49-58.
- Hayes, P. T., and Raup, R. B., 1968, Geologic map of the Huachuca and Mustang Mountains, southeastern Arizona: *U.S. Geol. Survey Misc. Inv. Map* 1-509.
- Hayes, P. T., 1970, Cretaceous paleogeography of southeastern Arizona and adjacent areas: *U.S. Geol. Survey Prof. Paper* 658-B, 42 p.
- Heindl, L. A., 1963, Cenozoic geology in the Mammoth area, Pinal County, Arizona: *U.S. Geol. Survey Bull.* 1141-E, 41 p.
- Keith, S. B., 1978, Origins of Arizona copper deposits: Hypotheses: *Arizona Bur. Geol. Min. Tech. Field notes*, v. 8, no. 1-2, p. 9-14.
- Knight, L. H. Jr., 1970, Structure and mineralization of the Oro Blanco Mining district, Santa Cruz County, Arizona [Ph.D. dissertation]: Tucson, Univ. of Ariz., 172 p.
- Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1971, Evolving subduction zones in the western United States as interpreted from igneous rocks: *Science*, v. 174, p. 821-825.
- Livingston, D. E., Damon, P. E., Mauger, R. L., Bennett, R. and Laughlin, A. W., 1967, Argon 40 in cogenetic feldspar-mica mineral assemblages: *J. Geophys. Res.*, v. 72, p. 1361-1375.
- Livingston, D. E., Mauger, R. L., and Damon, P. E., 1968, Geochronology of the emplacement, enrichment, and preservation of Arizona porphyry copper deposits: *Econ. Geol.*, v. 63, p. 30-36.
- Lowell, J. D., 1968, Geology of the Kalamazoo orebody, San Manuel district, Arizona: *Econ. Geol.*, v. 63, p. 645-654.
- Lowell, J. D., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: *Econ. Geol.*, v. 65, p. 373-408.
- Lukanuski, J. N., Nevin, A. E., and Williams, S. A., 1975, Locomotive-type post-ore ganglomerates as exploration guides for porphyry copper deposits: *Am. Inst. Min. Met. Eng., Preprint* 75-S-35, 18 p.
- Marjanemi, D., 1968, Tertiary volcanism in the northern Chiricahua Mountains, Cochise County, Arizona: *Ariz. Geol. Soc. Guidebook III*, p. 209-214.
- Marjanemi, D. K., 1969, Geologic history of an ash flow sequence and its source area in the Basin and Range province of southeastern Arizona [Ph.D. dissertation] : Tucson, Univ. of Ariz., 176 p.
- Marjanemi, D. K., 1970, Denuded caldera in the Basin and Range of Arizona [abs.] : *Geol. Soc. America, Abs. with Programs*, v. 2, p. 116.
- Marvin, R. F., Stern, T. W., Creasey, S. C., and Mehnert, H. H., 1973, Radiometric ages of igneous rocks from Pima, Santa Cruz, and Cochise Counties, southeastern Arizona: *U.S. Geol. Survey Bull.* 1379, 27 p.
- Marvin, R. F., and Cole, J. D., 1978, Radiometric ages: Compilation A, *U.S. Geol. Survey: Isochron/West*, no. 22 (in press).
- Mauger, R. L., 1966, A petrographic and geochemical study of Silver Bell and Pima Mining districts, Pima County, Arizona [Ph.D. dissertation] : Tucson, Univ. of Ariz., 140 p.
- Mauger, R. L., Damon, P. E., and Livingston, D. E., 1968, Cenozoic argon ages on metamorphic rocks from the Basin and Range Province: *Am. J. Sci.*, v. 266, p. 579-589.
- Mielke, J. E., 1965, Trace element investigation of the "Turkey Track" porphyry, southeastern Arizona: *Ariz. Geol. Soc. Digest*, v. 7, p. 87-96.
- Moore, B. N., Tolman, C. F., Butler, B. S., and Hennon, R. M., 1941, Geology of the Tucson quadrangle, Arizona: *U.S. Geol. Survey, open-file report*, 20 p.
- Nelson, F. J., 1968, Volcanic stratigraphy and structure of the Pena Blanca and Walker Canyon areas, Santa Cruz County, Arizona: *Ariz. Geol. Soc. Guidebook III*, p. 171-182.
- Pashley, F. F., 1966, Structure and stratigraphy of central, northern, and eastern parts of the Tucson Basin, Arizona [Ph.D. dissertation]: Tucson, Univ. of Ariz., 273 p.
- Percious, J. K., 1968, Geology and geochronology of the Del Bac Hills, Pima County, Arizona: *Ariz. Geol. Soc. Guidebook III*, p. 199-207.
- Perry, D. V., 1964, Genesis of the contact rocks at the Abril mine, Cochise County, Arizona [M.S. thesis] : Tucson, Univ. of Ariz., 97 p.
- Phillips, M. P., 1976, Geology of Tumamoc Hill, Sentinel Peak and vicinity, Pima County, Arizona [M.S. thesis] : Tucson, Univ. of Ariz., 83 p.
- Ransome, F. L., 1904, Geology and ore deposits of the Bisbee Quadrangle, Arizona: *U.S. Geol. Survey Prof. Paper* 21, 168 p.
- Rehrig, W. A., and Heidrick, T. L., 1976, Regional tectonic stress during the Laramide and late Tertiary intrusive periods, Basin and Range Province, Arizona: *Ariz. Geol. Soc. Digest*, v. 10, p. 205-229.
- Sabins, F. F., Jr., 1957, Stratigraphic relations in Chiricahua and Dos Cabezas Mountains, Arizona: *Amer. Assoc. Petrol. Geol. Bull.*, v. 41, p. 466-510.
- Schafroth, D. W., 1968, Stratigraphy of some Cretaceous formations of southeastern Arizona: *Ariz. Geol. Soc. Guidebook III*, p. 59-67.
- Shafiqullah, M., Damon, P. E., and Peirce, H. W., 1976a, Late Cenozoic tectonic development of Arizona Basin and Range Province [abs.] : 25th Intl. Geol. Congress, v. 1, p. 99.
- Shafiqullah, M., Lynch, D. J., Damon, P. E., and Peirce, H. W., 1976b, Geology, geochronology, and geochemistry of the Picacho Peak area, Pinal County, Arizona: *Ariz. Geol. Soc. Digest*, v. 10, p. 305-324.
- Steiger, R. H., and Jager, E., 1977, Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmochronology: *Earth and Planet. Sci. Letters*, v. 36, p. 359-362.
- Sumner, J. R., 1977, The Sonora earthquake of 1887: *Bull. Seism. Soc. Am.*, v. 67, p. 1219-1223.
- Taylor, O. J., 1959, Correlation of volcanic rocks in Santa Cruz County, Arizona [M.S. thesis] : Tucson, Univ. of Ariz., 59 p.

## MID-TERTIARY MAGMATISM

241

Vice, D. H., 1973, The geology and petrography of the Babocomari Ranch area, Santa Cruz-Cochise Counties, Arizona [Ph.D. dissertation] : Tempe, Ariz. State Univ., 152 p.

Webb, B. P., and Coryell, K. C., 1954, Preliminary regional mapping in the Ruby quadrangle, Arizona: U.S. Atomic Energy Comm. Tech. Rept. no. RME-2009, 12 p.

Wilson, E. D., Moore, R. T., and Cooper, J. R., 1969, Geologic map of Arizona: Arizona Bur. Mines and U.S. Geol. Survey, Special Geologic Map.

Wyllie, P. J., Huang, W. L., Stern, C. R., and Maaloe, S., 1976, Granitic magmas: possible and impossible sources, water contents and crystallization sequences: Can. J. Earth Sci., v. 13, p. 1007-1019.



New Mexico

Minerals Department

Arizona

9301 Indian School Road, N.E.  
Albuquerque 87112  
(505) 296-5461 Exploration  
(505) 298-7412 Mining and Milling

Exploration  
2020 North Forbes Blvd.  
Tucson 85705  
(602) 622-2895

**Long**  
**co.**  
**TECHNICAL SERVICE**

*Serving Rocky Mtn. area since 1951*

Post Office Box 1028 ● Casper, Wyoming 82601  
Telephone AC 307 237-2256

●

**MUD LOGGING**  
**WELL SITTING**

Joe Long, Pres. Ed Pallansch, Geologist  
Joe Long, Jr., Operation Mgr.

## BOOKS ON THE EARTH AND ITS MINERAL DEPOSITS

We are pleased to announce the availability of our research results in book form, including:

COAL DEPOSITS, 450 pages, \$132.00, 1978.  
COPPER DEPOSITS, 339 pages, \$72.00, 1975.  
EARTHQUAKES, 451 pages, \$108.00, 1977.  
THE EARTH'S TECTONOSPHERE, 468 pages, \$30.00, 1977.  
GEOTHERMAL DEPOSITS, 292 pages, \$84.00, 1976.  
GOLD DEPOSITS, 275 pages, \$72.00, 1975.  
IRON DEPOSITS, 450 pages, \$120.00, 1978 (in press).  
MINERAL DEPOSITS, 264 pages, \$64.00, 1973.  
PETROLEUM DEPOSITS, 278 pages, \$50.00, 1974.  
URANIUM DEPOSITS, 303 pages, \$96.00, 1976.

Details available. May be ordered directly from us or through book stores in all parts of the world.

**TATSCH ASSOCIATES**

120 Thunder Road  
Sudbury, Mass. 01776