K-Ar Geochronology and Geologic History of Southwestern Arizona and Adjacent Areas

by

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Abstract

This paper presents K-Ar ages of 174 samples from 154 localities in southwestern Arizona and adjacent areas with a summary of the geologic history. Ages are given for many rock units that had been "dated" previously only by lithologic correlations. These ages establish the timing of the magmatic and tectonic events that created and deformed the rocks.

We interpret the older Precambrian history of Arizona as the result of a long-enduring and evolving convergent continental margin with accretion to the southeast at the rate of 2 km/m.y. This process was terminated 1.4 b.y. ago by the intrusion of vast batholiths extending in a northeasterly direction far beyond Arizona. Younger Precambrian rocks accumulated in an epicontinental sea along the trend of the Cordilleran geosyncline. These rocks were intruded by extensive diabase sills that are best preserved in the central mountain region. There is no further record of Precambrian magmatism or sedimentation after intrusion of the diabase sills. Some Precambrian K-Ar dates have been reset by the thermal disturbance that accompanied these intrusions.

K-Ar ages that fall within the Paleozoic are reset ages and there is no evidence for any Paleozoic magmatism in the region. K-Ar ages of most of the pre-Laramide Mesozoic igneous rocks in the region have been reset by Laramide magmatism but evidence has been found for Early to Late Jurassic magmatism.

The Laramide history of southwestern Arizona started 75 m.y.B.P. with plutonism and volcanism related to an easterly progressing magmatic arc and terminated by 50 m.y.B.P. with the intrusion of coarsely crystalline, leucocratic granites that frequently contain two micas and garnet. The most extensive outcrop of these rocks is the Gunnery Range granite batholith exposed in the Yuma Gunnery Range restricted area and northwestern Sonora. These leucogranites are thought to be anatectically derived from crustal rocks. In some cases the leucogranites are directly associated with metamorphic core complexes whose evolution appears to have begun in Laramide time. Subvolcanic plutons associated with the migrating magmatic arc formed the porphyry copper deposits of Arizona in the period between 72 and 54 m.y.B.P.

Much of the Laramide volcanic cover of southwestern Arizona has been removed as a result of epeirogenic uplift which "rolled" from west to east as the continent began to override a thinner and hotter subducting Farallon plate. This 15-m.y. period of epeirogenic uplift and erosion was a time of orogenic and magmatic quiescence, which we call the Eocene magma gap, that followed the Laramide orogeny. Drainage at that time was to the northeast onto the Colorado Plateau.

The mid-Tertiary orogeny began as the magmatic arc returned to southwestern Arizona. The first, sparse magmatic arc volcanic rocks were andesites and rhyodacitic ignimbrites.

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Crustal disturbances created basins that filled with coarse, continental sediments. These sediments were deformed during later stages of the mid-Tertiary orogeny. The orogeny culminated with the extrusion of vast amounts of calc-alkalic ignimbrites and calcic latites (potassic basaltic andesites). This culmination occurred in the Sonoran Desert region during late Oligocene - early Miocene time. The age of the magmatic peak becomes younger from east to west at the rate of 3 to 4 cm/yr and probably represents the return passage of the magmatic arc. Magmatism was accompanied by thin-skinned tectonism and further evolution of metamorphic core complexes. Ultrapotassic rocks were extruded following the passage of the magmatic arc. High ^{87}Sr-^{86}Sr initial ratios, low solidification index, and high differentiation index support their derivation as a result of extreme fractional crystallization of mid-Tertiary calc-alkalic magmas.

A tectonic and magmatic transition occurred between 19 and 12 m.y.B.P. during which the processes of the mid-Tertiary orogeny waned and processes of the Basin and Range disturbance began. Orogenic calc-alkalic volcanism (rhyolites and andesites) was replaced by postorogenic basaltic volcanism, and basin subsidence began along high-angle normal faults. The grabens, filled with undeformed fluvial and lacustrine deposits, are superimposed on tilted beds deformed by earlier listric normal faulting. Listric faulting (of the mid-Tertiary orogeny) implies ductile shear at relatively shallow depths, whereas high-angle faulting implies brittle failure at shallow depths. The zone of ductile shear became deeper as the relatively thin Basin and Range crust cooled. The transition occurred during the time when motion along the west-coast plate boundary was changing from convergent to transform. This change in the nature of the tectonism is reflected in regional construction of local angular unconformities during this time. The concurrent change in volcanism was accompanied by lowering of initial strontium isotopic ratios indicative of more primitive magma sources and transit through a progressively cooler and more brittle crust without contamination.

The Basin and Range disturbance consisted of graben subsidence along high-angle normal faults without major crustal block rotation. Basin subsidence apparently began about 15 m.y. B.P. and had essentially ceased in the Sonoran Desert province by about 8 m.y.B.P. It continues to the present in the eastern and central mountain regions. Basaltic volcanic activity was initially prolific but decreased between 9 and 4 m.y.B.P. Renewed volcanism is restricted to four Plio-Pleistocene volcanic fields.

Basin subsidence disrupted the early Miocene drainage and created internal drainage leading to accumulation of fluvial, lacustrine, and evaporite deposits in some basins. The evaporite deposits indicate regionally integrated but internally directed drainage. Connection of the Colorado and Gila River system to the Gulf of California occurred after deposition of the Bouse Formation 5.5 m.y.B.P. Downcutting rates for tributaries of the Colorado River, based on dated volcanic units, are controlled by Plio-Pleistocene denudation and isostatic rebound of the Colorado Plateau. The upper Gila River system became integrated within the past 3 m.y. while the lower Gila reached its equilibrium profile and has remained relatively unchanged in that time.

Paleoclimatic indicators such as buried desert landforms, rock weathering patterns, and evaporite deposits indicate arid climate throughout most of the Cenozoic.

Introduction

Much of southwestern Arizona has been "terra incognita" since the days of the first European explorers. Neither horses nor the primitive automobiles could provide reliable transportation in this land of searing heat and little water in the days before World War II when the U.S. military, attracted by endless clear weather and the vast uninhabited desert, locked up much of the land as military firing range. Early prospectors, undeterred by even the worst of conditions, discovered a few small but rich ore deposits (Wilson, 1933; Stanton B. Keith, 1978). The first serious geologic exploration was accomplished by Eldred Wilson in the 1920s and early 1930s. His high-quality reconnaissance mapping and rock-type identifications are little changed on the most recent Arizona State Geologic Map (Wilson, Moore, and Cooper, 1969). Isotopic age determinations, most of them made since this map was compiled, require significant changes in age assignments of some rock units. Unfortunately, incorrect ages assigned from lithologic similarities have led to erroneous regional and local geologic interpretations.

The purpose of this paper is to review the chronology of the rocks of southwestern Arizona and adjacent areas from data gathered within the last two decades and to provide a model for the geologic evolution of the region. Some K-Ar ages reported in the appendix (square bracketed numbers in the text) have appeared in other publications, theses, dissertations, or reports of limited distribution but are published here with isotopic data so that they may be recomputed should values of the decay constants be further refined. This paper supplements our earlier paper on mid-Tertiary magmatism in southeastern Arizona (Shaffiqullah and others, 1978).

The study area extends from southern Nevada south to lat 30° N. and from the Mohave Desert of eastern California east to long 110° W. Topographic map coverage within Arizona is excellent, with most of the area mapped at a scale of 1:62,500 or larger. Mexico is covered by the Army Map Service (AMS) 1° x 2° maps at a scale of 1:250,000 now available from Detenal, an agency of the Mexican Government. LANDSAT imagery is available for the entire area, and Skylab color photography for some of it. Access to huge areas within Arizona is restricted by land-use policies. Permission to enter some air combat training areas can be gained from the range control offices at either Luke Air Force Base or the Marine Corps Air Station, Yuma, while unexploded live ordnance will make other areas "off limits" indefinitely. Travel restrictions are in effect within the Kofa and Cabeza Prieta Game Ranges and the Organ Pipe Cactus National Monument (Fig. 1).

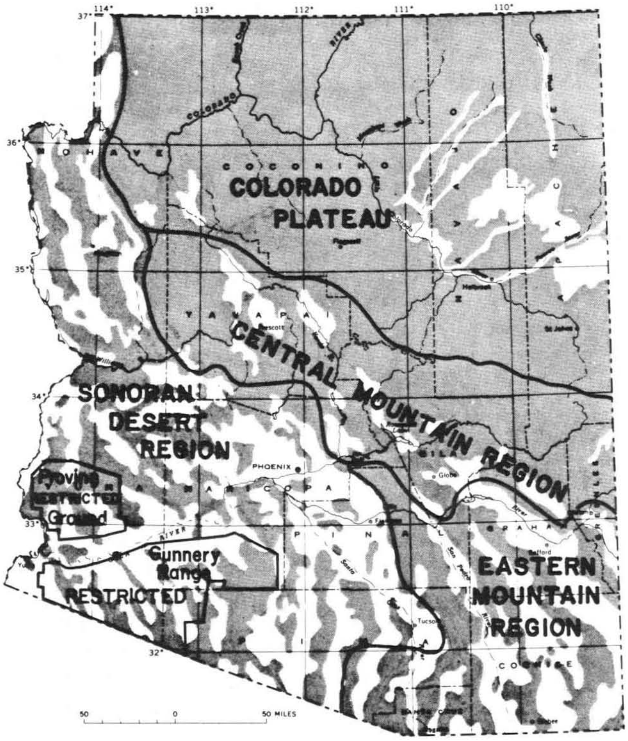

Fig. 1. Physiographic divisions of Arizona. Boundaries of the three regions of the southern Basin and Range physiographic province are shown along with the major restricted areas.

Physiographic Provinces

This region is in the northwestern part of the southern Basin and Range physiographic province (Fenneman, 1931; Heindl and Lance, 1960; Wilson and Moore, 1959b). Here the ranges are smaller and less regular and are separated by relatively wider basins in contrast to the adjacent Great Basin to the north. Paleozoic rocks occur only in scattered outcrops in this region, whereas thick sections of Paleozoic rock characterize the Great Basin north of Lake Mead. Northwestern Arizona occupies the transition between these two differing sections of the Basin-Range province (R. E. Anderson, Armstrong, and Marvin, 1972).

To the northeast of the study area, the Colorado Plateau, a broad saucer-shaped plateau, stands 1.5-3 km above sea level (Fig. 1). This crustal block has experienced relatively minor deformation since the younger Precambrian Grand Canyon supergroup was deposited (Ford and Breed, 1974).

The boundary between the Colorado Plateau and the southern Basin-Range province is a variously south-, southwest-, and west-facing erosional escarpment capped by gently dipping, resistant Permian Kaibab Limestone, which forms the surface of much of the southwestern Plateau. The base of the escarpment is commonly the soft Supai Formation, which is easily eroded. This boundary and its evolution are discussed in detail by Peirce, Damon, and Shafiqullah (1979).

South and west of the Colorado Plateau boundary is a mountainous transition zone between the high plateau and the lower Basin and Range province (Heindl and Lance, 1960). Although this central mountain region of diversely oriented ranges is part of the southern Basin and Range province, some of its structures are like those of the plateau. Its rocks are commonly either Precambrian crystalline or Tertiary volcanic rocks. Nearly flat lying remnants of Paleozoic strata in this region indicate that many of the area's tectonic events occurred in older Precambrian time.

Southeast of the central mountain region and east of the Sonoran Desert is an eastern mountain region, which exhibits a typical basin-range structure. Paleozoic and Mesozoic rocks are common here in addition to Precambrian and Tertiary rocks. Rocks of this region have been more intensely deformed by the Laramide orogeny than rocks in the region to the north.

Topography within the Sonoran Desert section of the southern Basin and Range province appears more mature and the basin-range physiography is more regular than in the other parts of the province. Scarps of the faults presumably responsible for the physiography have been eroded back considerable distances to form widespread pediments. Although the range fronts are deeply embayed, slopes are generally steep.

Experimental Considerations

Isotopic ages reported in the appendix were determined by the potassium-argon method and were calculated using the "closed-system hypothesis." This hypothesis is based on the idea that the amount of radiogenic argon-40 found in a rock or mineral separate has accumulated from decay of radioactive potassium-40 in that sample; the reported age is the time necessary to accumulate a measured amount of argon from a measured amount of potassium in accordance with the laws of radioactive decay (see, for example, Damon, 1970). Potassium content is measured by atomic absorption spectrophotometry with accuracy monitored by inclusion of a laboratory standard with each run. Argon isotopes are measured by mass spectrometry of the gas evolved from the fused samples to which has been added a precisely measured tracer of purified argon-38 for reference. Radiogenic argon-40 is total argon-40 minus the computed amount of atmospheric argon-40, which is a function of the argon-36 found in the sample, and is reported in the appendix as "Percent Atmospheric Argon-40." Replicate analyses of interlaboratory standards show that both analytical techniques are precise to better than 1.5 percent. Continuous refinement of the laboratory technique has both improved its accuracy and allowed age determinations to be made on rocks younger than one million years. The error reported with each age determination is based on laboratory data only and has no geologic significance.

The major limit on the K-Ar technique is failure of the "closed-system hypothesis" to take into account a loss (or gain) of argon at some time after the event that initially started the isotope clock. Heating a rock body may drive out some or all of its accumulated radiogenic argon-40, depending on temperature, duration of elevated temperature, and resistance of the rock or mineral to loss by diffusion (Damon, 1970). In some volcanic rocks, large phenocrysts or glass will retain some excess argon from the melt and the rock will yield a date older than the time since extrusion. For extruded volcanic rocks the clock-starting event is the rapid extrusion and freezing. Plutonic rocks yield ages that reflect a cooling period after which the minerals retain radiogenic argon quantitatively; therefore, the cooling ages may be younger than the ages of emplacement. The reader is cautioned that each reported age must be evaluated in the context of the field relationships and the mineralogy and petrology of the rock to determine its geologic relevance.

Previous Studies

The geology of southwestern Arizona has not been studied as thoroughly as that of most other parts of the western United States. Some of the first publications on the area were concerned with reconnaissance geology and hydrology. These were followed by pioneering works by Darton (1925), Gilluly (1937, 1946), and especially Wilson (1933, 1960). In the period from about 1950 to 1970, water-supply studies included reconnaissance geology emphasizing Tertiary stratigraphy. During this same period of time the geology of certain regions, mountain ranges, and mining districts was examined in relatively more detail. Around 1960, geologic maps of the western Arizona counties were published by the Arizona Bureau of Mines (Wilson, Moore, and Peirce, 1957; Arizona Bureau of Mines, 1958; Wilson and Moore, 1959a; Wilson, 1960). Since 1970, interest in the geology of the region has increased, resulting in a proliferation of publications and unpublished theses. For an exhaustive review of the literature the reader is referred to Reynolds (this volume) and Stanton B. Keith (1978).

Some of the most significant contributions of these more recent studies include:

1. Reassignment of most volcanic rocks from Cretaceous (Wilson and others, 1969) to mid-Tertiary (Shafiqullah and others, 1978; Eberly and Stanley, 1978; Rehrig, Shafiqullah, and Damon, this volume).
2. Recognition of a zone of Cretaceous-Tertiary metamorphic and plutonic complexes (Rehrig and Reynolds, 1977, n.d.) that had previously been mapped as Precambrian gneiss.
3. Documentation of late Oligocene(?)-Miocene age for numerous low-angle faults (dislocation surfaces) in the region (Shackelford, 1976, 1977; Davis and others, 1977, n.d.; Rehrig and Reynolds, 1977, n.d.; Suneson and Lucchitta, 1979).

Precambrian History

There are very little published isotopic age data for the Precambrian rocks within the Basin and Range province of Arizona. This is unfortunate because generalizations and hypotheses have been advanced concerning the Precambrian history of Arizona and adjacent areas that could be tested if adequate information were available. This dearth of data makes it useful merely to confirm the presence of Precambrian rocks in certain localities. Potassium-argon dates, like all mineral dates, are subject to resetting at varying temperatures for different minerals and different durations of thermal events (see, for example, Damon, 1968b), but nevertheless these dates serve to establish minimum ages and thus can confirm the Precambrian age of rock units prior to more intensive investigation. The reader may refer to the review by Livingston and Damon (1968) for the geochronology of the Precambrian rock sequence of Arizona and northern Sonora. Recent papers summarize the Precambrian of southeastern Arizona (Silver, 1978) and the Grand Canyon (Brown and others, 1979; Babcock and others, 1979; and Clark, 1979).

Outline of Precambrian Geology

C. A. Anderson and Silver (1976) have pointed out that the Yavapai Series of central Arizona resembles many of the older Precambrian greenstone belts that occur as scattered remnants within the African, Australian, and Canadian shields. They recognized two sequences of stratified rocks in Arizona: the Yavapai Series, which is dominated by volcanic rocks, and the Pinal series to the southeast in which volcanic rocks are subordinate to the greater volume of sedimentary rocks. Deposition of the older sequence began about 1,820 m.y. ago and ended about 1,720 m.y. ago. Deposition of the younger sequence continued where the older left off until deformation and plutonism terminated approximately 1,660 m.y. ago. Similar evidence exists for an older sedimentary-volcanic terrane to the northwest (i.e., the Vishnu Series of the Grand Canyon), based on unpublished data from this laboratory by Livingston and on the references cited above. C. A. Anderson and Silver (1976) suggested that the Yavapai Series greenstone belt could be interpreted as an ancient island arc or an intracratonic accumulation between former spreading sialic forelands.

P. Anderson (1976) has attempted to explain the evolution of the older Precambrian from a uniformitarian point of view as the result of plate tectonic processes at a convergent margin. If we accept this model, we conclude that the sea floor moved northwest from a spreading center, subduction took place, and northeast-trending volcanic arcs with adjacent geosynclines were formed. The arcs were invaded by batholithic plutons helping to weld prisms to the continent, which grew by accretion to the southeast. The intensive investigation of the Tonto Basin by Conway (1976) provides significant insight into the evolution of that area. He interpreted the volcanic rocks as a magmatic arc adjacent to a craton. Northwest-southeast compression caused extensive folding followed by low-angle reverse faulting and thrusting to the northwest onto the cratonic foreland. Compression was followed by the initiation of major left-lateral strike-slip faulting and relaxation. The final magmatic event in the Tonto Basin was the accumulation of a series of rhyolite ash-flow tuffs and lava flows over an area of more than 2,000 km^2, in a Yellowstone Plateau-like cauldron complex (Conway and Silver, 1976), possibly in an area of back-arc extension or hot-spot environment (Conway, 1976).

Some features found at modern convergent subduction boundaries appear to be absent or unreported for the Arizona Precambrian, for example, blue schists and extensive melanges. Nevertheless, long-enduring accretionary growth at a convergent boundary appears to explain many features of the older Precambrian geology of Arizona such as the older plutons (>1,650 m.y.), the younger ages of sedimentary-volcanic sequences to the southeast, and persistence of a northwest-southeast major compression axis with low-angle reverse faulting and thrusting toward the northwest onto a cratonic foreland. The northeast-trending line separating rocks of two orogenic cycles (Silver, 1976; Silver, Bickford, and Van Schmus, 1977) would then be a consequence of both accretion to the southeast (P. Anderson, 1976) and episodicity of plutonism (Silver, 1965). The rate of accretion need be only about 2 km/m.y. Silver's boundary between orogenic zones cuts across the Basin and Range province from the Mazatzal Mountains toward the Colorado River delta. According to Silver and Anderson (1974), this line was offset by a major left-lateral megashear zone in the vicinity of Lukeville, Arizona, during the interval between the mid-Triassic and mid-Jurassic (T. H. Anderson and Silver, 1979), resulting in 700 to 800 km of left-lateral offset. Although they suggest that offset occurred in Mesozoic time, the movement may have been mainly in late Precambrian time.

Following accretion, the older Precambrian sediments of Arizona were deformed along northwest-trending axes of compressional stress resulting in the dominantly northeast-trending fold belts observed today. This compressional event has been referred to as the Mazatzal orogeny (Wilson, 1936; Silver, 1965). The older Precambrian history of Arizona was terminated by transfer of huge masses of magma into the upper crust to form transcontinental batholiths comparable in magnitude to the Mesozoic cordilleran batholiths of western North America (Silver and others, 1977). Following the 1400-1450-m.y. B.P. period of batholith emplacement, northern and central Arizona became hedreocratonic; sedimentation was epicontinental in the east and shelf-facies in the west, as part of the Cordilleran geosyncline that developed following batholith emplacement. Thus, the batholith event resulted in a complete change of regimen (revolution) within the geologic framework of Arizona, indeed, of

North America as a whole. Apparently, the final magmatic event of the Precambrian was the emplacement of vast diabase sills that postdate the younger Precambrian Apache Group and Troy Sandstone (Shride, 1967) and include the Cardenas lavas of the Grand Canyon supergroup (Ford and Breed, 1974). These diabases and basalts were emplaced between 1,100 and 1,200 m.y. ago (Damon and others, 1962; Damon, 1968a; Ford and Breed, 1974; Silver, 1963) during a period of tectonic relaxation.

Discussion of Precambrian Ages

Precambrian ages reported in the appendix allow a preliminary update of the Arizona Bureau of Mines (1962) Precambrian Outcrop Map. On the revised map (Fig. 2), with sample locations from the appendix, rocks of known Precambrian age are added and those known to be younger are deleted. Apparent K-Ar ages of 1,450 m.y., 1,500 m.y., and 1,620 m.y [2, 3, 6] from the Yavapai Series in Yavapai and Gila Counties suggest that the late, post-orogenic pegmatitic phase may be that young because low greenschist temperatures do not generally reset pegmatitic muscovite (Damon, 1968b). On the other hand, biotite ages are reset at temperatures around 225°C or greater, so the biotite ages on the basement rocks of Mohave, Yavapai, Pima, and Graham Counties serve only to confirm their Precambrian ages [2,5,7,8,10,11, 13,15-20]. It is interesting, however, that the 1,320-m.y. K-Ar age on biotite from the Hualapai granite [10] is nearly concordant with a six-point Rb-Sr isochron for the Hualapai granite by Kessler (1976). Kessler obtained other Rb-Sr isochron ages of 1,397 ± 69, 1,364 ± 23, 1,312 ± 23, and 1,337 ± 38 m.y. on different units from the plutonic complex within the northern Hualapai Mountains. This suggests that both methods may be approximating the time of intrusion of the Precambrian plutonic complex in the northern Hualapai Mountains. K-Ar dates of 1,050 m.y. to 1,390 m.y. for biotites from granitic plutons of the Chloride mining district [7] are approximately concordant with Rb-Sr dates on biotite reported by Giletti and Damon (1961). However, the Rb-Sr and K-Ar biotite clocks were reset under approximately the same temperature conditions, so these dates demonstrate only that the Precambrian basement of the Chloride area dates back to at least 1,390 m.y. but is probably older.

The date of 1,375 ± 30 m.y. [9] for very coarse muscovite at the contact of a quartz monzonite pluton and the Pinal Schist of low metamorphic grade southeast of Tucson is probably close to the time of intrusion as demonstrated by the sharp contrast between the unmetamorphosed pluton and the Pinal Schist of low greenschist grade. The date is correlative with other dates for the Continental Granodiorite of Drewes (1968) but should not be confused with older granites that the "Continental Granodiorite" intrudes in some areas.

The 1,080 ± 30-m.y. date on the very thick biotite diorite from the Mineral Mountain area of Pinal County [14] is approximately correlative with biotite from the Sierra Ancha diabase (1,150 ± 40 m.y., Damon and others, 1962).

Basement in the Sonoran Desert subprovince is a lithologically varied series of metamorphic rocks that appear predominantly dark in outcrop in contrast with the lighter colored intrusive rocks. Rocks here are amphibolite gneisses and augen gneisses in contrast to rocks of similar age in the central mountain region that are greenschist grade. Unfortunately, this Sonoran Desert series has not been studied in detail over the region and cannot be directly correlated with any of the other Precambrian rocks in Arizona. Gilluly (1946) applied the name "Cardigan gneiss" to Precambrian basement rocks in the Ajo area. These rocks are remarkably similar to Precambrian rocks farther west.

The postulated megashear of Silver and Anderson (1974) crosses this area trending northwest between Lukeville and the Pinacate volcanic field. Existence of this structure would preclude the possibility that the Precambrian basement of the eastern part of the region is the same as that to the west. Uranium-lead isotopic ages reported for the metamorphic rocks west of the megashear along Mexico Highway 2 are Precambrian: 1,670 m.y. and 1,650 m.y., intruded by 1,450-m.y.-old granite (T. H. Anderson and Roldan-Quintana, 1979, road log addendum, p. 78; T. H. Anderson, personal commun., 1980).

Muscovite and biotite from gneiss outcrops immediately northeast of the Pinacate volcanic field [4] yielded K-Ar ages of 1,460 and 1,180 m.y., respectively. The muscovite age is concordant with the U-Pb isotopic age of 1,450 m.y. on a granite outcrop 40 km to the west (Anderson and Roldan-Quintana, 1979, p. 78). The discordantly younger biotite age (1,180 m.y.) is due to either partial degassing of the biotite at greenschist-facies temperature or partial resetting by a Mesozoic-Cenozoic thermal event.

The age of 1,660 m.y. on hornblende from the Bamori schist [1] south of Caborca, Sonora, provides an additional datum for the age of the terminal phase of metamorphism and pegmatite intrusion previously reported by Damon and others (1962) and confirmed by T. H. Anderson and Silver (1970, 1971).

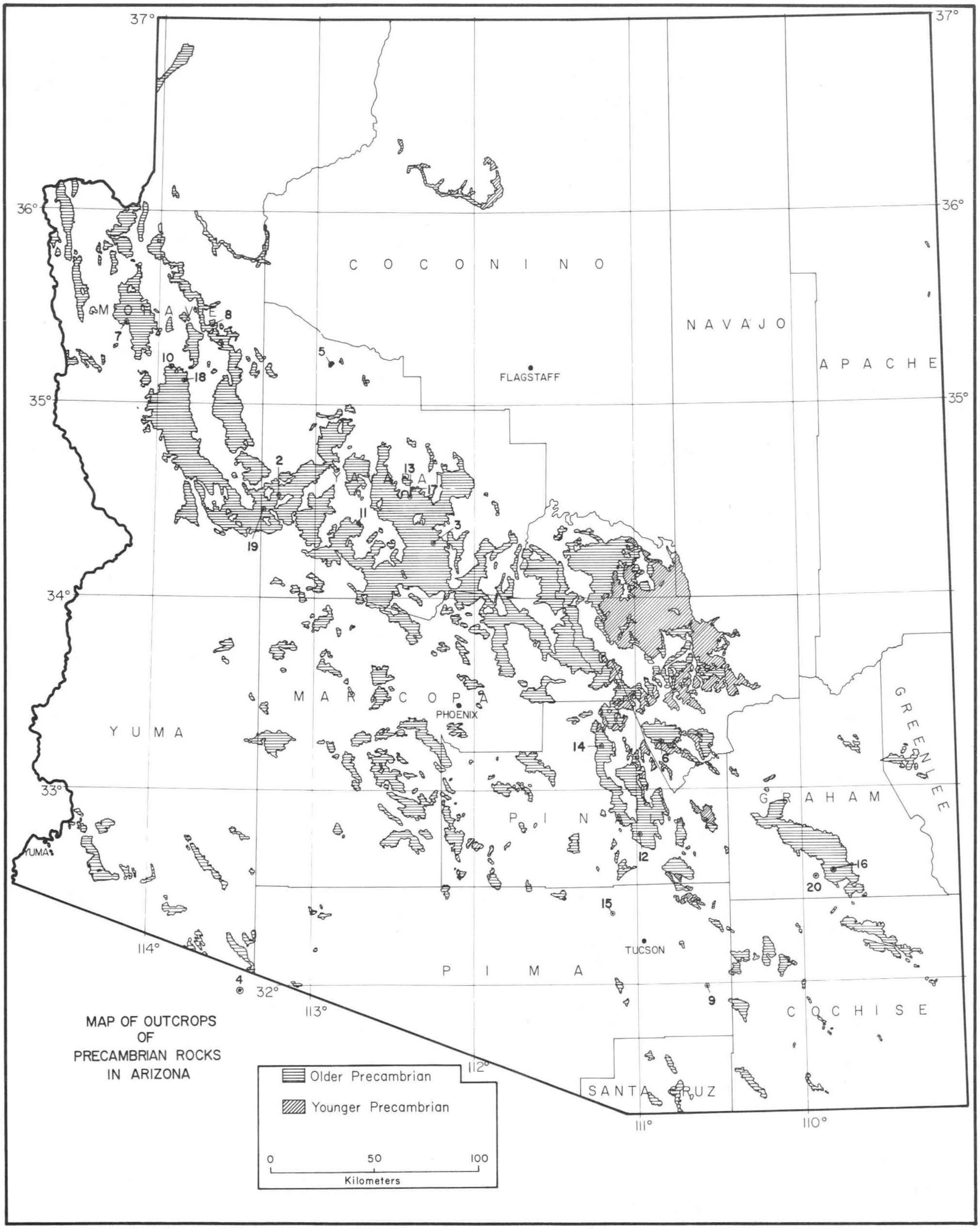

Fig. 2. Preliminary update of Precambrian outcrop map of Arizona, after Arizona Bureau of Mines (1962). Rocks recently identified as Precambrian have been added and those found to be younger have been deleted. Numbers indicate location of samples listed in Table 1.

In summary, these K-Ar dates for Precambrian basement rocks tend to fall into four groups: (1) pegmatitic muscovite with K-Ar ages equal to or exceeding 1,400 m.y. [2, 3, 6]; (2) biotite and muscovite from granitic and metamorphic rocks with a range from 1,320 to 1,460 m.y.B.P., some of which are concordant with other isotopic ages [4, 5, 7, 8, 9, 10]; (3) biotite ages from granitic rocks, metamorphic rocks, and a sill, which fall in the range of 1,080 m.y. to 1,180 m.y.B.P. [12, 13, 14]; and (4) a group of ages that do not correspond to any known thermal event. Because of the nature of the previously discussed process in which minerals have fairly discrete blocking temperatures, there is a tendency for K-Ar mineral clocks to respond to subsequent thermal events, as pointed out by Damon (1968b). Thus, the pegmatite dates mark post-Mazatzal orogeny events. The 1,320-m.y. to 1,460-m.y. dates correspond to reset and cooling ages associated with batholithic intrusions that terminated the older Precambrian of Arizona and Sonora. The 1,080-m.y. to 1,180-m.y. dates correspond to the thermal event that was associated with the intrusion of vast quantities of diabase sills throughout much of Arizona.

Paleozoic History

During Paleozoic time most of Arizona was part of a stable cratonic platform on which several kilometers of carbonate and clastic sediments accumulated (Peirce, 1976a). Cratonic Paleozoic sections are present in at least six mountain ranges in west-central Arizona (see Reynolds, this volume), but only a few additional Paleozoic exposures are known for the remainder of southwestern Arizona. Paleozoic rocks are present in the Growler Mountains south of Ajo (Wilson and others, 1960) and Gilluly (1946) reported Paleozoic clasts from a Tertiary conglomerate near Ajo. In the region, K-Ar age determinations [19, 20] occasionally yield Paleozoic dates. (Numbers in square brackets are serial numbers that identify age determinations reported in the appendix.) Pushkar and Damon (1974) investigated one such case within the Sierra Estrella mountains and were able to demonstrate by means of a Rb-Sr isochron that the K-Ar clocks had been reset. To our knowledge there is no evidence for Paleozoic magmatism within the state of Arizona.

Mesozoic History

The Mesozoic history of the region is incompletely understood because of the scarcity of detailed geologic and geochronologic studies on Mesozoic rocks. Rocks of probably Mesozoic age are now recognized as far north as the Rawhide Mountains, and scattered exposures are known to occur throughout much of southwestern Arizona and northern Sonora, Mexico.

Mesozoic rocks and structures of southwestern Arizona must be considered within the context of regional tectonics inferred from adjacent regions. In mid-Mesozoic time, southwestern Arizona was located within a northwest-trending magmatic arc that was related to an east- or northeast-dipping subduction zone (Coney and Reynolds, 1977; Coney, 1978b). Magmatism swept or jumped westward in the Late Jurassic, creating the Peninsular batholith, which was largely emplaced in the early and middle parts of the Cretaceous (Krummenacher and others, 1975). Magmatism then swept eastward across the region in the Late Cretaceous in response to shallowing of the dip of the subduction zones (Coney and Reynolds, 1977). Metamorphism in some parts of the region may be related to the passing of these magmatic pulses.

Rocks of known Mesozoic age (Fig. 3), exclusive of the latest Cretaceous rocks, which are discussed in the section on the Laramide, can be divided into two general groups: an older volcanic, plutonic, and sedimentary assemblage and a younger, predominantly clastic sequence. Older rocks of probably mid-Mesozoic age are intermediate to felsic volcanic units and interbedded clastic strata exposed in west-central Arizona, in southwestern Arizona, and on the Papago Indian Reservation (Crowl, 1979; Gilluly, 1946; Haxel and others, this

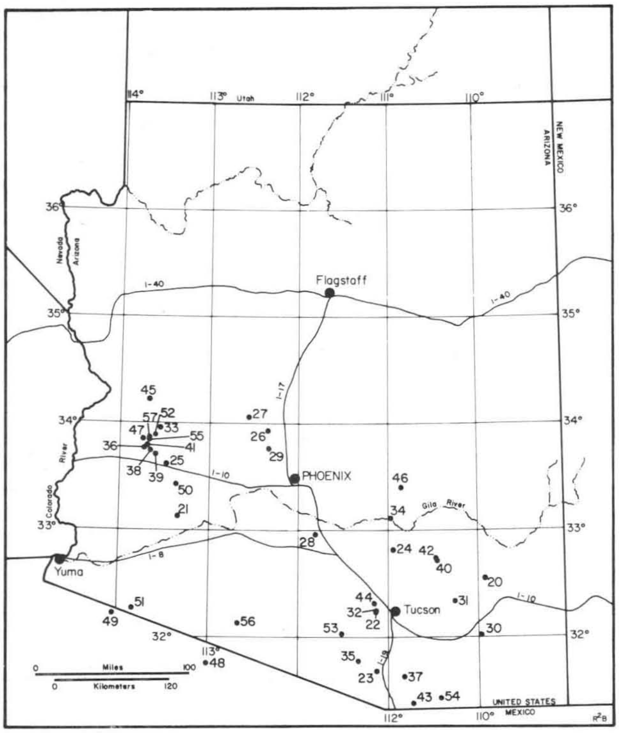

Fig. 3. Localities of Mesozoic and Laramide age samples as tabulated in appendix.

volume; Marshak, 1979; Miller, 1970; Rehrig and Reynolds, n.d.; Reynolds, this volume; Wilson, 1933). Mesozoic plutons include the 154-m.y.-old stock at Amado [23] and the 100-m.y.-old granodiorite in the Comobabi Mountains [28]. In the Tucson Mountains, the 153-m.y.-old Desert Museum andesite porphyry [22] (Mayo, 1961) is intrusive into the Recreation redbeds, which were previously considered to be Cretaceous (Wilson and others, 1969). This 153-m.y. Jurassic date requires that their age be revised to at least mid-Jurassic and possibly Triassic.

Depositionally overlying the mid-Mesozoic volcanics in west-central Arizona are thick sequences of variably metamorphosed, clastic sedimentary rocks (Wilson, 1960, 1962; Miller, 1970; Harding, 1978; Marshak, 1979; Robison, 1979). Similar rocks are exposed on the Papago Indian Reservation (Haxel and others, this volume). These rocks are younger than the mid-Mesozoic volcanics and granites but older than the Late Cretaceous plutons that locally intrude them (Rehrig and Reynolds, n.d.; Reynolds, this volume).

The significance of Mesozoic 167-94 m.y. K-Ar ages on other samples [21,24,25,26,27, 29] is more difficult to assess because of possibilities that they are partially reset ages resulting from partial degassing of argon from older rocks by Mesozoic or Cenozoic thermal events, or both.

Throughout many parts of the region, rocks of known or suspected Precambrian, Paleozoic, and Mesozoic age show evidence of episodes of deformation that are Mesozoic or early Tertiary (Wilson, 1962; Haxel and others, this volume; Reynolds, this volume). For example, in widespread areas of west-central Arizona, a cleavage has been imparted to greenschist-grade Paleozoic strata and Mesozoic volcanic and clastic rocks. In other areas such as the Granite Wash Mountains, Mesozoic rocks are highly deformed and metamorphosed to amphibolite grade (Rehrig and Reynolds, n.d.; Marshak, 1979). These metamorphic rocks are intruded by two Late Cretaceous plutons exposed in the eastern Granite Wash Mountains. Cross-cutting relationships of the plutons with the metamorphic rocks and K-Ar dates of 67.1 m.y. on metasediments [36], 64.6 m.y. on muscovite [41] from schist, and 66.5 m.y. on biotite [38] from granodiorite require that metamorphism in the Granite Wash Mountains was complete by Late Cretaceous or earliest Tertiary time.

Haxel and Dillon (1978) have reported rocks similar to the Orocopia Schist of southern California in southwesternmost Arizona. They describe the Orocopia Schist as quartzo-feldspathic schist, predominantly a metagraywacke, interlayered with lesser amounts of metapelite, metabasite, metachert, and other minor lithologies. The schist is overlain by a regional thrust fault, the Vincent-Chocolate Mountain thrust, above which lies an assemblage of Precambrian and Mesozoic rocks. The age of the protolith of the schist is unknown, but geochronologic data (Ehlig and others, 1975) indicate termination of metamorphism and thrusting by late Paleocene. Additional geologic and geochronologic studies are needed on this schist and the accompanying thrust before they can be related confidently to the geology of southwestern Arizona.

On the Papago Indian Reservation, Haxel and others (this volume) have documented that both the mid-Mesozoic volcanic-sedimentary rocks and the younger, predominantly clastic upper Mesozoic sequence have been affected by a Laramide metamorphic event and possibly a Jurassic metamorphic event. Similar complexities should be expected for the poorly understood areas of southwestern Arizona.

The Laramide

The term "Laramide" is used informally by many geologists in the sense of a geologic period to cover the time of the Laramide orogeny. We continue this usage for that time period between 75 and 50 m.y. ago when the continental sediments of the Wasatch, Fort Union, Laramie, and Horsethief Formations were deposited in the central Rocky Mountains (Damon and others, 1964). Coney (1976) and Coney and Reynolds (1977) included in their definition the interval from 80 m.y. ago (end of the Sevier orogeny in Nevada and Utah) to 40 m.y. ago (age of the bend in the Emperor-Hawaiian seamount chain) on the basis of major changes in global patterns of sea-floor spreading and plate motion. The time period of our definition includes 90 percent of a large group of "Laramide" K-Ar ages from the Basin and Range province, while the definition of Coney (1976) includes a period of magmatic and tectonic quiescence (Eocene magma gap shown by Damon and others, 1964) that followed the "classical" Laramide.

The Laramide orogeny involved "uplift, volcanism, intense compressive deformation, and plutonism—in that order. This activity swept from southwest to northeast across the region. . ." (Coney, 1978a, p. 287). The compressive deformation is clearly expressed in the structure of Paleozoic and Mesozoic sedimentary rocks. The plutonism is best known from the copper-ore-bearing porphyries. Specifically, 27 of the 28 Arizona, New Mexico, and Sonora porphyry copper deposits have Laramide ages (Banks and others, 1972; Damon, Mauger, and Bikerman, 1964; Damon and

Mauger, 1966; Creasey and Kistler, 1962; Laughlin, Lovering, and Mauger, 1969; Livingston, 1973; Livingston, Mauger, and Damon, 1968; Mauger, Damon, and Giletti, 1965; Shafiqullah and Langlois, 1978). Other metals such as molybdenum, gold, silver, lead, and zinc were also emplaced during the Laramide. The appendix lists ages of rocks [30,34,35,37,40, 43,46] associated with "Laramide" ore deposits (Fig. 3).

Eruption of intermediate to silicic lavas was contemporaneous with emplacement of some early and mid-Laramide intrusions (Damon and Mauger, 1966). Most Laramide volcanic rocks occur in the eastern mountain region and adjacent sections of the Sonoran Desert, but this distribution is more probably an artifact of erosion than of original extrusion. Locally, accumulations approach a thousand meters in thickness, as in the Glory Hole volcanic sequence and associated rocks of the Galiuro Mountains [31,40,42].

Laramide plutons in western Arizona occur at Ajo, in the Granite Wash Mountains, and on the Yuma Gunnery Range of southern Yuma County. K-Ar ages on the New Cornelia stock, a copper porphyry at Ajo, range between 54 and 65 m.y. (Damon, Mauger, and Bikerman, 1964; Rose and Cook, 1965; McDowell, 1971). T. H. Anderson and Roldan-Quintana (1979, road log addendum, p. 80) mentioned a "Late Cretaceous granite" south of Ajo in Sonora, 25 km west of Sonoyta, Mexico.

Two distinct plutons, which are exposed in the Granite Wash Mountains [38,39,47] and western Harcuvar Mountains [52,55,57] yield a range of K-Ar biotite ages between 67 and 44 m.y. (Rehrig and Reynolds, n.d.). A preliminary Rb-Sr isochron on the granite of Tank Pass suggests a Late Cretaceous age (Rehrig and Reynolds, unpublished data). Intrusive relations show and K-Ar data [38, 47] suggest that the granodiorite of Granite Wash Pass is younger than the granite but older than 67 m.y. K-Ar ages younger than 67 m.y. are "closure ages," which represent cooling of the pluton followed by various plutonic and metamorphic events.

High-grade gneisses in the Buckskin and Rawhide Mountains to the north are tectonically overlain by Paleozoic, Mesozoic, and Miocene rocks (Shackelford, 1976; G. A. Davis and others, n.d.; Rehrig and Reynolds, n.d.). Hornblende and biotite from these gneisses yielded K-Ar ages of 57.6 and 52.2 m.y., respectively [45] (G. A. Davis and others, n.d.). The discordance of ages suggests that metamorphic rocks in the Rawhide Mountains may have had a history similar to those of the Harcuvar Mountains.

The largest exposed pluton of Laramide age in southwestern Arizona is a leucocratic two-mica granite batholith in the Yuma Gunnery Range south of the Gila River for which we propose the name "Gunnery Range batholith." It crops out in mountain ranges within an oval-shaped area of nearly 15,000 km^2, which extends from the Tinajas Altas Mountains eastward to the Granite Mountains. Contacts with the surrounding gneisses are sharp, and gneissic roof pendants "float" in the granite in the Cabeza Prieta Mountains (Fig. 4).

Ages determined on biotites from the batholith and on a biotite and a muscovite from similar rock 70 km to the southeast are remarkably concordant. Biotite ages of 53.1 and 52.5 m.y. were determined on the western part of the batholith [49,51]. Muscovite [48] collected from Adobe Blanco near Sonoyta, Mexico, yielded an age of 53.2 m.y. [48] and biotite from a nearby outcrop yielded an age of 52.8 m.y. (Damon, Mauger, and Bikerman, 1964). Other K-Ar ages from sites near enough to the batholith to be considered wall rock can be interpreted as partially reset by the intrusion. Eberly and Stanley (1978) reported on two K-Ar ages of 59 and 57 m.y. for rock from the "Border Hills" west of Tinajas Altas, while T. H. Anderson and Roldan-Quintana (1979, road log addendum, p. 76) reported 95 ± 3 m.y. for the same locality. Eberly and Stanley collected other samples from the gneisses 15 km to the north of the batholith along Interstate 8 in the Gila Mountains that yielded K-Ar ages of 319 and 199 m.y. that are clearly reset. If the pluton had been emplaced in Cretaceous time and held at a depth where the temperature was above the closure temperatures of both biotite and muscovite for some long period, all of the wall rock would yield similar, concordant ages.

Leucocratic, porphyritic gravite from a stock 300 km to the east at Texas Canyon has an appearance similar to that of the granite of the Gunnery Range batholith and yielded K-Ar ages of 50.9 and 51.7 m.y. on biotite and 53.7 and 55.4 m.y. on muscovite (Livingston and others, 1967). Keith and others (n.d.) reported similar but somewhat younger ages for the two-mica Wilderness granite of the Santa Cataline Mountains north of Tucson. Haxel and others (this volume) reported a muscovite-bearing granite on the Papago Reservation with a U-Pb age of 58 ± 3 m.y. Several other plutons of this age range occur in southern Arizona (Stanley B. Keith, personal commun., 1980). These ages apparently record a late-Laramide plutonic event that is not well understood.

A diorite [50] intrusive into metasedimentary rock in the northern Eagle Tail Mountains has the same K-Ar age as the Gunnery Range batholith, but the two are probably not related. Two discordant biotite ages from a stock [56] in the eastern Gunsight Hills southeast of the New Cornelia stock at Ajo are partially reset ages caused by a mid-Tertiary thermal event; the actual age of the rock may be Laramide.

Correspondence between volcanism and depth of a Benioff zone has been known for over a decade. Petrogenetic processes are active at certain depths on the subducting slab (Ringwood, 1975) and the K_2O content of lavas is a function of this depth (Dickinson and Hatherton, 1967; Dickinson, 1975). Keith (1978b) has inferred from compositions of Laramide-age igneous rocks that this depth beneath Arizona was between 150 and 250 km. Coney and Reynolds (1977) have analyzed age versus position for Mesozoic and younger igneous rocks in the southwestern United States and have postulated that the apparent sweep of magmatism from the west to east across Arizona and into New Mexico prior to and during the Laramide orogeny resulted from eastward movement of this "magic zone of magma production" as the inclination of the Benioff zone decreased in response to increased velocity of plate convergence. Maximum convergence rates occurred between 50 and 70 m.y. ago (Coney, 1976), the time of most intense compressional deformation. Magmatism then swept raggedly westward as convergence velocities decreased and compression relaxed. The time between the slowing of convergence and the return of volcanism was the time of the magmatic hiatus—tectonic quiescence—in Arizona.

Eocene Erosion Surface

The quiescence that followed the magmatism and deformation of the Laramide orogeny apparently was a time of general erosion or nondeposition, or both, over the region. The oldest Tertiary volcanic rocks are either on or near a surface eroded on the pre-Tertiary basement rocks. Southern Arizona was part of a broad Eocene erosion surface of low relief that shed sediments northward toward the great Eocene lakes of Utah and Colorado. This major erosion surface was recognized all over western North America (Lindgren and others, 1910; Schmitt, 1933; Mackin, 1960) after Dutton (1882) invoked "the great denudation" to explain the regional unconformity between Tertiary and older rocks.

Marine sedimentary rocks of Late Cretaceous age, found only on the Colorado Plateau, contain wedges of coarse clastic sediments derived from the southwest. Isostatic adjustments that accompanied plate convergence during Laramide time caused broad epeirogenic uplift on the continental margin, tilting the margin toward the east (Damon, 1979) and providing a source for the sediments. This uplift "rolled" from west to east as plate convergence rates increased and finally terminated marine sedimentation in Arizona. The eastward inclination persisted for a considerable period of time and the paucity of both Paleozoic sedimentary rocks and Laramide volcanic rocks in western Arizona, as compared to southeastern Arizona, probably reflects longer and deeper erosion in the west. Additional evidence for a long period of deep erosion comes from the "Rim" gravel deposits of the modern Colorado Plateau margin, a southwest-facing escarpment of considerable relief. Dated clasts within these gravel deposits were derived from a source to the southwest and transported northeastward across the site of the modern Mogollon Rim between 54 and 28 m.y. ago (Peirce and others, 1979).

The Eocene erosion surface and the processes that created it were disrupted by the beginning of the mid-Tertiary orogeny. The erosion surface was further modified by subsequent deformation, erosion, and deposition of continental sediments. Relicts of the Eocene erosion surface are exposed predominantly in the transition zone and in isolated exposures within the southwestern Basin and Range province. Sediments of Oligocene age such as the Whitetail Conglomerate (Pederson, 1969; Krieger and others, 1979) and the basal Pantano Formation (Brennan, 1962; Finnell, 1970; Shafiqullah and others, 1978) rest on this surface. Early Oligocene volcanic rocks such as the 39.4-m.y.-old basaltic andesite from Higley basin [58], the 30.1-m.y.-old rhyolite tuff in the Laguna Mountains [60], and the 29.4-m.y.-old rhyolite tuff [61] in the Gila Mountains serve to further demonstrate the age of this erosion surface.

Mid-Tertiary Orogeny

Damon (1964) coined the term "mid-Tertiary orogeny" to describe the second of two pulses of magmatism with crustal heating and tectonism that he found in the late Mesozoic-Cenozoic record of Arizona. The Laramide orogeny, the mid-Tertiary orogeny, and the quiescent period that separated them appeared in the distribution of his earliest K-Ar determinations (Damon, 1964; Damon and Mauger, 1966; Damon, 1971). We attribute the causes of the mountain-building event to changes in plate motions described by Coney and Reynolds (1977) and Coney (1978), compounded by overriding of the progressively thinner and hotter subducted Farallon plate (Damon, 1979; Pilger and Henyey, 1979). This was a time of crustal melting, plutonism, uplift, extrusion of voluminous lavas of a wide range in composition, deformation in metamor-

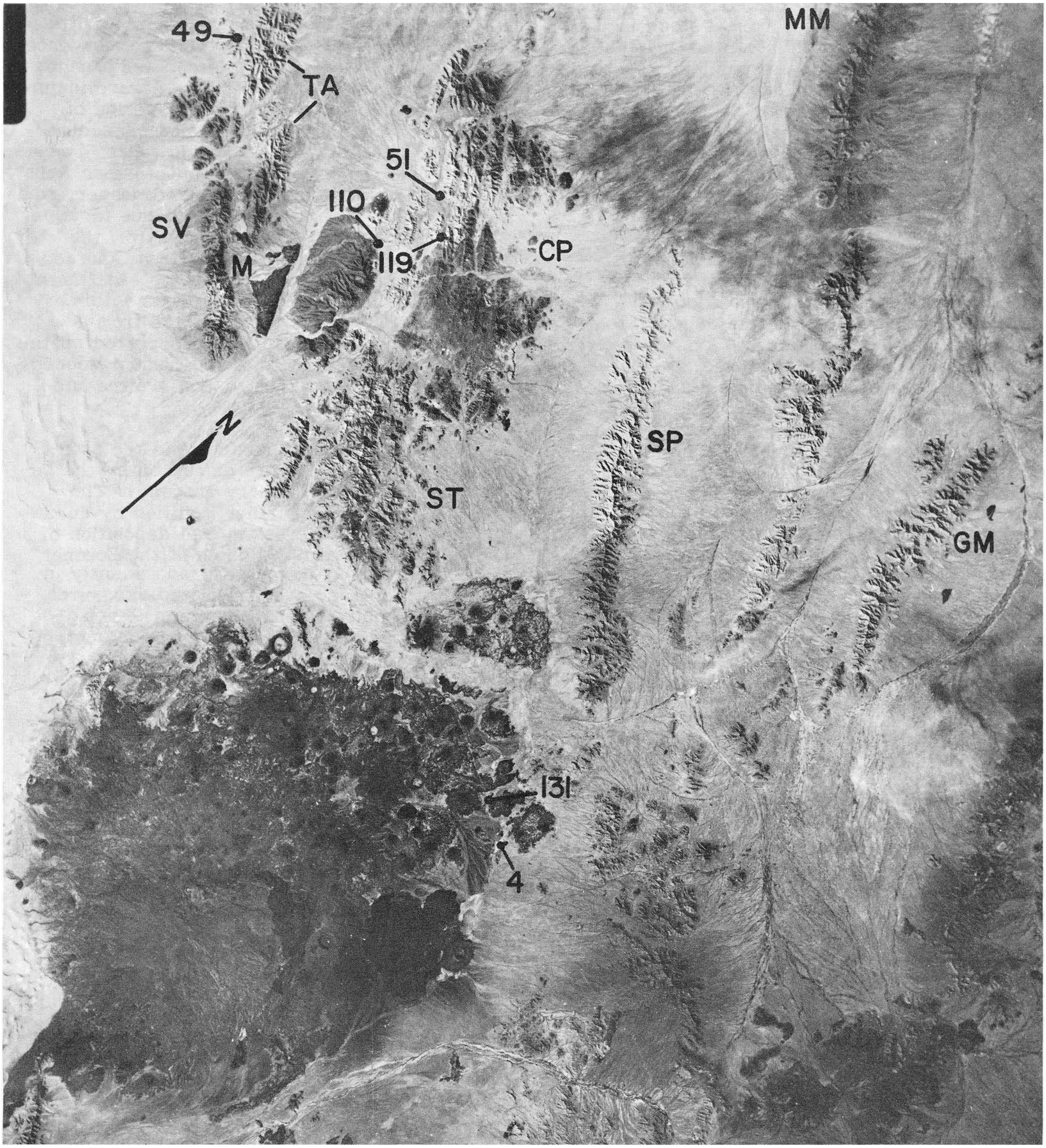

Fig. 4. Skylab photo of the Arizona-Sonora border region east of Yuma. Sand dunes of the Gran Desierto fill the left margin and the Pinacate volcanic field lies to the lower left. The black lavas on the east are the youngest in the region. Sharp contacts between the leucocratic Gunnery Range granite and the dark Precambrian metamorphic rock are easily seen in the mountains. TA - Tinajas Altas Mountains; MM - Mohawk Mountains; SV - Sierra Vieja; M - Mesas de Malpais; CP - Cabeza Prieta Mountains; ST - Sierra del Tule; SP - Sierra Pinta; GM - Granite Mountains. Numbers refer to sample sites from appendix. Photo courtesy NASA.

phic core complexes, thin-skinned tectonics, and deposition of continental sediments in nearby basins.

Unraveling the complex history of the mid-Tertiary orogeny is difficult because not only were early events overprinted, but convenient regional time markers common in the marine record are virtually absent in continental deposits within isolated basins. Isotopic age determinations are often the most effective method of correlation if datable units are available. Laboratory and field studies within the last two decades have provided data that are useful in unraveling various manifestations of the mid-Tertiary orogeny and the subsequent Basin and Range disturbance.

Mid-Tertiary volcanism and accumulation of the earliest post-Eocene continental sediments began at approximately the same time in Arizona. These oldest lava flows either underlie the lower members of what were to become widespread conglomerate and fanglomerate deposits or are intercalated with them. Oligocene volcanics are *rhyolites, andesites,* and *doreites* (calcic latites or high-potassium basaltic andesites), the so-called RAD series (Shaffiqullah and others, 1978).

In New Mexico, voluminous rhyolite ash-flow tuffs were erupted from cauldron complexes of the Hidalgo County volcanic field between 40 and 30 m.y. ago (Deal and others, 1978). The same type of rhyolitic volcanism moved into southeastern Arizona in the Chiricahua, Galiuro, Tucson-Roskruge, and Kofa Mountains between 30 and 20 m.y. ago (Shafiqullah and others, 1978; Bikerman, 1968; Eastwood, 1970). The only well-defined cauldron complex in the southwestern study area, the Superstition-Superior volcanic field, was active toward the end of the orogeny.

More than a million cubic kilometers of silicic lavas were extruded during the mid-Tertiary orogeny within the North America Cordillera extending from the Cascades, Great Basin, San Juan Mountains, and Mogollon-Datil volcanic field to the Sierra Madre Occidental. Most extrusions were from caldera complexes of batholithic proportions (Elston and Bornhorst, 1979) and left a landscape buried in ash flows and punctured by calderas. These volcanic rocks preserved the porphyry copper and other economic deposits from erosion and destruction (Livingston and others, 1968). We assume that similar plutons are now hidden beneath the volcanics in the Sierra Madre Occidental and some have recently been dated in the Sierra Madre Occidental of Silaloa, Mexico (Clark and Damon, 1977).

There was a time-dependent sweep of volcanism from east to west. The peak of mid-Tertiary magmatism was about 32 m.y., 26 m.y., and 21 m.y. ago, respectively in western New Mexico, the eastern mountain region of Arizona, and the Sonoran Desert area. This implies a westward drift for the axis of volcanism of 3-4 cm per year, or 30-40 km per million years. Coney and Reynolds (1977) postulated that the locus of volcanism was a function of the dip of the Benioff zone. According to them decelerating plate convergence and attendant increasing dip during the mid-Tertiary orogeny returned magmatism to Arizona after the post-Laramide quiescence. We suggest that it may also be due to more rapid fusion of the hotter basaltic superstratum of the subducting, newly created, thin oceanic plate as the spreading center approached the trench, resulting in the volcanic axis' moving closer to the trench (see also Pliger and Henyey, 1979).

The coarse clastic continental sediments that accumulated during Oligocene and early Miocene time are well indurated. Poorly sorted, coarse clastic deposits imply short transport distances, which, in turn, implies considerable relief, probably much like that of today. The sizes and shapes of these original basins have been obscured by later events. These clastic units cover approximately 25,000 km^2 of southern Arizona. The older clastic units correlate with the Pantano Formation of Brennan (1962) and its equivalents (Shafiqullah and others, 1978; Marvin and others, 1978). The relationship be-between high-energy coarse clastics and low-energy lacustrine or playa deposits such as siltstone, shale, limestone, tuff, and gypsum may have been largely controlled by distance from basin margin to center. Coarse fanglomerates and conglomerates were deposited in the foothills and on the flanks of the ranges, while evaporites and limestone were deposited in central parts of basins.

The mid-Tertiary orogeny was a time of plutonism, mylonitization, uplift, and cooling of metamorphic core complexes in Arizona. Tectonically overlying the complexes are highly tilted mid-Tertiary rocks, which are sliced by low-angle faults. Both the core complexes and tilting are interrelated manifestations of the mid-Tertiary orogeny.

Discussion of Mid-Tertiary Ages

Most Tertiary plutonic and volcanic rocks older than approximately 30 m.y. are found east of the Sonoran Desert or near its eastern margin (Fig. 5). Marvin and others (1978) cataloged 23 such ages and Shafiqullah and others (1978) reported 5 more.

Thin andesite and rhyolite flows, the oldest volcanic rocks of the orogeny, are found beneath or within the lower units of coarse and poorly sorted continental deposits. The 39.4-m.y.-old andesite flow encountered at a depth of 2,720 m in the Higley basin [58] is contemporaneous with the Rillito andesite in the Tucson Mountains (Bikerman and Damon, 1966). Rhyolite tuffs of similar age have been found in the basal Pantano Formation (Brennan, 1962; Finnel, 1970) of the eastern mountain region (Damon and Bikerman, 1964; Marvin and others, 1973, 1978; Shafiqullah and others, 1978).

The oldest coarse clastic continental sediments in western Arizona lie beneath the earliest lava flows. Conglomerates (fanglomerates) and breccias composed of locally derived detritus, with some clasts in excess of a meter in diameter, rest on crystalline basement rock in the Yuma area. Olmstead and others (1973, p. H2) described two units: a lower, highly deformed assemblage of breccias and arkosic red beds assemblage of breccias and arkosic red beds with dips as great as 60 degrees and an overlying, less deformed assemblage composed "chiefly of conglomerate (fanglomerate) with subordinate breccia, arkosic sandstone and tuffaceous beds," which they named the Kinter Formation. Discontinuity of outcrop and lithologic similarity between units of both assemblages make correlation from range to range extremely difficult. A rhyolite tuff intercalated within the lower unit in the Laguna Mountains has an age of 30.1 m.y. [60].

Olmstead and others (1973) reported an age of 23 m.y. for a tuff bed in the type Kinter section, while another tuff in remarkably similar rocks found in the Muggins Mountains has an age of 22.5 m.y. [78]. This latter tuff lies beneath a horizon containing bones of an early Miocene camel (Lance and Wood, 1958).

Two lava flows in the Chocolate Mountains [66,67] have ages between 25 and 26 m.y., suggesting that the associated clastic rocks are equivalent to the Kinter Formation. These flows are part of the volcanic series in the Chocolate Mountains that ranges in composition from rhyolite ignimbrite to pyroxene andesite (Crowe, 1978). To the north, in the Parker area, two basaltic andesite flows [118,117] of about 16 m.y. are related to Kinter Formation-like fanglomerate. One [118] is a mesa-capping flow, and the other [117] is interstratified with the fanglomerate. This suggests that Kinter-like fanglomerates may have been deposited over a time span of at least 10 m.y.

Mattick and others (1973) noted the presence of Miocene marine rocks in some water and oil exploration drill holes near Yuma. Microfossils provide only a general age, but these rocks unconformably underlie the post-5.5-m.y. [147] marine-brackish water Bouse Formation. Although Olmstead and others (1973) suggested the possibility that these marine rocks may interfinger with the Kinter Formation, according to Eberly and Stanely (1978), they are post-Kinter, Unit II sediments. These marine sediments were deposited before Pliocene time, prior to 5.5 m.y. ago. The Gulf of California did not exist prior to 17 m.y B.P. (Gastil and others, 1979), and that sea did not appear in the Imperial Valley area until late Miocene or early Pliocene time. These mid- to late Miocene marine sediments are approximately 500 m thick near Yuma (Eberly and Stanley, 1978), thickening to over 3,000 m in Sonora, Mexico. They have attracted the attention of oil explorationists.

With the exception of the absence of marine sediments, similar relationships were found in the Gila Bend–Buckeye Hills area during investigations conducted in conjunction with Fugro Associates for the Palo Verde Nuclear Generating Station site study (Shoustra and others, 1976). Volcanism took place in three episodes: 30-27 m.y., 21-15 m.y., and 4-2 m.y. ago Fig. 5). The oldest Tertiary unit in the area contains arkosic red beds, fanglomerates, and breccias resting on the crystalline basement (Miller and others, 1977). Grading to these units and overlying them in the Gila Mountains is a thick, aeolian cross-bedded sandstone of the Sil Murk Formation (Heindl and Armstrong, 1963). These sediments are capped by silicic flows, including a 29.4-m.y.-old, reddish-brown welded tuff [61] and a 26-m.y.-old basaltic andesite [65]. Several basaltic andesite [90,92,97] to andesitic basalt flows [85,88, 94,109] extruded between 21 and 18 m.y. ago. The sequence is intruded by high-potassium basaltic andesite dikes [89,95] that may have been feeders for the flows. The youngest basaltic andesite (16.9 m.y.) was encountered in a drill hole [114]. All of these flows have been tilted and faulted, so considerable difficulty is encountered in tracing or correlating them. They are separated from each other by layers of fanglomerate and for this reason are considered to have been erupted in a tectonically active area. As volcanism and deformation waned, additional weakly consolidated fanglomerate was deposited above this sequence and capped by a 15-m.y.-old basalt [124]. The last of the older fanglomerates north of the area are capped by 14.3-m.y.-old basaltic andesite in the southern Vulture Mountains[126] and by 13.5-m.y.-old basalt in the northern Vulture Mountains (Rehrig and others, this volume). The uppermost basalts are related to the Basin and Range disturbance. The transition from calc-alkalic to basaltic volcanism took place between 16.9 and 15 m.y. ago when the angular unconformity was created in this area.

The Superstition-Superior volcanic field, an extensive rhyolite ash-flow and cauldron complex (Fodor, 1969; Hillier, 1978; Nelson, 1966, D.W. Peterson, 1968; Sheridan, 1978; Stuckless and Sheridan, 1971; Suneson, 1976) is the westernmost of the large Tertiary rhyolite volcanic complexes grouped in New Mexico and eastern Arizona (Deal and others, 1978; Elston and others, 1976). Three calderas were active in this field at different times in the period between 22 and 15 m.y. ago with the most intense volcanism occurring between 21 and 18 m.y. ago. We are reporting three additional ages related to this volcanism [86, 20.6 m.y.], [102, 18.4 m.y. on biotite, 18.8 m.y. on plagioclase], and [103, 18.4 m.y.] including one age [103] on a possible subvolcanic pluton.

Basaltic and trachytic lavas were erupted contemporaneously in the area to the northwest of the Superstition-Superior volcanic field in the same time period. Although the stratigraphy of these flows has not been worked out in detail, dating of some of them has enabled us to assign a maximum age to normal faulting in this area. Two basalt flows [104, 18.3 m.y., and 106, 18.2 m.y.] rest on deformed fanglomerates near the Verde-Salt River confluence. At least two ultrapotassic trachyte flows are mixed with red-bed fanglomerates in the same vicinity; the older, 18.7 m.y., is represented by a boulder [101] in a fanglomerate that underlies the younger, 18.0-m.y., flow [107]. A rhyolite ash flow [111], 17.7 m.y., possibly from one of the calderas to the southeast, overlies this whole sequence. This ash flow and an underlying ultrapotassic trachyte breccia [107], roughly contemporaneous with the rhyolite ash flow at 18.0 m.y., have been erroneously assigned Cretaceous ages on the geologic map. A basaltic andesite [122], 15.5 m.y., is 2 m.y. younger than the rhyolite ash flow and rests on conglomerates containing mid-Tertiary volcanic cobbles as well as metamorphic and granitic cobbles. These conglomerates are also overlain by a younger (14.8 m.y.) basaltic andesite [125]. All of these flows are cut by east-west-oriented, high-angle normal faults that are younger than 15 m.y. The direction of these faults is anomalous with respect to the basin-range direction of north-south to N. 40° W. and may be related to the trend of the Gila–Salt River trough.

We propose the name "Cabeza Prieta volcanics" for the series of intermediate-composition lava flows and associated intrusions found in the southern Cabeza Prieta Mountains (Fig. 6). Rock types include gray hornblende andesite, agglomeratic andesite, and latite. The gray hornblende andesite occurs in an oval outcrop area in the southwestern part of the range and in nearby vertical intrusions (a dike and four circular pipes) within the underlying granite (Figs. 4, 7). Hornblende from the dike [110] yielded an age of 17.9 m.y. The series of parallel, northwest-trending ridges east of Cabeza Prieta Peak are composed of agglomeratic andesite and latite erupted onto a steep topography developed on the Gunnery Range granite. The sinuous latite dike (Fig. 8) extending southward from the base of Cabeza Prieta Peak may have been one of the conduits for the volcanism. A 16.1-m.y. age [119] was determined on whole rock from a flow of this series exposed on Cabeza Prieta Peak.

Structural relationships of the Cabeza Peak volcanics are enigmatic. If the dips are initial and not the result of faulting and block rotation, presence of a large stratovolcano is implied. Removal of a large mountain to leave only these limited exposures is unlikely. The most plausible explanation for the parallel ridges and apparent stratigraphic thickness is faulting and block rotation. Parting in one section of the sinuous dike (Fig. 8) appears to dip southwestward, perpendicular to the flows. However, the ends of this dike are vertical as are other pipes and dikes in the area, providing some evidence against block rotation. Relationships of the flows to the canyons cut in the granite fail to support the idea of posteruptive rotation. Two traverses across the ridges

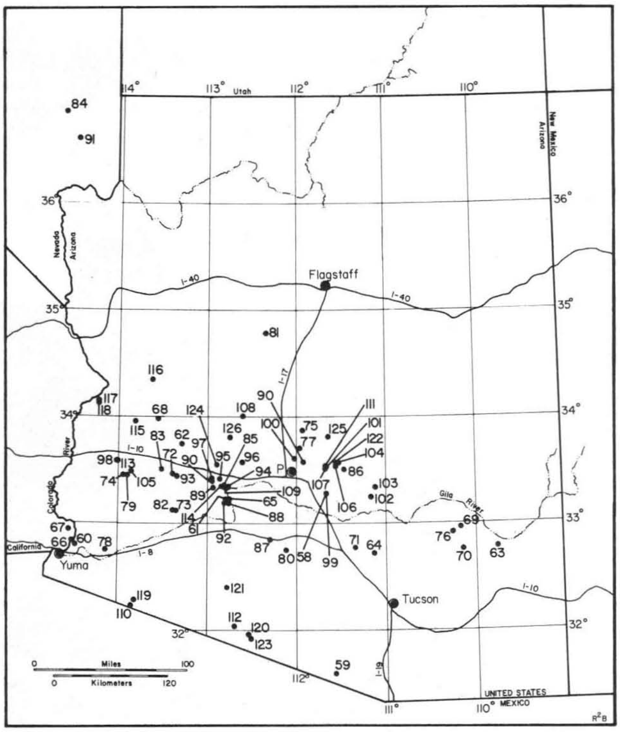

Fig. 5. Sample location for samples with K-Ar ages between 40 and 14 m.y. tabulated in appendix.

failed to find either faults or repetition of section.

Potassic trachyandesites and ultrapotassic trachytes were extruded after 24 m.y.B.P. The ultrapotassic trachytes are commonly reddish-purple, autobrecciated lavas containing more than 8% K_2O. The first such rocks described in Arizona were found at Picacho Peak where K-Ar ages range between 20 and 23 m.y. (Shafiqullah, Lynch, and others, 1976). Further investigations have found similar rocks with K-Ar ages between 16 and 23 m.y. at Turtleback Mountains [82], the southern end of the Painted Rock Mountains, in the Granite Reef area of the Salt River [101,107], at nearly 1,500 m depth in the Paradise Basin [77], and in the Vulture Mountains (Rehrig and others, this volume.)

High-potassium latite occurs at Sullivan Buttes as host rock for eclogite nodules [81]. Younger ages have been determined on ultrapotassic flows in the Picacho basin (15 m.y., Shafiqullah, Lynch, and others, 1976), in the Thumb Formation of southern Nevada (11-12 m.y. [134,135]), and in the Exxon drill hole near Hyder (13.9 m.y. [129]). Rocks of similar major-element composition have been described from rifts such as the Rhine Graben and East African Rift, areas of extensional tectonics.

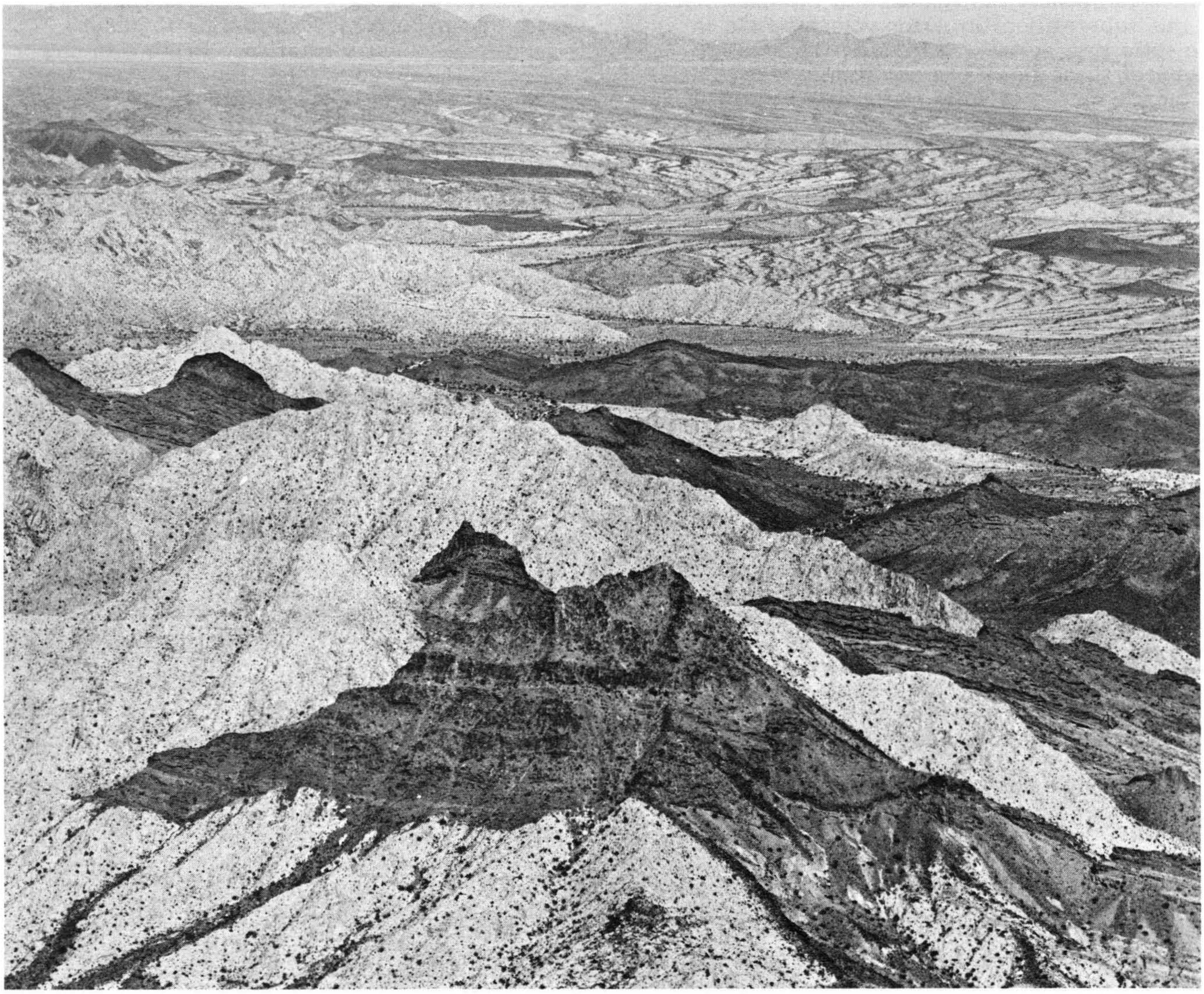

Fig. 6. Cabeza Prieta Peak and the Gunnery Range granite. Dark colored agglomeratic andesite and latite flows dip 30° away from the observer. The agglomerates were erupted into canyons of a steep topography cut in the leucocratic Gunnery Range granite. The lowest flow unit in the foreground ridge yields an age of 16.1 m.y. [121]. Photo by D. Lynch.

Two hypotheses have been suggested to acacount for the genesis of these ultrapotassic rocks in Arizona. They may have formed by fractional crystallization of RAD series magma with removal of plagioclase and ferromagnesian minerals (except magnetite) by filter pressing the residual fluid, which was very rich in the potassium-feldspar component (Shafiqullah and others, 1978). These ultrapotassic rocks have been referred to as the secondary RAD series. The chemical compositions, Sr isotope ratios, and late occurrence following the peak of RAD volcanism suggest that they represent the residuum of differentiated magmas. On the other hand, Keith (1978b) suggested that these magmas were derived from the mantle and attempted to explain their high K-Si ratios as a function of the well-known relationship between potassium and silica and the depth to the Benioff zone (Dickinson, 1975). Whereas chemical composition and timing may be explained by this hypothesis, the high initial Sr ratios of the RAD series require a large crustal component. The low solidification index and high differentiation index support the mechanism of extreme fractional crystallization (Rehrig and others, this volume).

Metamorphic Core Complexes

Metamorphic core complexes and members of the metamorphic core complex "family" have been recognized in southwestern Arizona (Rehrig and Reynolds, 1977; Coney, 1979; Reynolds, this volume; Davis and others, n.d.). Metamorphic core complexes are distinctive geologic features characterized by deformed plutonic rocks and metamorphic rocks whose foliation commonly dips gently and forms broad, asymmetrical arches or domes (Davis and Coney, 1979). The structurally lowest part of the core complex may contain undeformed plutonic rocks. Higher in the structure, the rocks are overprinted by a gently inclined mylonitic foliation, which contains a conspicuous lineation generally consistent in trend over the entire mountain range and often related to other structural features in the region. In some places, upper levels of mylonitic rock may be jointed or brecciated with chloritic or hematitic alteration. The mylonitic rocks converted to chlorite breccia are overlain by a low-angle fault or dislocation surface with steeply tilted or faulted rocks in the upper plate.

In western Arizona, the Harquahala, Harcuvar, Buckskin, and Rawhide Mountains have characteristics of metamorphic core complexes, and in central Arizona, the White Tank and South Mountains and the Buckeye Hills are similar to typical metamorphic core complexes (Rehrig and Reynolds, n.d.). In addition G. H. Davis (n.d.) has described metamorphic core complexes on the Papago Indian Reservation and near Tucson. In the western Arizona and Papago core complexes there is evidence for a Cretaceous or Tertiary metamorphic event (Rehrig and Reynolds, 1977, n.d.; G. A. Davis and others, n.d.; Haxel and others, this volume) the record of which has been locally overprinted by early to middle Tertiary mylonitization and dislocation phenomena related to core-complex processes. The 44-m.y. to 70-m.y. K-Ar ages reported in the appendix for the Rawhide [45], Harcuvar [33,52,55,57], Granite Wash [36,38, 39,41,47], and probably also for the Little Harquahala Mountains [25] reflect cooling after the high-grade metamorphic event Fig. 5). Mid-Tertiary K-Ar ages in the Harcuvar [68,115], Harquahala [62], White Tank [96], Santa Teresa [76], Baboquivari [59]. Pinaleno [63,69,70], Tortolita [64], and Picacho [71] Mountains are probably related to later events of plutonism, mylonitization, and subsequent cooling. Much of the cooling in the core complexes evidently occurred during and slightly after the peak of mid-Tertiary magmatism, while dislocation continued almost until the beginning of the Basin and Range disturbance. The 6.5-m.y. discordance between ages of coexisting biotite and

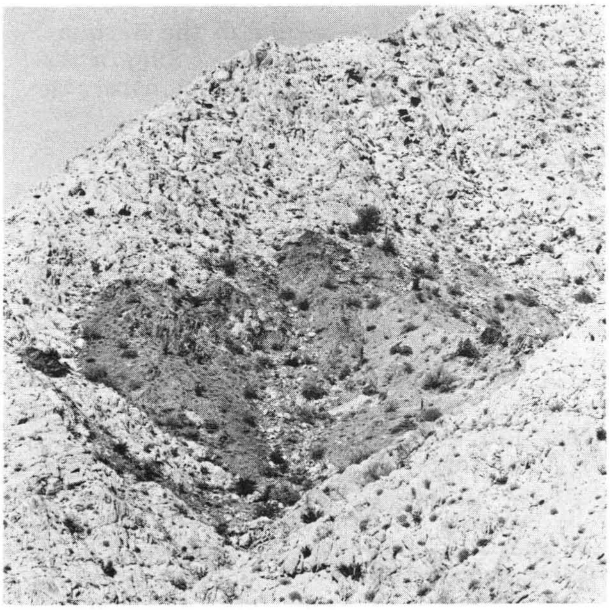

Fig. 7. Hornblende andesite pipe intruded into the Gunnery Range granite. The pipe is of nearly circular cross section, 50 m in diameter with vertical contacts. Light patches are altered blocks of granite entrained in it. The odd outcrop shape is due to erosion and the angle of view. A dike of identical rock located 5 km to the southeast yields an age of 17.8 m.y. [111]. This pipe is located in the granite ridge that extends south from Tordillo Mountain in the western Cabeza Prieta Mountains. Photo by D. Lynch.

hornblende from a diorite dike in the Harquahala Mountains [62] implies slow cooling of the area from 450°C to 250°C during the core-complex evolution.

Mid-Tertiary Angular Unconformity

Older mid-Tertiary rocks are generally tilted, some to vertical attitudes, and the time of rotation can be bracketed in some places by the ages of lava flows within the tilted sequences compared to younger associated flat-lying lava flows. The tilting has created a profound unconformity of regional extent but local construction; different sections were created at different times between 17 and 12 m.y. B.P. (Table 1; Fig. 9; Damon and others, 1973). Eberly and Stanley (1978) confirmed the presence of this unconformity in many of the basins by refraction profiling, but they suggested that it is a time marker created in a relatively short period between 13 and 12 m.y. ago, a conclusion not supported by our data.. The nature of the tilting process is well displayed in the Kofa Mountains where three lava flows have different attitudes. The oldest, a 23.6-m.y.-old rhyolite [74] that rests on a surface eroded on metamorphic rock, dips 53 degrees. Unconsolidated gravels lying on this flow separate it from a 21.7-m.y.-old olivine basalt [79] with a 30° tilt. The sequence was erosionally beveled, and a flat-lying 18.3 m.y.-old basaltic andesite [105] caps the surface. Rotation apparently progressed here over several million years.

In the Rawhide-Buckskin-Artillery Mountains area of western Arizona, tilted, nonmarine, brick-red, arkosic sandstone, conglomerate, and breccias of the Chapin Wash Formation unconformably overlie the Artillery Formation. A 16.3-m.y.-old basalt flow [116] occurs within the disrupted and deformed Chapin Wash Formation. Eberly and Stanley (1978) reported a 13 ± 2-m.y. age for a tilted flow overlying the Chapin Wash Formation in the Artillery Moun-

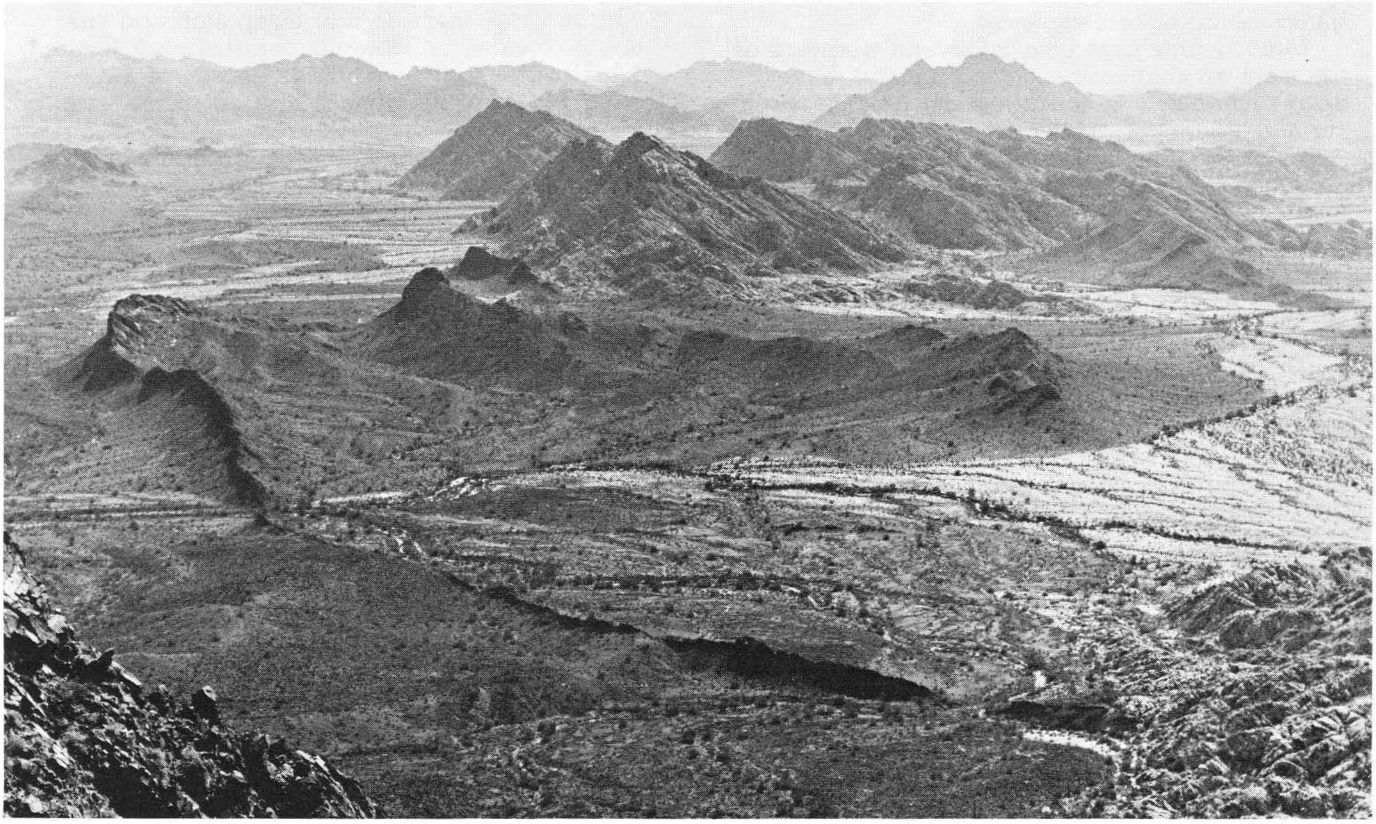

Fig. 8. Prominent dike in the Cabeza Prieta Mountains. This dike extends 3.2 km from the base of the Cabeza Prieta Peak (lower right) to unnamed hills of Gunnery Range granite (middle background). It is vertical at both ends although parting in the curved portion (left) appears to dip about 45° to the southwest, nearly parallel to jointing in the hills of granite in the middle background. The dike may have been a conduit for the Cabeza Prieta volcanics. Photo by D. Lynch.

Table 1. Potassium-argon ages bracketing local unconformities in the Arizona Basin and Range province. The first column gives the time by which rotation must have ceased, because the dated flow and flows younger than it are flat lying. The second column lists ages of flows involved in the rotational tectonics, showing the tilting episode to have been in progress at the time the flows were erupted.

	K-Ar Ages, m.y.		Reference	
Area	Oldest flat-lying volcanic flows	Youngest tilted volcanic flows	Appendix	Other than Appendix
Kofa Mountains Yuma County	18.3	21.5	[105,79]	
Black Mesa Yuma County	17.2	19.4	[113,98]	
Rawhide Mountains Mohave County	9.6	16.3	[140,116]	
Castaneda Hills, Mohave County	10.3	16.5		Suneson and Lucchitta, 1979
Lake Mead area, Mohave County	11.0	14.0		Anderson and others, 1972
Vulture Mountains, Maricopa County	13.5	16.0		Rehrig and others, this volume
Palo Verde, Maricopa County	15.0	16.9	[124,114]	
Florence area, Pinal County	14.1	18.0		Damon and others, 1973
Picacho area, Pinal County	15.1	20.7		Shafiqullah and others, 1976
Roskruge Mountains, Pima County	13.0	23.5		Bikerman, 1967
Ajo Mountains, Pima County	15.4	17.4	[123,112]	

tains. A 9.6-m.y.-old basalt flow [140] from Manganese Mesa is nearly flat lying. These ages bracket the tectonic deformation in the Rawhide Mountains between 13 and 9.6 m.y. B.P. Suneson and Lucchitta (1978) noted that 16.5-m.y.-old flows in the nearby Castaneda Hills are steeply tilted, while 15.1- to 10.3-m.y.-old flows have shallow dips or are flat lying. Their data show that major tilting took place between 16.5 and 15.1 m.y. B.P.

At Black Mesa in the Eagle Tail Mountains east of Quartzsite and in the Organ Pipe Cactus National Monument, relationships between tilted and flat-lying flows are inferential. The older sample from Black Mesa [98] is a 19.4-m.y.-old rhyolite vitrophyre breccia that is assumed to be related to steeply tilted ash-flow units on a nearby hill, although the attitude of the sampled outcrop is obscured by detritus. Vitrophyre is often found within rhyolite flows. Unconsolidated gravels 10 to 15 m thick separate this rock unit from the mesa-capping basalt ([113], 17.2 m.y.) (Fig. 10).

Rhyolite flows and associated pyroclastic rocks in the Eagle Tail Mountains are cut by a large porphyritic rhyolite dike that strikes N. 50° W. The flows are tilted approximately 40° SW., and the dike dips about 80° NE. The flows rest on metasedimentary and plutonic basement rocks; a dated granodiorite yielded an age of 52.8 m.y. [50]. Age of the lowermost rhyolite flow [72] is 23.7 m.y., making it contemporaneous with similar rocks in the nearby mountains: Kofa [74], Muggins [78], and Vulture (28 m.y., Rehrig and others, this volume). Courthouse Rock [93], an apophysis of the major dike, is 20 m.y. old. Tilting of this structural block occurred after 23.7 m.y. B.P. , and apparently the dike was intruded in a nearly vertical attitude.

Remnants of gently tilted basalt cap some of the Eagle Tail ridges. Gravel separates this basalt from the underlying tilted volcanic rocks in the Eagle Tail Mountains in a manner similar to the relationships at Black Mesa. A 20.9-m.y.-old basalt flow [83] resting on gravel in a small hill north of Courthouse Rock was sampled on a reconnaissance trip on the assumption that it was the same unit as the ridge-capping flow remnants. Tilting in this area appears to have occurred between 23.7 and 20.9 m.y. B.P.

A tilted, 17.4-m.y.-old rhyolite flow [112] in the Organ Pipe Cactus National Monument in the Ajo Range is stratigraphically above the distinctive porphyritic, red-brown Childs Latite, which dips 20° E in some places (Jones, 1974; May and Peterson, unpublished geologic mapping). A younger, 15.7-m.y.-old rhyolite [120] and a 15.4-m.y.-old basaltic andesite [123] in the Gu Vo Hills are nearly horizontal. Tilting in the Ajo area began before 17.4 m.y. B.P. and ended around 15 m.y. B.P. The basaltic andesite [123] is correlative with the 15.5-m.y.-old Batamote Andesite [121] at Ajo.

As discussed previously, a volcanic and tectonic transition within the Palo Verde area took place between 16.9 m.y. B.P. [114] and 15 m.y. B.P. [124]. Immediately north of the area, Rehrig and others (this volume) bracketed the transition between 16 and 13.5 m.y. B.P.

Tilting was apparently accomplished by rotation of relatively small crustal blocks along shallow listric normal faults in a manner similar to that proposed by Proffett (1977), although only a few of the curved fault surfaces are exposed. Nearly horizontal fault surfaces are exposed in some places where thin allochthonous plates have been transported indeterminate distances. One of the best-documented examples in Arizona is found in the Rawhide and Buckskin Mountains where movement was to the northeast (Shackelford, 1976; Davis and others, n.d.). A basalt flow [116] within the Chapin Wash Formation, which was overridden along the Artillery Fault by Precambrian gneisses near the front of this allochthonous

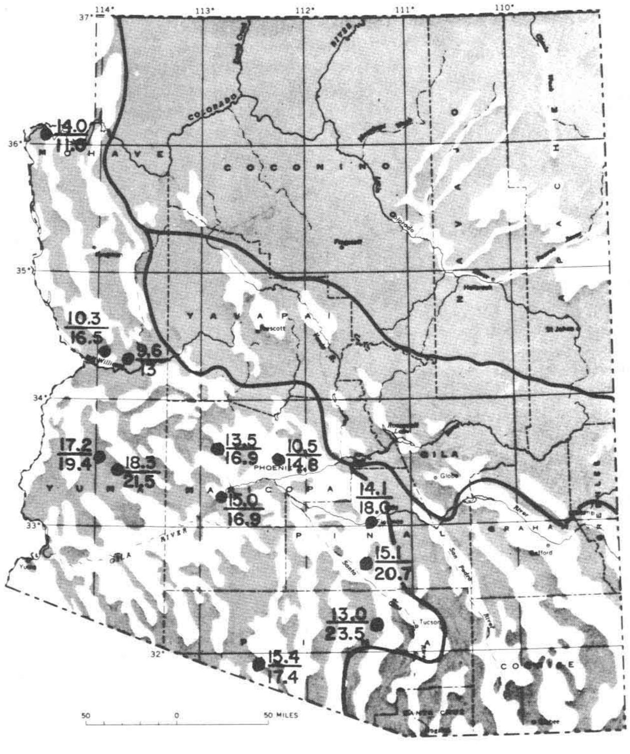

Fig. 9. Location and ages of rocks associated with the angular unconformity. Figure shows the youngest deformed rock and the oldest undeformed rock in each area where the unconformity is developed.

terrain, has an age of 16.3 m.y., showing that at least part of the motion along the fault was contemporaneous with tilting in other places. Lasky and Webber (1949) considered it an Eocene thrust.

Suneson and Lucchitta (1979) noted pre-16.5-m.y.-old low-angle faulting in the Castaneda Hills quadrangle of west-central Arizona. Shafiqullah and Langlois (1978) described motion on the nearly horizontal San Xavier thrust south of Tucson as younger than 24 m.y.

In the Whipple Mountains of southeastern California, nearly vertical Tertiary volcanic and sedimentary strata stand on a nearly horizontal dislocation surface like books on a shelf (Davis and others, 1979). Gilluly (1946) described a similar feature on North Ajo Peak where the 30°-S.-dipping Locomotive Fanglomerate and Ajo Volcanics rest on a horizontal contact with underlying Cardigan gneiss. He identified this as a sedimentary contact on an erosion surface of considerable relief, but it can also be interpreted as a listric fault contact.

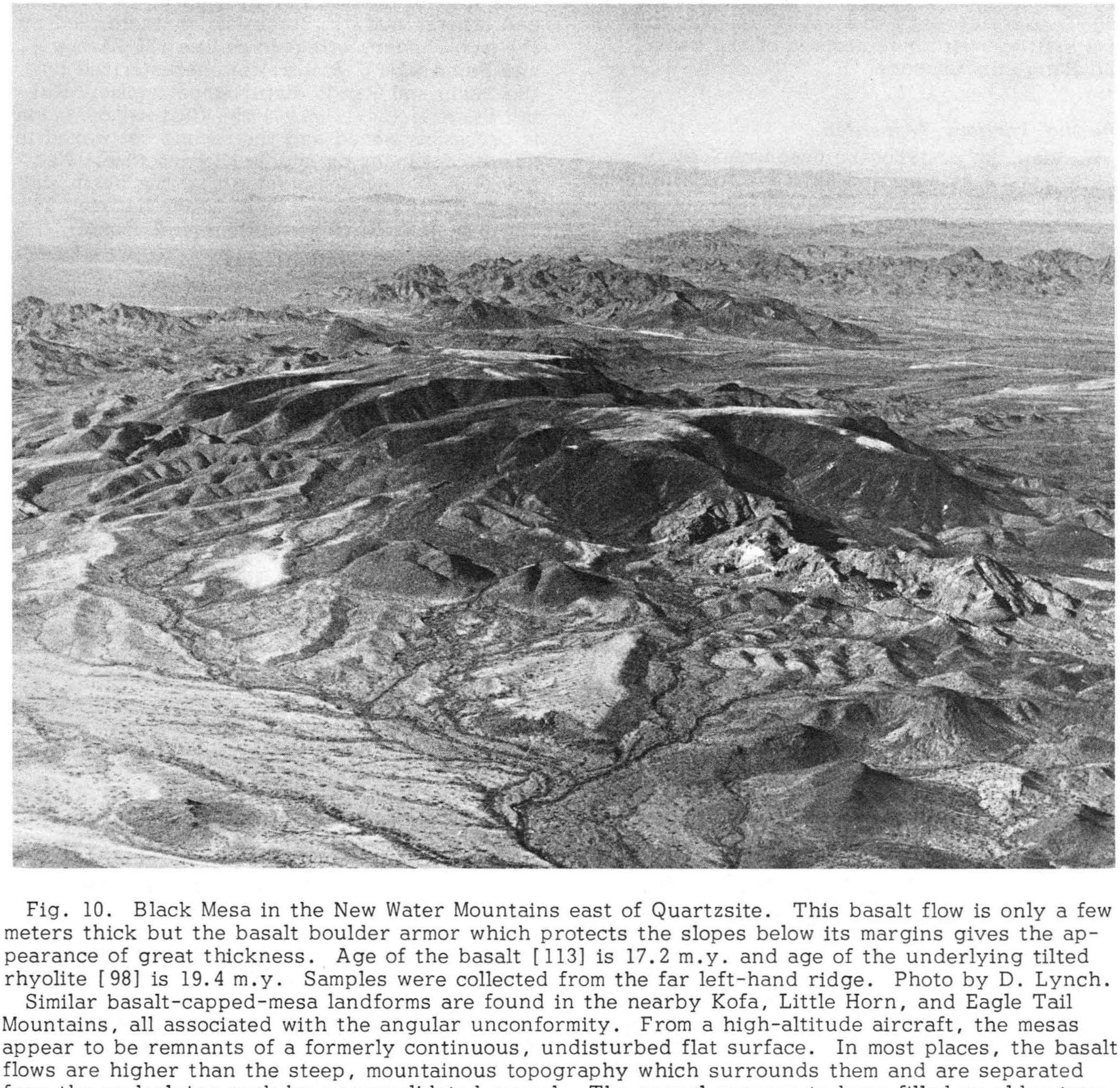

Fig. 10. Black Mesa in the New Water Mountains east of Quartzsite. This basalt flow is only a few meters thick but the basalt boulder armor which protects the slopes below its margins gives the appearance of great thickness. Age of the basalt [113] is 17.2 m.y. and age of the underlying tilted rhyolite [98] is 19.4 m.y. Samples were collected from the far left-hand ridge. Photo by D. Lynch.

Similar basalt-capped-mesa landforms are found in the nearby Kofa, Little Horn, and Eagle Tail Mountains, all associated with the angular unconformity. From a high-altitude aircraft, the mesas appear to be remnants of a formerly continuous, undisturbed flat surface. In most places, the basalt flows are higher than the steep, mountainous topography which surrounds them and are separated from the underlying rock by unconsolidated gravel. The gravel appears to have filled an older topography which has been subsequently exhumed.

The 25-m.y. date (Eberly and Stanley, 1978, their #108) for the flow resting on the andesite breccia of the Ajo Volcanics establishes a maximum age for this deformation.

In summary, the mid-Tertiary angular unconformity was created over a 6-m.y. period by rotation of crustal blocks along shallow listric normal faults. This rotation can be viewed as the time-transgressive termination of the mid-Tertiary orogeny that occurred at different times in different places. The flat-lying beds that mark the end of the rotation signify a change in style of tectonism from listric faulting associated with ductile strain during the mid-Tertiary orogeny to steep normal faulting of a brittle crust characteristic of the Basin and Range disturbance.

The Mid-Tertiary Transition

We view the post-Eocene geochronology of southwestern Arizona and adjacent areas in terms of a mid-Tertiary orogeny followed by the Basin and Range disturbance, two geologic "events" with differing processes. However, the two "events" are not completely separate in time, and processes characteristic of the Basin and Range disturbance apparently began while those of the mid-Tertiary orogeny were waning. For example, although basaltic magmatism is characteristic of middle Miocene to present time, there is evidence for some scattered and sparse basaltic volcanism in early Miocene time [73,75,79,80,83,85,87,88,104, 106]. Also, although listric faulting is characteristic of the mid-Tertiary, there may be some overlap with the steep normal faulting characteristic of the Basin and Range disturbance. We believe that this sort of overlap is characteristic of many geologic phenomena.

Extensive intrusive bodies, mylonitization, and listric faulting can best be explained by batholithic intrusions of magma into the crust. Such batholiths, once in existence, do not solidify rapidly, nor do elevated geothermal gradients undergo sudden change. The ascent of uncontaminated basaltic magmas to the surface during the Basin and Range disturbance is evidence of a relatively cool and chemically inert crust (Damon, 1971). There was a transition from high-silica basalts with somewhat elevated initial Sr ratios to normal alkaline olivine basalts with primitive ratios during this physical transition (Damon, 1971; Damon and others, n.d.; Damon and Shafiqullah, 1976; Leeman, 1970; Shafiqullah and others, 1978). This can be explained by the lowering of geothermal gradients after solidification of crustal batholiths. The existence of large volumes of partially to completely melted magma within the crust has been referred to as the invasion of the lithosphere by the asthenosphere by Damon (1971). These physical processes imply a transition as solidification and cooling began high in the crust and proceeded downward until finally in middle to late Miocene time, the crust was sufficiently brittle to allow transit of uncontaminated basalts to the surface.

The beginning of oblique shear that occurred in mid-Miocene time, as evidenced by movement along the San Andreas transform (Atwater, 1970) may have accelerated a transition, already underway, between the two tectonic regimes. In any case, because of the practical difficulty of completely separating these two tectonic regimes, we have used a three-stage concept in other papers (Shafiqullah and others, 1976, 1978; Damon and others, n.d.). Stage I is characterized by the mid-Tertiary orogenic regime (36-24 m.y.), and Stage III (12-0 m.y.) is characterized by the Basin and Range disturbance regime. During Stage II (24-12 m.y.) the first set of tectonic processes waned and the second set waxed to become dominant by middle Miocene time. We have the distinct impression that the Basin and Range disturbance was most active between 14 and 8 m.y. B.P. in southwestern Arizona.

The Basin and Range Disturbance

The Basin and Range disturbance, which succeeded the mid-Tertiary orogeny, was characterized by brittle failure of the crust along steep normal faults. The crust broke, forming a series of essentially parallel horsts and grabens that form the ranges and basins of the modern physiography. Erosion has widened the valleys, burying the bounding faults beneath alluvial fans and causing mountain fronts to retreat across wide pediments. Refraction profiling described by Eberly and Stanley (1978) shows the underlying horst-graben structure in the alluviated basins. Thin-skinned rotational tectonics persisted in some areas until 14 m.y. B.P., but this was not a characteristic of the Basin and Range disturbance, as was suggested by Proffett (1977) for the Yerington, Nevada area. Some investigators have carried the beginnings of the Basin and Range disturbance back into Oligocene time, to as early as 32 m.y. B.P. (Crowe, 1978), because some structures of the mid-Tertiary orogeny are parallel to the modern basins. Peirce (1976a) clearly separated formation of deep basins from the earlier rotational events.

Lava flows encountered by drilling in the deep basins indicate that basin subsidence began some time after 19.4 m.y. B.P. and most probably after 15 m.y. B.P. (Shafiqullah and others, 1976). Subsidence of all the deep basins in the Sonoran Desert region was probably not simultaneous, but most of the deepening occurred prior to about 8 m.y. B.P. At that time in the Sonoran Desert, differential vertical movement essentially ceased, pediments formed, and basins filled. Vertical movements of the Basin and Range disturbance have continued into modern time in the eastern and central mountain regions where relatively new fault scarps are found in varying stages of erosion. The most recent fault scarp, along the eastern margin of San Bernardino Valley, was created by a large earthquake in 1887 (Aguillera, 1888; Sumner, 1977).

Land-subsidence fissures are found in many of the alluviated basins of southern Arizona where ground water withdrawal has caused compaction of the valley-fill sediments and subsidence of the surface (Holzer and others, 1979; Laney and others, 1978; Raymond and others, 1978; Peirce, 1979). Often the fissures form over or near the basin-margin faults, giving the appearance of a close relationship between tectonic and compaction features. In the Picacho Basin, an area of nearly 300 km^2 has subsided 2 to 4 m within the past 25 years. This unusually rapid subsidence rate, in excess of 100 km/m.y., can only continue for a geologically short period of time, until the sediments are compacted. Active tectonism is not a good explanation for these features because movement is both rapid and aseismic.

The mechanism of horst-graben formation requires crustal extension in a direction perpendicular to the trends of the structures. The strong north-south to N. 40° W. trends of southwestern Arizona basins and ranges suggest westward- to southwestward-directed crustal extension in this region, but this model is complicated by structures that cut the main, basin-range, trends at sharp angles. Most prominent of these structures is the N. 60° E.-trending Harcuvar-Harquahala Mountains. Others are the Gila trough, a graben 10 to 25 km wide and over 100 km long, which extends N. 75° E. from the Gila Mountains to the Maricopa Mountains, and the Salt River trough, which trends parallel to the Gila trough in the Phoenix-Luke area. Subsidence of these basins as grabens required extension in a nearly north-south direction. Eberly and Stanley (1978) suggested reactivation of Precambrian structures to account for the Gila trough, and their refraction profiling shows that this graben is filled with mid-Tertiary sediments, making it older than the Basin and Range disturbance. Displacement of the 15-m.y.-old lava flows [106,125] east of the Phoenix area along east-west-trending faults suggests the possibility that this structural direction may have been active during the time of main basin subsidence.

Volcanism associated with the Basin and Range disturbance was almost entirely basaltic, with strontium isotopic ratios between 0.703 and 0.705 indicating origin in the mantle and transit through the crust without appreciable contamination (Damon, 1971; Damon, Shafiqullah, and Lynch, n.d.; Damon and Shafiqullah, 1976; Shafiqullah and others, 1978; Leeman and Rogers, 1970; Leeman, 1970). Although volcanism was concurrent with regional faulting, the volcanoes were not directly related to the individual faults either in time or space. The younger volcanoes are grouped in volcanic fields. This precludes the oft-invoked idea that movement along "deep basin-range faults" is somehow responsible for genesis of the magmas. Suneson and Lucchitta (1979) reported bimodal basalt-rhyolite volcanism in the Castaneda Hills of west-central Arizona.

Discussion of Ages

The best older age limit, 19.4 m.y., on basin subsidence is provided by a poorly welded tuff [99] encountered at a depth of 2,400 m in the Higley Basin. Dacite tuff in the San Tan Mountains on one side of this basin has been correlated with tuffs of the Superstition volcanic field on the other side (Balla, 1972; Stuckless and Sheridan, 1971), and both are correlative with this 19.4-m.y.-old unit now 3,000 m structurally below them. The inference is tuff eruption over a surface of low relief followed some time later by basin subsidence. Unfortunately, units like this mark only the maximum time for the beginning of subsidence. The tuff [99] is separated from an older andesite [58] beneath it by a 300-m-thick layer of gravel. Many of the other lava flows [62,74,75,77-80,87,90,98,107, 111,116,117,119] within the age range from 22 to 15 m.y. rest on similar gravel layers, suggesting that erosion may have beveled much of the area and drainage systems may have distributed gravel across the area before the onset of basin subsidence (Figs. 5 and 11). The last few cited samples are further evidence for a 15-m.y. B.P. beginning of subsidence.

Most of the preserved gravel layers on range blocks occur at elevations between 1,000 and 1,400 meters (San Tan, Mc Dowell, Eagle Tail, and Kofa Mountains and Table Top Mountain). This may be coincidental or may be related to the idea emphasized by Peirce (1976a) Peirce and others (1979), and Damon and others (n.d.) that the basins subsided while the surrounding ranges did not change absolute elevation. Isostatic considerations would favor such a model.

A thick sequence of nonmarine sediments accumulated in the Lake Mead area of southern Nevada and northwestern Arizona during the mid-Tertiary. The depositional basin predated

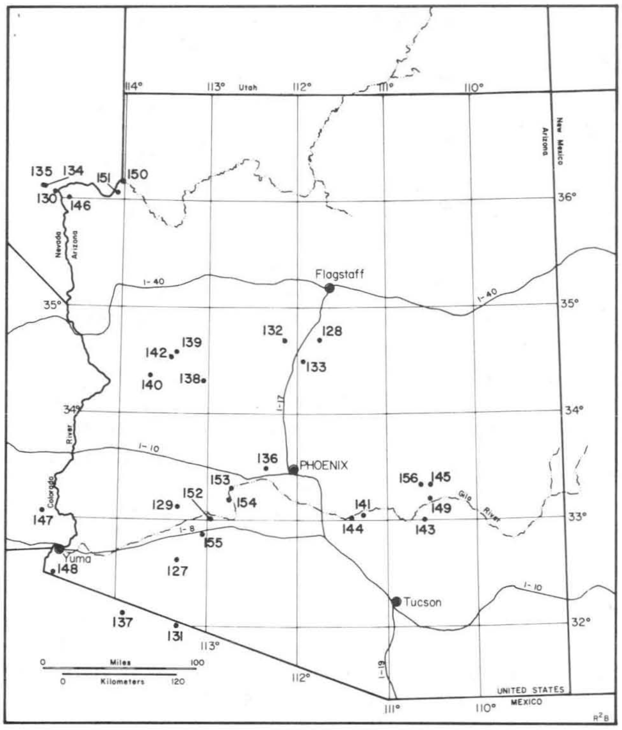

Fig. 11. Sample location map for samples younger than 14 m.y. tabulated in appendix.

the Basin and Range disturbance. Coarse biotite from andesitic tuff intercalated within the Rox conglomerate in Meadow Valley Wash, near Rox, Nevada yielded a 20.7-m.y. age [84]. The Rox conglomerate, deposited on a major thrust plate of the Sevier orogeny, is related to the doming of Mormon Mountain, and correlates with the base of the Muddy Creek Formation (Olmore, 1971).

One of the Horse Spring Formation tuff layers [91] near Glendale, north of the Muddy Mountains, yielded a 20-m.y. date; Armstrong (1970) obtained a 21.7-m.y. date from a similar tuff from an adjacent locality. The Rox conglomerate apparently overlaps in age the Horse Springs Formation of Anderson and others (1972). Both Thumb and Horse Springs Formations are complexly faulted and laced with sills and flows that yielded 13.6- to 11.2-m.y. ages [130,134,135]. Some of the flows are highly potassic trachytes. Our data confirm a Miocene age assignment of the Thumb Formation. Bohannon (1978) correlated the Horse Spring Formation with the lower clastic unit of the Thumb Formation. The tectonic deformation in the area occurred between 15 and 11.1 m.y. B.P. and consisted of simultaneous volcanism, plutonism, uplift, and faulting, followed by initiation of the Basin and Range disturbance between 12.7 and 11.1 m.y. B. P. (Anderson and others, 1972).

Lava flows in the Sonoran Desert region that are older than about 9 m.y. have been affected by high-angle normal faults. The 14-m.y.-old basalt table at the north end of the Aguila Mountains [127] is stepped "piano-key" fashion along closely spaced vertical faults that strike N. 40° W. (see Fig. 3, Geologic Road Logs, this volume). To the south, across the border in Sonora, a remnant andesite flow east of Los Vidrios [131] (13.35 m.y.) is cut by north-south faults and part of the table is tilted to the west. The 10.5-m.y.-old Mesas de Malpais flow [137] on the Sierra Vieja-Tinajas Altas Mountain block is offset by vertical faults that strike N. 60° W. These examples record motion along faults that are within range blocks and are not basin-margin faults. The lava flow at China Wash east of Florence [141] may be on or near the eastern basin-margin fault. Scarborough (1976, personal commun.) noted only a few meters of offset on this 8.9-m.y.-old lava flow. Neither the lava flows of the Sentinel Plain-Arlington volcanic field (younger than 3.2 m.y.) nor the flows of the Pinacate volcanic field (younger than 1 m.y.) are offset.

Vertebrate fossils of "...definitely Pliocene and probably late Pliocene age..." have been collected from the Big Sandy Formation (Sheppard and Gude, 1972). Lance (1960) identified the fauna as Hemphillian. A basalt flow intercalated within the sediments near the fossil horizon yielded an age of 9.6 m.y. [139] and the basalt flows from Burro Creek, 5 km south, which are contemporaneous with the sedimentation, yielded ages of 8.8 and 8.2 m.y. [142]. K-Ar age determinations show a late Miocene age for these sediments.

The Big Sandy Formation consists of nearly horizontal, green and brown lacustrine and fluviatile sediments. Sediments similar to these are capped by a 10.0-m.y.-old basalt flow [138] at Malpais Mesa on the Santa Maria River, about 35 km to the southeast. Apparently, these relatively thin deposits accumulated in isolated basins along the margins of the central mountain region during the early part of the Basin and Range disturbance.

Plio-Pleistocene Volcanism

Ages of basalt volcanism in the time of the Basin and Range disturbance appear to fall into two groups, with few ages in the period between 8 and 4 m.y. The post-4-m.y. volcanism is restricted to four volcanic fields: the Sentinel Plain-Arlington and Pinacate volcanic fields in the Sonoran Desert and the San Carlos-Peridot and San Bernardino volcanic fields in the eastern mountain region. Contemporaneous basaltic volcanism is found on the Colorado Plateau and its margin. Except for Santa Clara volcano in the Pinacate volcanic field, all of these young volcanoes appear to be monogenetic.

Monogenetic volcanoes are created in single eruptions of relatively short duration by magma passing through a conduit which is open for that single eruption only. Wood (n.d.) found that modern cinder cones were built by eruptions that lasted from a week to a few months. Since the volume of basalt extruded in the average young volcano is between 10^5 and 10^8 cubic meters, magma velocity and heat transfer considerations suggest similar week to month-long eruptions (Fedotov, 1976). Apparently, basalt magma is generated in small batches within the upper mantle at depths ranging from 60 km to the base of the crust (Leeman and Rogers, 1970; Evans and Nash, 1979). Conditions under which the magma is generated, collects into a body and begins to rise are obscure but each batch bores its own conduit through the crust as a dike-like body oriented parallel to the maximum and intermediate stress directions (Nakamura, 1977; Fedotov, 1976).

The Pinacate volcanic field is the most recently active and largest of these young volcanic fields. Some cones and lava flows are only slightly desert varnished and are essentially not eroded, suggesting eruption within the past few thousand years at most. K-Ar ages and erosional morphology indicate continuing episodic volcanism over the past million years, which is currently dormant but not extinct. Monogenetic volcanism covers nearly 2,000 km^2 of desert adjacent to the Gulf of California including much of Santa Clara volcano, a trachyte shield volcano that is slightly older than the overlying basalt. Santa Clara was created by successive eruptions from a single magma body through the same conduit complex, as the magma differentiated from basalt to trachyte over a half-million year period (Lynch, 1978b).

The Pinacate volcanic field has more than 500 cinder and agglutinate cones and ten maar crater tuff rings, the latter products of steam-blast explosions (Gutmann, 1976, 1979; Jahns, 1959). Like cones of the San Bernardino volcanic field (Lynch, 1978a), the Pinacate cones show a complete range of erosional morphology from fresh cones to remnant plugs. Spacing between cones ranges from a few hundred to a few thousand meters. Unlike San Bernardino, there is no strong alignment of contemporaneous volcanoes.

The Sentinel Plain-Arlington volcanic field near Gila Bend covers an area almost as large as the Pinacate volcanic field but it is much different in appearance. Only 16 eruptive centers can be identified, 12 on the Sentinel Plain south and east of the Painted Rock Mountains and another four arrayed along an axis that stretches 50 km N. 45° E. from Sentinel Plain to Arlington. Cone spacing is 6 to 25 km and all cones appear to be of the same age, as there is no range of erosional morphology. Lava flows are thin, 1-3 m, and most of the cones are broad, low-aspect lava cones indicative of low-viscosity lava that erupted without significant cinder production. The cone and flow surfaces appear old. All are weathered to "round rocks," and caliche is well developed in cracks and beneath cobbles. No occurrence of two or more lava flows stacked one on another has been observed in this field and the general impression is of nearly simultaneous eruption from all vents, although this may be an effect of erosion.

The Sentinel Plain-Arlington volcanic field generated considerable interest because of its proximity to the Palo Verde Nuclear Generating Plant Site (Fig. 12). K-Ar ages were determined on a large number of samples for the site safety report (Shoustra and others, 1976). Ages determined by this laboratory are reported in the appendix [152-155]. The ages determined cover a large range, even for different parts of the same volcano, and some appear to conflict with field interpretations. This range attests to the difficulty encountered in dating young volcanic rocks. Experience gained from this work has led to further improvement of our dating technique for young volcanic rocks.

Only two ages have been determined on the Sentinel Plain portion of the field. A sample from an I-8 roadcut near Midway cone [155] was dated at 1.71 m.y. and Eberly and Stanley (1978) [108] reported 3.0 m.y. for the eroded flow margin south of the Gila River on the Sentinel-Agua Caliente road. Warford Ranch cone, closest to the northeast, yielded an age of 3.19 m.y. [152]. Woolsey cone in the pass southeast of Woolsey Peak is next in line to the northeast. The three ages reported by Shoustra and others (1977) for Woolsey cone are equivocal but less than 6.5 m.y.

Gillespie cone, next to Gillespie Dam, and Arlington cone, 10 km to the northeast, are closest to the nuclear power plant site and are the most thoroughly investigated. Euge and others (1978) referred to "ten radiometric dates" ranging from 4.2 to 1.3 m.y. for the "composite of several flows" of the Gillespie cone, with an average age of 3.3 m.y. for the median five. Two of the ages, including the youngest from the vent area, are listed in the appendix [154]. The Arlington cone has six radiometric age determinations ranging from 3.2 to 1.6 m.y. [153], with the youngest being on the vent area. Cone and flow morphology imply that the time range of volcanism, as indicated by the radiometric ages, is too long. Theoretical considerations and reconnaissance field work suggest that Gillespie and Arlington cones are monogenetic volcanoes.

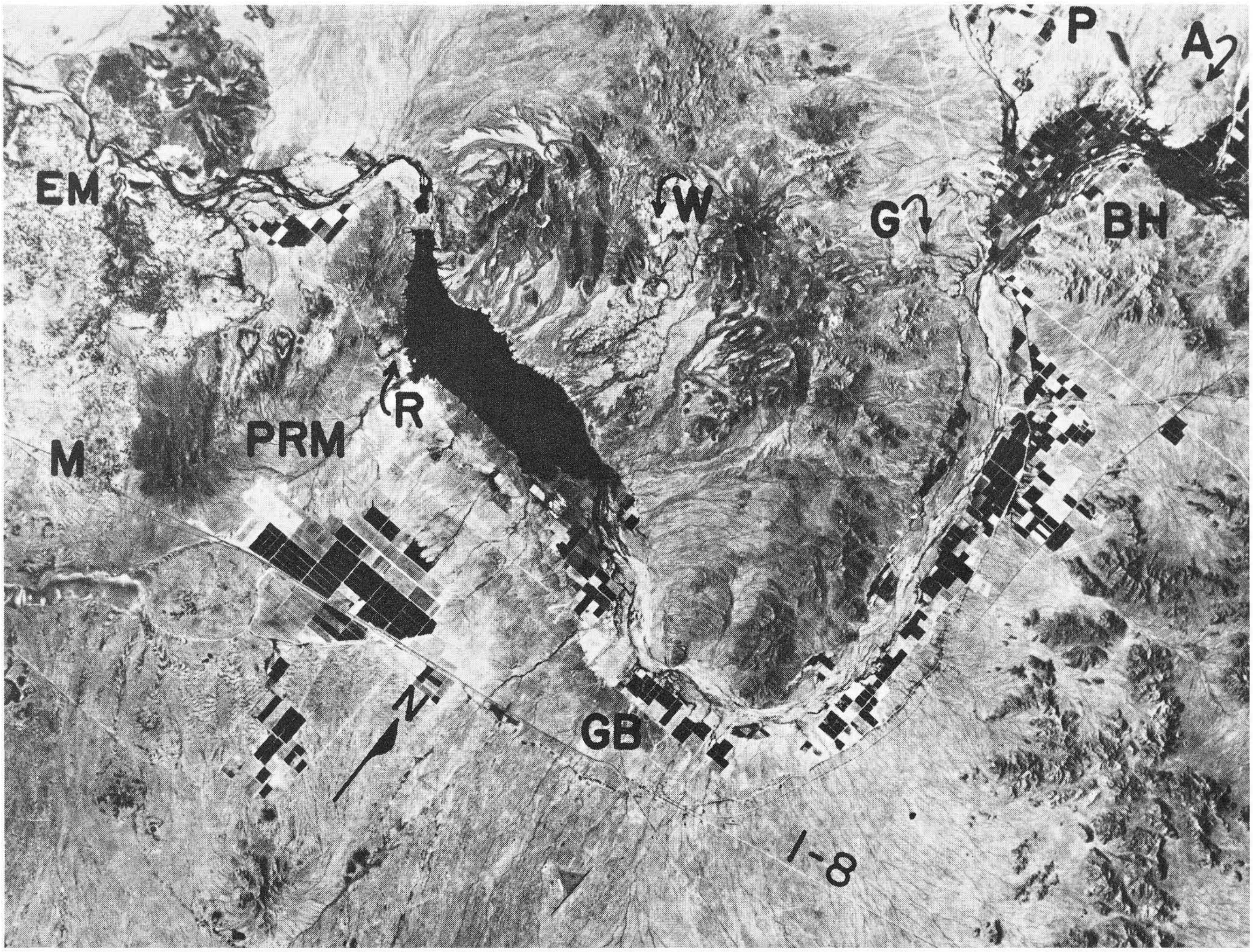

Fig. 12. The "Gila Bend" and the Sentinel Plain-Arlington volcanic field. Most of the young basalt flow surfaces in this volcanic field have a characteristic "stipple" pattern. GB, town of Gila Bend; PRM, Painted Rock Mountains, basalt-covered Sentinel Plain to the left, Painted Rock Reservoir (black) to the right; EM, meanders of the Gila River entrenched 40 m through the basalt surface; M, Midway cone [155]; R, Warford Ranch cone [152]; W, Woolsey cone, the lava flow extends down toward the east end of the reservoir; G, Gillespie cone [154]; BH, Buckeye Hills; A, Arlington cone [153]; P, Palo Verde Nuclear Generating Plant site. Skylab photograph courtesy of NASA.

Preliminary analysis of cone shape and distribution on the Sentinel Plain suggests a crude N. 40° W. alignment direction, parallel to the topographic grain of the mountain ranges to the southwest. Cone distribution along the N. 45° E. extension of this field to Arlington cone is too linear to be random and is probably related to the sources of magma.

The San Carlos-Peridot volcanic field is also located on the Gila River but, unlike Sentinel Plain-Arlington, it consists primarily of lava flow remnants because the gravels upon which the flows were erupted have been deeply eroded. Despite the presence of Peridot Mesa, a famous source of olivine megacrysts (gem peridot) and a vast array of ultramafic nodules of mantle origin (Ross and others, 1954), this volcanic field has not been studied in great detail. Holloway and Cross (1978) described rock compositions from this field as alkali-basaltic; the dated vent at Soda Springs is mugearite, a member of the basalt-alkali differentiation suite. An age of 5.28 m.y. was determined on an anorthoclase megacryst from the mugearite [149]. Basalt from Peridot Mesa [156] yielded an age of 0.93 m.y. Wohletz (1978) described the Peridot Mesa vent as a diatreme/tuff ring and suggested that the lava flow is a rootless flow produced by lava fountaining over the first-erupted bedded tuffs. The volume of the flow is rather large for such an origin.

Cenozoic Climate

Cenozoic climate in southern Arizona was arid as indicated by red beds, evaporite deposits, the condition of clasts in fanglomerates, preserved landforms, and the weathering state of bedrock. Earliest rocks of the mid-Tertiary orogeny are red beds and fanglomerates, typical arid continental deposits. Gypsiferous mudstones are not uncommon in these beds. Pre-29-m.y. sand dunes are preserved as aeolian cross-bedding in the Sil Murk Formation of the Gila Bend Mountains (Heindl and Armstrong, 1963) and as scattered outcrops in the Aguila Mountains. Thick evaporite deposits accumulated in the Red Lake, Luke, and Picacho basins. Some evaporite lenses are found in the Tucson, Safford, San Pedro, Elfrida, and other basins.

Certain arid landforms are preserved beneath lava flows in western Arizona (Lynch, 1976). Nearly flat alluvial surfaces are found under the basalts of Raven Butte and Mesas de Malpais [137] in the Tinajas Altas Mountains. Clasts of Gunnery Range granite in the alluvium are no more deeply weathered than the nearby bedrock. A vertical-walled arroyo nearly 2 m deep was filled by the lowest basalt flow on the north end of the Aguila Mountains [127].

The most spectacular examples of buried arid landforms are the steep-walled canyons cut in Gunnery Range granite of the Cabeza Prieta Mountains and filled with the Cabeza Prieta volcanics of around 16 m.y. age [119]. The buried canyon walls are identical in form to the exposed mountain slopes. The equigranular granite weathers slowly in the modern arid climate of sporadic rainfall, which usually comes in the form of thunderstorms. Copious runoff sweeps to the desert floor whatever detrital material has loosened since the last storm. For this reason, slopes are clear of loose material. Lava-buried slopes are similarly clean, implying similar weathering conditions before burial.

Evolution of the Drainage

The Colorado and Gila River systems and the Gulf of California into which they flow are the major elements of the modern Arizona drainage. Age constraints on drainage evolution are provided by lava flows associated either with channels or alluvial deposits, but the record is discontinuous. Tectonism has obscured the earlier drainage patterns and inferences must be drawn from scattered river features.

The Gulf of California, ultimate base level, did not exist as a structural basin prior to 17 m.y.B.P. (Gastil and others, 1979). The modern gulf contains transform faults and spreading centers on the plate boundary between the Pacific and North American plates, but these have been active only over the last 4 to 5 m.y. (Atwater, 1970; Moore and Buffington, 1968). A proto-gulf structural basin existed in the site before it became a plate boundary (Karig and Jensky, 1972; Moore, 1973). The northern gulf and Salton Trough apparently accumulated continental sediments until mid- to late Miocene time when the sea invaded the trough and marine rocks accumulated (Smith, 1970).

The most important unit in dating the evolution of the modern drainage is the Bouse Formation (Metzger, 1968). Deposition of the Bouse Formation predated accumulation of any river sediments in the present Colorado River delta from either the Colorado or Gila rivers. This marine to brackish water deposit consists mainly of mudstone, siltstone, and sandstone. A Pliocene age of 5.5 m.y., determined on glass from a tuff near the base of the Bouse Formation [147], is in agreement with paleontological evidence (Smith, 1970). Ingle (1973) reported a similar lithology and age for the Imperial Formation in the Salton Trough to the west. In the Exxon Yuma Federal No. 1 drill hole, nearly 660 m of Bouse Formation overlies 500 m of mixed marine sediments. Drill chips from a basalt dike [148] below this sequence yielded a 5.4-m.y. age.

The Lower Colorado River

Several other dates in the appendix are related to critical stages in the evolution of the lower Colorado River. The samples from locality 146 are from the lowest basalt layer on Fortification Hill, type section for the Fortification Hill basalt member of the Muddy Creek Formation (Longwell, 1963). At Fortification Hill, the basalt member rests on lower lacustrine members of the formation. According to Longwell (1963), the Muddy Creek Formation predates the Colorado River. West of the Black Canyon of the Colorado River, the Fortification Hill basalt member rests directly on tilted Mount Davis volcanics. To the east, in the Black Mountains, it rests on Precambrian basement of considerable relief. Between the river and the Black Mountains, it rests on the basin-fill members of the Muddy Creek Formation. The paleogeography appears to be that of a closed basin flanked on the east by hills of Precambrian crystalline rock and on the west by a less rugged surface cut on the tilted Mount Davis volcanics. The basalts were extruded onto the basin fill and the flanking volcanic and Precambrian rocks. The date on the basal flow is 5.9 m.y. at Fortification Hill [146]. Armstrong (1970) obtained a date of 5.8 m.y. on a sample collected from the basalt at Malpais Mesa about 30 km to the south. Since extrusion of the basalt in latest Miocene (5.8-5.9 m.y.), the river has cut down through the Muddy Creek Formation and the underlying volcanics, removing 925 m of rock and sediment.

At Grand Wash Bay near Iceberg Canyon along Lake Mead, a 3.8-m.y.-old basalt [150] rests on eroded Muddy Creek fanglomerate and Colorado River gravels. A basalt of similar composition and identical age [151] rests on Colorado River gravels at Sandy Point. Presumably these basalts are remnants of a lava that flowed down the river from Grand Wash Bay to Sandy Point. The river has lowered its bed 110 m since extrusion of the lava 3.8 m.y. ago, for an average rate of downcutting of only 30 m/m.y. The river channel between Sentinel Island and Fortification Hill must have been lowered about 815 m (925 m minus 110 m) during the period 5.9 to 3.8 m.y.B.P., a rate of downcutting of about 390 m/m.y. Thus, the juvenile river rapidly cut its gorge in lower Pliocene time but has very slowly lowered its grade since 3.8 m.y. B.P.

Tributaries to the Colorado River such as the Virgin River and Little Colorado River are downcutting at the rate of about 100 m/m.y. (Damon and others, 1974; Hamblin and others, 1976). According to Ritter (1967), the rate of denudation for the drainage region of the Colorado River is 160 m/m.y. To maintain isostatic balance, removal of 160 m of sial with a density of 2.60 g/cm^3 must be compensated by an influx of h meters of sima with a density of about 3.25 g/cm^3. Consequently,

$$h = \frac{2.60 \times 160}{3.25} = 130 \text{ m/m.y.}$$

Summarizing, the present average rate of denudation of the drainage region of the Colorado River is approximately 160 m/m.y. To achieve isostatic equilibrium, the Colorado Plateau province must rebound approximately 130 m/m.y. In response to this uplift, the Virgin River and Little Colorado River tributaries are downcutting at a rate of 100 m/m.y. whereas the Colorado River itself is downcutting at a rate of only 30 m/m.y.

Although the entire plateau drainage region is being denuded at the rate of 160 m/m.y., the basins are being eroded at a greater rate than the isolated plateau areas bordering the river and its tributaries. Much denudation took place by removal of sediments accumulated in the basins during an earlier period of closed drainage. As a result, basin areas were enlarged and lowered with respect to sea level but isolated parts of the plateau, although reduced somewhat in size, were elevated with respect to sea level by isostatic rebound of the entire plateau. The net effect to the observer may be the appearance of Pliocene tectonic uplift (McKee and McKee, 1972; Luchitta, 1979) whereas on the average the Colorado Plateau is being lowered with respect to sea level. Summing the amount of erosion and isostatic rebound during the last 5.9 m.y. for the southwestern plateau, an average of 940 m of sediment have been eroded, with a total rebound of 770 m. Thus, the average lowering of the plateau is 170 m, but some isolated areas may have risen somewhat less than 770 m and some basins may have been stripped of more than 940 m of rock and sediment.

The tectonic uplift that began the process must have occurred in pre-Pliocene time (Peirce and others, 1979; see also Damon, 1979). During Pliocene and Pleistocene time the Colorado Plateau has been responding to the development of through-flowing drainage to the sea. If some other form of regional tectonic uplift has been occurring in Plio-Pleistocene time, we conclude that it must be subordinate to isostatic adjustment, at least in the southern part of the Colorado Plateau. However, the western margin of the Colorado Plateau is part of the intermountain seismic belt (Smith and Sbar, 1975) and the rate of movement along the Hurricane fault (Hamblin and others, 1975; and additional unpublished data from this laboratory) suggests that the high plateau region in Utah has been elevated in Pliocene and Pleistocene time at a rate that cannot be due dominantly to isostatic adjustment.

Since the Bouse Formation was deposited, it has been subsiding at the rate of 180 m/m.y. in the Colorado River delta area near the Mexican border, but has been uplifted north of Parker in the Basin and Range province at an average rate of 100 m/m.y. (Luchitta, 1979). Luchitta suggested that the Colorado Plateau edge at the Grand Wash Cliffs has been uplifted at a rate of 160 m/m.y. Coincidentally, this rate is the same as the average rate of denudation of the Colorado Plateau, which we have suggested is largely due to removal of sediments accumulated during the pre-Pliocene epoch of internal drainage. Actually, we would expect the Grand Wash Cliffs to be uplifting at the rate of rebound of the Colorado Plateau, 130 m/m.y., or somewhat less due to some erosion. Perhaps the southwestern rim of the plateau is being uplifted at a somewhat greater rate than can be attributed to rebound, but the difference is within the limits of error of calculations.

We suggest the following history for the evolution of the Colorado River. The Colorado River became a through-flowing stream in its present course after 5.9 m.y.B.P., in earliest Pliocene time. At that time it began unloading the extensive deposits of sediments that had accumulated in the basins of the Colorado Plateau, and it began to cut the Black Canyon gorge at the rate of 390 m/m.y. Since then the Colorado Plateau has been rebounding, initially at the rate of 130 m/m.y., resulting in continued downcutting by the Colorado River and its tributaries within the Colorado Plateau. As a consequence of the work of the Colorado River in removing sediments from the Colorado Plateau, the plateau has been subjected to differential uplift and erosion. The net effect is the scouring and lowering of basins, the retreat of scarps, and the uplift of isolated plateau areas, even though the average elevation of the plateau is decreasing, except for the tectonically active high plateau region along the intermountain seismic belt.

The Gila River

Evolution of the Gila River system was controlled by the Basin and Range disturbance. Basin subsidence disrupted an ancestral Gila River, creating internal drainage for a period of time. Gradually the basins filled and the Gila eventually became tributary to the Colorado River, draining much of southern Arizona into the Gulf of California. The critical events in this evolution are the initial disruption and eventual reintegration.

Pre-Oligocene drainage in central Arizona was toward the northeast from a highland in the southwest (Cooley and Davidson, 1963), which deposited the distinctive "Rim gravels" (Hunt, 1956; Koons, 1948; Peirce and others, 1979; Price, 1950). This pre-28-m.y.B.P. drainage was disrupted when the Mogollon Rim of the Colorado Plateau came into existence as a physiographic feature (Peirce and others, 1979). During the later stages of the mid-Tertiary orogeny, the apparent drainage from central Arizona was from the southwest toward the northeast and then along the base of the developing escarpment. Gravels underlying Buckhead Mesa and along both Wet and Dry Beaver Creeks [128] (Peirce and others, 1979) are related to this drainage. By 13 m.y.B.P., nearly 600 m of relief had developed along the Mogollon Rim by erosion (Peirce and others, 1979; Elston and others, 1974; Scott, 1974).

Basins that developed south of the rim from 28 to 13 m.y.B.P. accumulated coarse conglomerates and continental red beds (Bloody and Tonto basins; Cave Creek area) and fluvial-lacustrine sediments such as those exposed along the Black Canyon Highway and in the New River and Cave Creek areas. Some of the fine-grained sediments contain uranium mineralization (Scarborough, 1979).

The first key event, disruption of the older drainage pattern, was caused by the beginning of basin subsidence at the onset of the Basin and Range disturbance (Peirce, 1976b). Thick deposits of halite and anhydrite, accompanied by stringers of fine sediments, which occupy the basins west and south of Phoenix, an area called "the Gila Low" by Peirce (1976b), indicate regionally integrated but internally directed drainage during the early part of the Basin and Range disturbance (Scarborough and Peirce, 1978). The Picacho basin contains 2,000 m of anhydrite with minor halite, while the Luke basin contains evaporites that may be 4,000 m thick (Eaton and others, 1972; Eberly and Stanley, 1978; Scarborough and Peirce, 1978). These contemporaneous deposits grade upward into red mudstone. Thinner evaporite deposits interbedded with coarse clastic material are found in the Higley, Paradise, Red Rock, and Tucson basins. Peirce (1976b) suggested that interconnection of basins allowed the coarser alluvial material to be deposited in the higher basins resulting in concentration of relatively clean brines in successive basins. Most of the evaporites within the Sonoran Desert subprovince accumulated in the early part of the Basin and Range disturbance. The younger basins within the central and eastern mountain regions such as Verde, Tonto, Payson, Elfrida, Safford, and San Pedro also contain some evaporites (Peirce, 1976b; Pederson, 1969; Twenter, 1962; Twenter and Metzger, 1963). The evaporites do not represent marine incursions into the area. As evaporites accumulated to the south, basalts of the Hickey Formation (Anderson and Creasey, 1958) were erupted onto surfaces eroded on Precambrian [133] and Paleozoic rocks [132], as well as onto the gravels, poorly indurated tuffs, and other beds [125,128] of the Hickey Formation (McKee and Anderson, 1971; Elston and others, 1974). A 13.1-m.y.-old basalt flow [133] caps Government Hill and the Black Hills, which form the highland to the south of the Verde Valley. Eruption of these flows appears to predate subsidence of the Verde Valley.

The second key event, integration of the rivers to the Gulf of California, is constrained by the 5.5-m.y. age of the Bouse Formation [147], which predates river deposits in the northern Gulf. Probably both the Gila and Colorado Rivers became connected to the sea at about the same time. If evaporite accumulation began soon after eruption of the 15-m.y.-old lava flow in the Picacho basin, drainage within the lower Gila system was internal for 10 m.y.

Evaporite accumulation ended in most basins some time after 10 m.y.B.P. A 10.5-m.y.-old basalt flow [136] near the top of the Luke Salt is one of the few time markers available within the evaporite sequences. Contemporaneous basalt flows are found capping remnants of formerly deeper and more extensive basin-fill sediments to the north and west of the Gila Low. Malpais Mesa basalt [138], 10.0 ± 0.4 m.y. old, caps horizontal lacustrine and fluvial sediments in the Santa Maria River valley and a similar "mesa-capping flow" was dated at 9.2 ±

0.2 m.y.B.P. by Suneson and Lucchitta (1979), 50 km downstream on the Bill Williams River. The Mesas de Malpais basalt flow [137] in the southern Tinajas Altas Mountains (Sonora) preserves an 11-m.y.-old alluvial surface, which stands above the modern valley floor. Dissection of alluvial surfaces began after 10 m.y. B.P., as flows of this age are remnants on the surfaces.

Younger basins in the central and eastern mountain region started to form between 10 and 6 m.y.B.P., primarily due to tectonism, and in some cases, aided by lava dams. Verde lake beds were deposited between 7.5 and 3 m.y. B.P. (Elston and others, 1974; Scott, 1974). Four basaltic lava flows near the confluence of the Gila-San Pedro Rivers yielded 8.0 to 7.5-m.y. [141,143,144,145] ages. These isolated lava remnants probably had only a temporary influence on the drainage. The lava at China Wash [141] (8.9 m.y.) lies beneath Gila River gravel and above fine-grained valley-fill material. Miocene gravel of the "Tablelands" is capped by an 8.5-m.y.-old flow [143]. The Bucket Mountain flow [145] overlies a pediment surface, while Poston Butte [144] resembles a dissected cone. Dated ash beds from early Pliocene fluviolacustrine sequences in southeastern Arizona suggest that sedimentation in the Gila-Safford and San Pedro basins was in progress until about 2.2 m.y.B.P. (Scarborough, 1975, personal commun., 1980).

Another time constraint is provided by the 3.2-m.y.-old basalt at Warford Ranch cone [152] and other lavas of the Sentinel Plain-Arlington volcanic field [153-155]. Presence of quartzite pebble gravels all across the Sentinel Plain from the Gila River to the Aguila and Crater Mountains indicates that the Gila River aggraded prior to eruption of the Sentinel Plain flows, presumably between 5 and 3 m.y.B.P., and alluviated the Gila-Salt River trough. Eberly and Stanley (1978) reported a great thickness of "younger alluvium" in the basins west of the Painted Rock Mountains. The aggradation may have forced the river into the channel it now occupies between the Gila Bend and Painted Rock Mountains; the Sentinel Plain lavas did not dam and divert the river. In the 3.2 m.y. since eruption of the Warford Ranch cone, the river has cut only 40 m into its old alluvial surface. Lee and Bell (1975) identified three paired terraces (24, 12, and 6 m) along the Gila River near Gillespie Dam site. The 12-m terrace is locally covered by 3.2-m.y.-old basalt flows. The Gillespie flow dammed the Gila River at the west end of the Buckeye Hills and diverted stream flow a few hundred meters to the east. The 24-m terrace is clearly older than the Gillespie flow. The 6-m terrace contains about 1100-year-old potsherds of the Hohokam Indian culture (Lee and Bell, 1975).

Alluvial surfaces preserved beneath lava flows of about 10-m.y. age are found in the Tinajas Altas, Cabeza Prieta, and Agua Dulce Mountains. These preserved surfaces and attendant superposed drainage indicate that valley-fill alluvium in this area was much thicker at that time than it is now and the drainage became superposed on the topography as the material was removed. Some of the superposed stream channels are quite spectacular (Fig. 13). A tiny, 2 km^2 basin west of the higher Mesas de Malpais drains eastward through a 30-m deep gorge between two of the mesas. La Jolla Wash, 5 km to the west, drains a large area of the southern Lechugilla Valley from Tordillo Mountain to the Lechugilla Hills. Neither of these features could have been created by simple stream capture.

The upper Gila River contrasts most markedly with the lower Gila in its active downcutting. Lava flows in the vicinity of San Carlos lie on at least two alluvial surfaces that are higher than the present surface. The Peridot flow of around 1-m.y. age is 50 m above the currently active alluvial surface, resting on an older surface that was being dissected at that time; the flow occupies a channel near the town of San Carlos. The Peridot Mesa surface is lower than the pediment beneath the lavas on Bucket Mountain [145] (7.5 m.y.). The 2-m.y.-old Gillespie flow overlies a 12-m terrace and the Sentinel flow has been downcut a maximum of 40 m in the last 3 m.y. The rate of downcutting has been slow for the last 2 m.y., slower than that of the Colorado River at Grand Wash Bay for the last 3.8 m.y. In fact, there is some evidence for episodes of aggradation preceding the present channel cutting. For example, gravel deposits of the Blue Point terrace (Péwé, 1978) overlie a buried river channel near the confluence of the Salt and Verde Rivers. Extensive drilling by the Water and Power Resources Service (formerly U.S. Bureau of Reclamation) indicate that the buried channel had a gradient five times that of the present Salt River (Laney, personal commun., 1980). Near Granite Reef Dam, the gravel unit is 56 m thick below the present channel.

The upper Gila River and its tributaries are actively downcutting some reaches upstream from the eastern boundary of the Sonoran Desert, while the lower Gila appears to be on its equilibrium profile in the desert. This is in keeping with the idea that tectonism of the Basin and Range disturbance has essentially ceased in the west but continues in the east. Physiography along the lower Gila River has apparently changed little in the past 3 m.y.

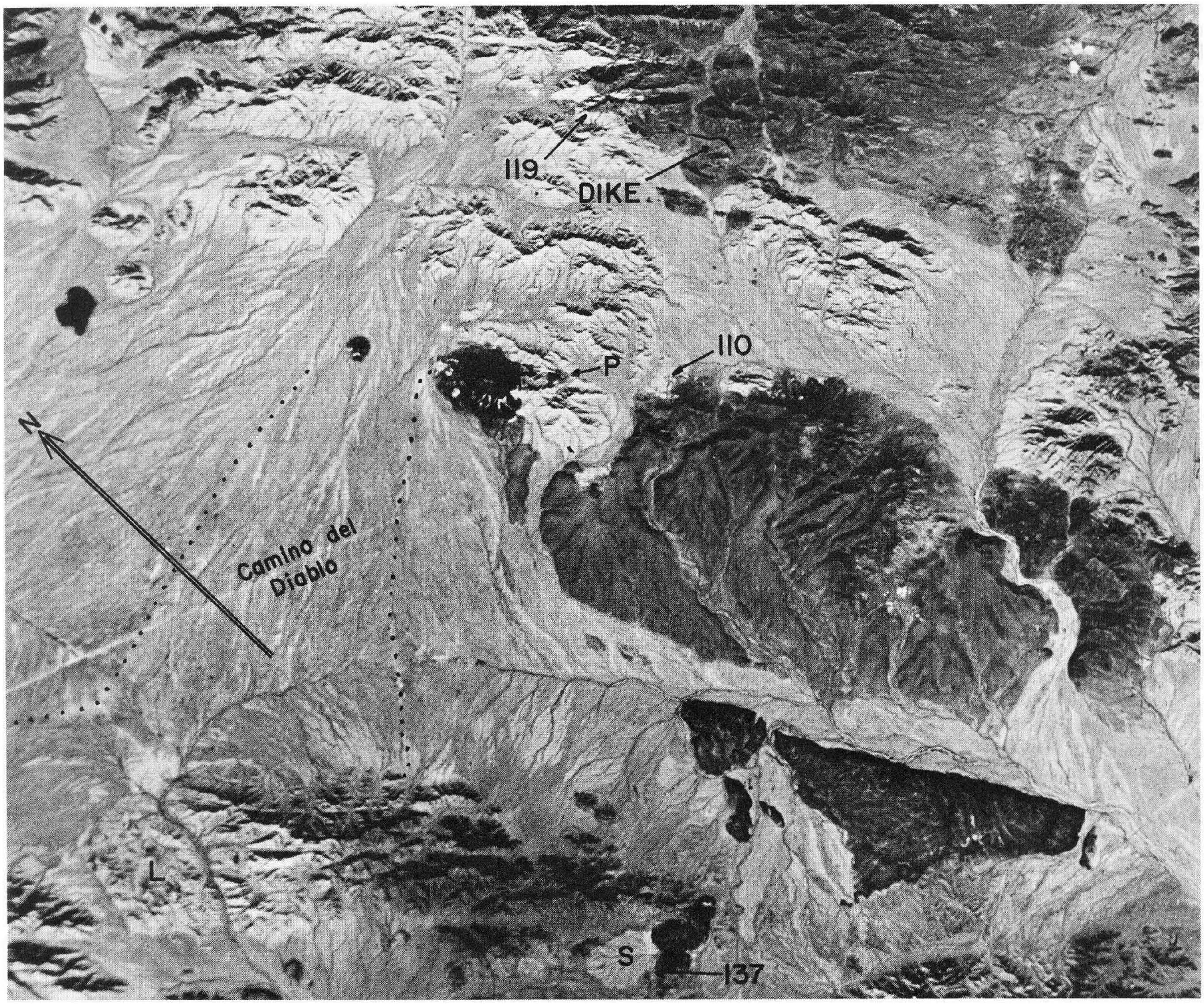

Fig. 13. Mesas de Malpais and the southern Lechugilla Valley. Several examples of drainage channels superposed on the topography occur in this small area. La Jolla Wash (L), which cuts through the Lechugilla Hills (lower left) drains the area outlined by dots. A 2-km^2 basin (S - center bottom) drains southeastward (to the right) between the higher mesas and then northeastward (toward the top of photo) between the lower mesas. The channel that cuts the oval area of hornblende andesite (right side) is superposed upon it. Tordillo Mountain (T) is a basalt-capped pediment; the Mesas de Malpais are basalt-capped alluvial fans. The andesite-buried topography of the Cabeza Prieta (Fig. 6) is upper center. D is the dike of Fig. 8 and P is the pipe of Fig. 7. Numbers locate dated samples listed in the appendix. Skylab photo, courtesy NASA.

Acknowledgments

We wish to express our profuse thanks to those who waited so patiently for this paper and who waded so patiently through its first drafts: T. H. Anderson, P. J. Coney, F. W. Cropp, G. H. Davis, G. Haxel, J. P. Jenney, S. B. Keith, D. J. May, H. W. Peirce, D. W. Peterson, S. B. Scarborough, T. L. Smiley, and R. M. Tosdal. R. Butcher prepared the drafted illustrations and Salley Wallin typed and retyped. Some analyses were carried out in cooperation with Bear Creek Mining, Cities Service, Conoco, Exxon, Fugro, and Kennecott Mining corporations, and the U. S. Bureau of Reclamation. Gratitude is offered the countless multitudes who helped us lug rocks from distant outcrops, toil over crusher and separatory funnel, hurl imprecations at recalcitrant electronic devices so, through this

alchemy, we could turn the "lead" of lifeless rock into the "gold" of potassium-argon ages. Particular thanks to the taxpayers who supported us through the University of Arizona and the National Science Foundation, grant EAR-78-11535.

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Appendix. Potassium-Argon Data on Samples from Southwestern Arizona

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
1	UAKA-61-47	Hornblende, schist	0.145	0.145	684.4	28.2	1660 ± 50
		Metamorphic basement complex in Caborca area, 3.2 km north of Bamori (#PED-47-61) Sonora, Mexico Lat 30° 21'N, Long 112° 05'W					
2	UAKA-60-06	Muscovite, coarse pegmatite-vein A	8.57	8.57	36880	2.2	1560 ± 50
		Muscovite, pegmatite-vein B	8.70	8.70	33560	2.5	1450 ± 50
		Biotite, schistose wallrock	6.98	6.98	19820	3.6	1170 ± 40
		Yavapai series basement complex, host rock for massive Sulfide deposit at Old Dick Mine, Bagdad (#PED-6-60) Bagdad Quad., Yavapai Co., AZ Lat 34° 32.8'N, Long 113° 13.7'W					
3	UAKA-60-04	Muscovite, pegmatite vein	8.94	8.94	36210	3.7	1500 ± 50
		Precambrian basement in Prescott area, 2 km west of Cleator, (#PED-4-60) Cleator Quad., Yavapai Co., AZ Lat 34° 16.5'N, Long 112° 14.7'W					
4	UAKA-58-12	Muscovite, gneiss	8.34	8.34	32620	1.2	1460 ± 40
		Biotite, gneiss	7.41	7.41	21440	5.0	1180 ± 40
		Basement in most of southwestern Arizona - southwestern Sonora. Samples from inselbergs on Highway 2 at Riena cinder mine road intersection. Muscovite from hill 200 m north of highway. Biotite from hill at intersection. Sonoyta AMS 1x2 Quad., Sonora, Mexico Lat 31° 59.5'W, Long 113° 22.3'N					
5	UAKA-59-25	Muscovite, granite	8.64	8.64	33840	1.2	1460 + 50
		Biotite, granite	6.96	6.96	24000	1.6	1340 ± 50
		Coexisting minerals from granite of Chino creek pluton approx. 10 km south of Seligman. Precambrian basement in Seligman area (#PED-25-59) Yavapai Co., AZ Lat 35° 15'N, Long 112° 54'W					
6	UAKA-59-1	Muscovite, Pinal Schist (#PED-1a-59)	7.05 6.98	7.02	25560	0.8	1400 ± 40
		Muscovite, from pegmatite intrusive into Pinal Schist (#PED-1b-59) north of Old Pioneer Stagecoach Station, Pinal Mountains El Capitain Mt. Quad., Gila Co., AZ Lat 33° 14'N, Long 110° 50'W	8.60 8.55	8.57	38680	1.0	1620 ± 40
7	UAKA-57-17	Biotite, Diana granite (#PED-17-57) Lat 35° 25.15'N, Long 114° 13.47'W	7.24	7.24	26250	0.7	1390 ± 40
	UAKA-57-18	Biotite. Chloride granite that intrudes Diana granite. 1 km north of Chloride (#PED-18-57) Lat 35° 25.51'N, Long 114° 11.8'W	6.95	6.95	20040	1.0	1180 ± 30

Constants used

$\lambda_\beta = 4.963 \times 10^{-10}\ yr^{-1}$

$\lambda\varepsilon = 0.581 \times 10^{-10}\ yr^{-1}$

$\lambda = 5.444 \times 10^{-10}\ yr^{-1}$

$^{40}K/K = 1.167 \times 10^{-4}$ atom/atom

altitude in feet,

drill hole depth in meters,

samples with UAKA prefix analyzed at the Laboratory of Isotope Geochemistry, University of Arizona.

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}\text{Ar}_{\text{rad}}$ x10-12 mole/g	% air argon-40	Age in m.y.
7	UAKA-57-19	Biotite, Cerbat granite 2 km east of Chloride (#PED-19-57) Lat 35° 24.9'N, Long 114° 09.0'W	7.13	7.13	20580	2.1	1180 ± 40
	UAKA-57-20	Biotite, pegmatite, in schistose metasediments. Lat 35° 14.8'N, Long 114° 08.4'W	6.30	6.30	15480	3.4	1050 ± 30
		Precambrian plutonic-metamorphic complex in the Chloride mining district. Chloride Quad., Mohave Co., AZ					
8	UAKA-57-15	Biotite, equigranular granite Precambrian basement complex overlain by Tertiary gravels. West of Peach Springs on Highway 66, (#PED-15-57). Milkweed Canyon SW Quad., Mohave Co., AZ Lat 35° 32'N, Long 113° 40.5'W	7.22	7.22	26150	5.3	1390 ± 40
9	UAKA-59-14	Muscovite, quartz monzonite Precambrian basement complex, 1.9 km NNW of Murphy Ranch. (#PED-14-59) Empire Mtns. Quad., Pima Co., AZ. Lat 31° 57.51'N, Long 110° 37.06'W	7.33 7.34	7.34	26230	0.4	1375 ± 30
10	UAKA-21-57	Biotite, granite of Gatz Ranch Precambrian basement complex north end of Hualapai Mtns. (#PED-21-57) Rattlesnake Hill Quad., Mohave Co., AZ. Lat 35° 10.42'N, Long 113° 53.2'W	7.485 7.495	7.490	25210	0.5	1320 ± 40
11	UAKA-60-07	Biotite, Kirkland granite (also called K-granite) (#PED-7-60) Kirkland, Kirkland Quad., Yavapai Co., AZ Lat 34° 25'N, Long 112° 42'W	7.855	7.855	24590	1.4	1250 ± 28
12	UAKA-63-31	Biotite, Pegmatite intrusive into Oracle Granite North of Oracle Junction in the Black Mtns. (#PED-31-63) Black Mtn. Quad., Pinal Co., AZ Lat 32° 46.1'N, Long 110° 56.9'W	6.41	6.41	17800	0.8	1150 ± 30
13	UAKA-57-06	Biotite, granite of Granite Dells East side of Granite Creek (#PED-6-57) Prescott Quad., Yavapai Co., AZ Lat 34° 36.19'N, Long 112° 24.85'W	6.14	6.14	16280	13.4	1110 ± 40
14	UAKA-65-03	Biotite, diorite 450 m thick diorite sill, Reymert mine. The attitude of the contact as well as attitudes of primary foliation indicate a nearly flat lying sill. The general dip is ∿10° to the southwest. Hole 1, a hundred meters south of the mining camp about 20 km southwest of Superior. (#PED-3-65) Mineral Mtn. Quad., Pinal Co., AZ Lat 33° 14.7'N, Long 111° 12.1'W, Alt. 3200 ft.	6.93	6.93	17700	0.3	1080 ± 30
15	UAKA-74-20	Muscovite, quartz monzonite, partially reset age Rock is in fault contact with Paleozoic strata south of Arizona Portland Cement Quarry, Busterville, north end of the Tucson Mtns. Avra Quad., Pima Co., AZ Lat 32° 21.00'N, Long 111° 11.75'W	8.76 8.68	8.72	17610 17400	1.5 1.5	895 ± 20
16	PN-1	Biotite, granite, partially reset age Sphene-bearing porphyritic granite found near Ladybug Saddle. Age precludes mid-Tertiary thermal resetting. Stockton Pass, Graham Co., AZ Lat 32° 37.4'N, Long 109° 49.8'W	7.15	7.15	13410	0.4	875 ± 30

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
17	UAKA-57-4	Biotite, Yavapai Schist, partially rest age Underlies Tertiary volcanics 8 km east on Highway 69 from Junction of Highway 89 & 69. The samples may have been reset by a basic dike that intrudes the schist in the road cut from which the sample was collected. Prescott Quad., Yavapai Co., AZ Lat 34° 33.08'N, Long 112° 22.58'W, Alt. 5350 ft.	5.52	5.52	9140	19.8	766 ± 25
18	UAKA-57-22	Chlorite, porphyritic Enterprise granite - reset age (#PED-22-57) Hualapai Peak NE Quad., Mohave Co., AZ Lat 35° 08.78'N, Long 113° 49.24'W	1.21	1.21	1630	0.2	649 ± 60
19	UAKA-64-19	Biotite, Mohave Border granite, partially reset Sampled near rest area 8 km Northwest of Bagdad road intersection on Highway 93 (#PED-19-64) Arrastra Mountain NE Quad, Yavapai Co., AZ Lat 34° 28.55'N, Long 113° 19.37'W	7.53	7.53	8880	6.6	577 ± 17
20	UAKA-60-12	Chlorite, granite gneiss-partially reset Sample from roadcut, state Route 226, 16 km east of Bonita (#PED-12-60) Pinaleño Mtns. Fort Grant Quad., Graham Co., AZ Lat 32° 35.45'N, Long 109° 56.33'W	1.92 1.87	1.90	1170	1.2	325 ± 6
21	UAKA-72-57	Whole rock, granite - partially reset Drill chips from 771-777 m level Exxon State 14-1 drill hole. Eberly and Stanley (1978) Nr #103. Rb-Sr model-age of 1080 m.y. on this rock shows the K-Ar clock was reset by a Jurassic or younger thermal event. Hyder NE Quad., Yuma Co., AZ Lat 33° 08'N, Long 113° 21'W	3.71 3.68	3.70	1122	6.3	167 ± 4
22	UAKA-67-200	Plagioclase, andesite porphyry Museum porphyry plug intrudes Jurassic/Triassic Recreation red beds west of the Arizona-Sonora Desert Museum in the Tucson Mtns. (#PHK-1-67) Brown Mountain Quad., Pima Co., AZ Lat 32° 14.8'N, Long 111° 08.5'W	1.62	1.62	450	12.9	155 ± 5
23	UAKA-73-65	Biotite, granodiorite Amado granodiorite intrudes Paleozoic sedimentary rocks on the north and is covered by Tertiary volcanics on the south. The stock lies adjacent to the major NNW Sierrita - Santa Rita - Patagonia Laramide intrusive lineament. Tubac Quad., Santa Cruz Co., AZ Lat 31° 41.50'N, Long 111° 08.12'W	5.06 5.08	5.07	1410 1416 1411	5.7 7.2 7.8	154 ± 4
24	UAKA-63-32	Biotite, granite - partially reset age Rock lithology strongly resembles Oracle Granite. Age probably reset by nearby Mid-Tertiary granite intrusion. (#PED-32-63) Black Mtn. Quad., Pinal Co., AZ Lat 32° 49.6'N, Long 110° 57.0'W	7.85 7.88	7.86	2000	3.8	141 ± 3
25	UAKA-73-20	Biotite, granite - partially reset age Porphyritic granite in the Little Lone Mtn. Quad., Yuma Co., AZ Lat 33° 38.2'N, Long 113° 29.9'W	6.72 6.72	6.72	1700 1700 1705	8.4	140 ± 4
26	UAKA-77-69	Paragonite, Spring Valley granodiorite - partially reset This stock intrudes Yavapai schist. Governors Peak Quad., Yavapai Co., AZ Lat 33° 56'N, Long 112° 22'W	0.631	0.631	146	8.0	129 ± 3

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
27	UAKA-72-25	Biotite, monzonite porphyry - partially reset age Foliated host rock for Ni, Cu, Au, Ag mineralization zones. Constellation mining district. Morgan Butte Quad., Yavapai Co., AZ Lat 34° 04.0'N, Long 112° 34.5'W	5.75 5.78 5.71	5.75	1143	6.5	111 ± 3
28	UAKA-73-49	Hornblende, diorite - Comobabi intrusion Cretaceous sedimentary rocks are in disconformable contact with this rock. Papago Indian Reservation Sells Quad., Pima Co., AZ Lat 31° 58'N, Long 111° 48'W	0.668 0.662	0.665	120 118	11.0 11.5	100 ± 2
29	UAKA-76-114	Biotite, diorite - possible reset age Nonfoliated diorite intrudes Precambrian schist Baldy Mtn. Quad., Maricopa Co., AZ Lat 33° 46.3'N, Long 112° 21.3'W	6.661 6.596 6.591	6.616	1118 1114 1113	9.2 9.7 10.2	94.7 ± 2.0
30	UAKA-74-24	Whole rock, basalt intrusion Dike strikes NE and cuts mineralized veins in the Abrigo Formation. Dike is also mineralized with gold and sulfide ores. Golden Rule mine, Dragoon Mountains. Cochise Quad., Cochise Co., AZ Lat 32° 01.8'N, Long 109° 58.0'W	1.49	1.49	195.3	4.2	74.1 ± 2.0
31	UAKA-74-42	Hornblende, andesite Oldest exposed volcanic unit beneath the Galiuro volcanic series. Overlies sandstone, shale, limestone and conglomerate which may correlate with the Cretaceous Bisbee group or possibly with the Williamson Canyon volcanics. Turkey Track porphyry overlies this flow in this location. Hooker's Hot Spring Redington Quad., Cochise Co., AZ Lat 32° 20'N, Long 110° 16'W	0.598 0.597	0.598	78.62 77.15	19.9 21.0	73.7 ± 1.8
32	UAKA-75-49	Biotite, Silver Lily quartz latite dike Intrudes both Tucson Mountain chaos and Cat Mountain rhyolite. Avra Quad., Pima Co., AZ Lat 32° 15'N, Long 111° 08'W	6.203 6.192	6.198	773 771	11.2 11.3	70.5 ± 1.7
33	S JR-HV 78-1	Hornblende, amphibolite Amphibolite in banded gneiss of the Harcuvar Mountains Sample from north of Cunningham Pass. Age records metamorphic event which predates mylonitization. Salome Quad., Yuma Co., AZ Lat 33° 58.94'N, Long 113° 33.67'W	1.21	1.21	152.3 148.5	32.7 45.1	70.3 ± 2.9
34	UAKA-70-06	Biotite, Tortilla diorite Age of host rock, Ray Mine area (#PED-6-70) Tortilla Mountains, Sonora Quad., Pinal Co., AZ Lat 33° 07.55'N, Long 110° 58.17'W	7.23	7.23	899.2	19.0	70.3 ± 1.7
35	UAKA-77-50	Hornblende, andesite This andesite covers large areas of the valley between the Las Guijas Mountains and the Cerro Colorado Mountains. Andesite and Mesozoic (?) shales are in fault contact with the mid-Tertiary Las Guijas alaskite and are overlain by mid-Tertiary basaltic andesites, rhyolites, tuffs and ash flows. Las Guijas, Arivaca Quad., Pima Co., AZ Lat 31° 39.08'N, Long 111° 20.02'W	0.689 0.682 0.677	0.683	82.97 82.60 82.84 82.81	15.5 15.1 15.5 15.4	68.6 ± 1.4

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
36	UAKA-77-64	Whole rock, metamorphosed Age records cooling after an earlier metamorphic event or resetting by the adjacent granodiorite. Granite Wash, Salome Quad., Yuma Co., AZ Lat 33° 46.8'N, Long 113° 44.0'W	1.475 1.468	1.472	173.2 174.3 174.7	16.0 16.5 16.6	67.1 ± 1.4
37	UAKA-73-158	Sericite, Alteration zone - Mount Wrightson Fm. Age of mineralization, quartz-sericite-pyrite alteration assemblage in Triassic volcanic rock similar assemblage is also found in nearby Cretaceous Josephine Diorite. Temporal Prospect Mount Wrightson Quad., Santa Cruz Co., AZ Lat 31° 38'N, Long 110° 50'W	5.967 5.998	5.983	706.0 707.4	4.0 4.6	66.9 ± 1.5
38	UAKA-66-03	Biotite, granodiorite Granodiorite of Granite Wash Pass, (#PED-3-66) Hope Quad., Yuma Co., AZ Lat 33° 45.0'N, Long 113° 40.5'W	6.23	6.23	731.8	78.0	66.5 ± 3.6
39	L.Ha-1	Biotite, granite porphyry Age of cooling after metamorphic event or reset by intrusion of granodiorite of Granite Wash Pass. Little Harquahala Mountains Hope Quad., Yuma Co., AZ Lat 33° 43.0'N, Long 113° 36.3'W	5.19	5.19	613.1 596.8	40.9 58.9	66.0 ± 2.2
40	UAKA-71-17	Biotite (chloritized), Copper Creek andesite porphyry This rock is a late-stage phase of the Copper Creek granodiorite which contains sulphide mineralization. Copper Creek, Rhodes Peak Quad., Pinal Co., AZ Lat 32° 44.83'N, Long 110° 28.72'W	4.881 4.856	4.869	565.4	14.7	65.8 ± 1.6
41	Hvr-1	Muscovite, quartz schist Near intrusive contact with Granite Wash Pass granodiorite. Salome Quad., Yuma Co., AZ Lat 33° 47.0'N, Long 113° 41.3'W	8.18	8.18	927.4 938.4	54.3 76.9	64.6 ± 1.5
42	UAKA-71-18	Whole rock, basaltic andesite From upper part of Glory Hole volcanic sequence. This sequence is overlain by mid-Tertiary volcanics, and underlain by Paleozoic limestones. Oak Grove Canyon Quad., Pinal Co., AZ Lat 32° 45.75'N, Long 110° 29.75'W	1.786 1.791	1.789	204.1 200.8 191.1 196.5	6.3 6.8 6.8 6.8	62.8 ± 1.3
43	UAKA-77-29	Biotite, granodiorite From a breccia pipe at Four Metals Mine, Red Hill, north side of Providencia Canyon, Patagonia Mountains. Harshaw Quad., Santa Cruz Co., AZ Lat 31° 23.84'N, Long 110° 44.17'W	7.493 7.573 7.528	7.531	832.1 825.2 835.7	6.5 6.8 6.3	62.5 ± 1.3
44	UAKA-73-86	Whole rock, rhyolite porphyry Sample from south of the Arizona Portland cement quarry, Busterville. Flows underlie rhyolite breccia and consolidated sediments. Avra Quad., Pima Co., AZ Lat 32° 19.5'N, Long 111° 10.8'W	4.056 4.090	4.073	412.2 429.8	15.06 15.38	58.6 ± 1.4
45	UAKA-75-61	Hornblende, hornblende-plagioclase orthogneiss	1.222 1.231	1.227	124.5	13.5	57.6 ± 1.2
		Biotite, biotite schist Banded basement gneiss about a mile south of McGuffey cabin. Rawhide Mountain, Artillery Peak Quad., Pima Co., AZ Lat 34° 15'N, Long 113° 41'W	5.877 5.859	5.868	536.4	41.0	52.2 ± 1.2

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
46	UAKA-69-10	Biotite granite Drill core, 320m depth. Barren granite intrusive into mineralized Pinal Schist. (#PED-10-69) Globe Quad., Pinal Co., AZ Lat 33° 24.3'N, Long 110° 52.0'W	7.74	7.74	760	17.6	55.8 ± 1.4
47	UAKA-77-63	Biotite, quartz monzonite Reflects Tertiary cooling history Granite Wash, Utting Quad., Yuma Co., AZ Lat 33° 51.2'N, Long 113° 45.1'W	7.139 7.165	7.152	709.8 697.8 682.0 681.4	19.5 22.0 20.4 21.2	55.0 ± 1.2
48	UAKA-58-11	Muscovite, granite Coarse-grained, leucocratic, two-mica granite at Adobe Blanco. Lithologically similar to granite of (#49,51) Gunnery Range batholith (PED-11-58). Sonoyta 1°x2° Quad., Sonora, MEX Lat 31° 46.7'N, Long 113° 00.8'W	8.65 8.69	8.67	810.9	20.4	53.2 ± 1.6
49	UAKA-77-40	Biotite, Gunnery Range Granite Coarse grained leucocratic granite of the Gunnery Range Batholith. San Luis AMS 1°x2° Quad., Sonora, MEX Lat 32° 13.9'W, Long 114° 03.2'W, Alt. 300m	7.624 7.653 7.703	7.660	706.6 725.8	22.3 21.8	53.1 ± 1.3
50	UAKA-73-125	Biotite, medium-grained diorite The diorite intrudes a metasedimentary sequence along the northeastern flank of Eagle tail Mountain, and is overlain by thick gravels and mid-Tertiary volcanics. The rock is partly altered and biotite is somewhat chloritized. Eagle tale Mtns. Quad., Yuma Co., AZ Lat 33° 28.00'N, Long 113° 22.83'W	5.226 5.258	5.242	481.6 492.9	25.4 25.3	52.8 ± 1.1
51	UAKA-75-99	Biotite, Gunnery Range Granite Coarse grained, leucocratic granite of the Gunnery Range Batholith, Cabeza Prieta Mountains. Cabeza Prieta Quad., Yuma Co., AZ Lat 32° 18.32'N, Long 113° 49.12'W	7.501 7.582	7.542	694.2 700.1	10.9 10.7	52.5 ± 1.3
52	UAKA-77-65	Biotite, quartz monzonite Reflects Tertiary cooling Harcuvar Mtns, Salome Quad., Yuma Co., AZ lat 33 53.10'N, Long 113 37.8'W	7.237 7.252 7.252	7.247	654.6 645.1	13.1 13.5	51.0 ± 1.1
53	UAKA-77-60	Whole rock, andesite Dark grey andesitic basalt that overlies "Laramide" andesite flow. Sample is partially propylitized. Roadside formation. San Vicente Quad., Pima Co., AZ Lat 32° 02.17'N, Long 111° 31.33'W	1.902 1.904	1.903	171.2 170.3 169.0	11.3 11.6 12.0	50.8 ± 1.1
54	UAKA-75-115	Sericite, massive quartz vein Intrusive into Bolsa quartzite (Cambrian) at the Reef Mine. Huachuca Mountains. Miller Peak Quad., Cochise Co., AZ Lat 31° 25.6'N, Long 110° 17.3'W	8.026 8.056	8.041	666.4 685.4	1.7 1.7	47.8 ± 1.0
55	UAKA-73-126	Biotite, granite Age of cooling after metamorphic-plutonic event or resetting by Tertiary thermal event. Salome Quad., Yuma Co., AZ Lat 33° 50.67'N, Long 113° 41.55'W	6.571 6.683	6.627	554.3 552.7	13.74 14.04	47.5 ± 1.0
56	UAKA-72-63	Biotite, Granodiorite - possible reset age Lat 32° 09.3'N, Long 112° 39.3'W	7.125 7.170 7.295	7.20	593.7	13.9	47.0 ± 1.0

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
56	UAKA-72-39	Biotite, Granodiorite - possible reset age Lat 32° 08.0'N, Long 112° 37.7'W This granodiorite pluton forms part of the basement for mid-Tertiary volcanic rocks in the area south of Ajo. The age variation suggests partial resetting of the biotites, possibly by hydrothermal activity. Mt. Ajo Quad., Pima Co., AZ	7.304 7.300 7.317	7.307	516.4	13.6 13.7	40.1 ± 1.0
57	HVR-2	Biotite, granite Undeformed biotite-granite east of Tank Pass a cooling age. Salome Quad., Yuma Co., AZ Lat 33° 52.0'N, Long 113° 41.3'W, Alt. 2700 ft.	7.09	7.09	546.3 550.3	53.9 47.0	44.1 ± 1.3
58	UAKA-74-130	Whole rock, basaltic andesite Drill core, 2720-2735 m depth, Geothermal Kinetics drill hole, Higley basin. Probably correlates with Rillito andesite at base of Pantano Fm. and ash bed in lower Whitetail conglomerate. Higley Quad., Pinal Co., AZ Lat 33° 17.0'N, Long 111° 41.3'W	1.946 1.966	1.956	136.2 136.0 134.9 133.0	10.6 10.6 14.8 15.3	39.4 ± 0.9
59	UAKA-73-70	Muscovite, pegmatite Thin dike in foliated to gneissic quartz monzonite of the southern Baboquivari Mountains. The dikes have a northerly strike. Preliminary zircon U-Pb data indicates a Jurassic age for the host rocks, (Haxel and other, this vol). The K-Ar clock was reset by a mid-Tertiary thermal event. Presumidio Peak Quad., Pima Co., AZ Lat 31° 35.0'N, Long 111° 35.6'W	8.686 8.641	8.664	451.7 466.2	23.3 23.6	30.3 ± 0.6
60	UAKA-65-04	Biotite, rhyolite tuff Top of a felsic to intermediate sequence, about 60 m thick, which unconformably overlies granite breccia and a basement complex of granitic rocks. The tuff is overlain by Kinter Fm.of Olmstead and others (1973) Laguna Mtns. Quad., Yuma Co., AZ Lat 32° 48.9'N, Long 114° 28.3'W	7.40	7.40	389.0	40.0	30.1 ± 1.0
61	UAKA-73-25	Biotite, reddish-brown tuff Associated with aeolian cross bedded sandstone, Gila Bend Mountains. Spring Mtn. Quad., Maricopa Co., AZ Lat 33° 12'N, Long 112° 47'W	6.707 6.761	6.734	347.5 345.4	10.1 12.7	29.4 ± 0.6
62	HLa-2	Hornblende, diorite dike	1.49	1.49	78.05	18.6	28.6 ± 1.9
		Biotite, diorite dike Ages from co-existing minerals in a NW-trending dike that cuts metamorphic and granitic rocks in the Harquahala Mountains. Gladden Quad., Yuma Co., AZ Lat 33° 45.7'N, Long 113° 17.8'W	4.94	4.94	182.1 198.5	17.6 14.4	22.1 ± 1.3
63	GR-My-1	Whole rock, ultramylonite Sample from a mylonitic zone cutting Precambrian granite, northern Pinaleño Mountains. Thacher Quad., Graham Co., AZ Lat 32° 46.2'N, Long 109° 46.7'W, Alt. 4320 ft.	2.90	2.90	149.5 137.1	20.3 28.7	28.3 ± 0.7
64	UAKA-63-36	Biotite, granite Coarse-grained granite appears similar to Oracle Granite. Sample collected from small inselberg north of the Tortolita Mountains near Brady Wash. (#PED-36-63) Tortolita Mtns. Quad., Pinal Co., AZ Lat 32° 43.6'N, Long 111° 08.2'W	7.26	7.26	351.5	9.42	27.7 ± 0.7

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
65	UAKA 73-26	Whole rock, basaltic andesite Porphyritic andesite flow underlies fanglomerates and younger lava flows. Gila Bend Mountains Woolsley Peak Quad., Maricopa Co., AZ Lat 33° 12'N, Long 112° 46'W	1.715 1.753	1.734	82.8 82.6	13.1 13.1	27.41 ± 0.66
66	UAKA-68-09	Whole rock, basaltic andesite Unconformably overlies breccia and conglomerate of heterogeneous composition, probably older than Kinter Fm., Chocolate Mountains (#PED-9-68) Picacho Peak Quad., Imperial Co., CA Lat 32° 49.88'N, Long 114° 31.65'W	1.522 1.525	1.524	68.6	72.9	25.8 ± 1.6
67	UAKA-67-01	Hornblende, hornblende andesite Flow intercalated near top of a volcanic-sedimentary sequence, Chocolate Mountains, (#PED-1-67) Picacho Peak Quad., Imperial Co., CA Lat 32° 56.93'N, Long 114° 33.20'W	0.736	0.736	32.56	77.9	25.4 ± 1.5
68	UAKA-75-107	Biotite, gneissic quartz monzonite 5 km NNE of Cunningham Pass in the Harcuvar Mountains. Rock is associated with the Harcuvar metamorphic core complex. Salome Quad., Yuma Co., AZ Lat 33° 59'N, Long 113° 34'W	7.651 7.622	7.636	338.0 336.6	14.8 16.4	25.33 ± 0.54
69	UAKA-73-16	Biotite, granite - Goodwin Canyon Stock Coarse-grained sodic granite intrudes Precambrian gneisses in the Fisher Prospect, north end of the Pinaleño Mountains. Jackson Mtns. Quad., Graham Co., AZ Lat 32° 57'N, Long 110° 15'W	7.810 7.864	7.837	341.3	45.4	24.95 ± .69
70	UAKA-74-129	Biotite, rhyodacite intrusion Vertical dike strikes N 55 E in the Northern Pinaleño Mountains. Bufford Hill Quad., Graham Co., AZ Lat 32° 45.6'N, Long 110° 08.1'W	7.453 7.523	7.488	317.2 327.1	18.6 17.5	24.65 ± 0.60
71	UAKA-73-64	Biotite, Northstar granodiorite stock Small pluton and associated northerly trending dikes intrude the Precambrian basement. Picacho Reservoir SE Quad., Pinal Co., AZ Lat 32° 48.10'N, Long 111° 21.30'W	6.059 6.054	6.057	259.1 255.6	54.1 53.2	24.35 ± 0.73
72	UAKA-72-73	Biotite, latite ash-flow tuff This flow unconformably overlies basement rocks. Eagle Tail Mtn. Quad., Yuma Co., AZ Lat 33° 29.05'N, Long 113° 23.83'W	6.039 6.022	6.030	253.5 245.3	21.6 23.1	23.70 ± 0.70
73	UAKA-74-117	Whole rock, basalt - drill chips Sample from 180-190 meter depth, Exxon Stratigraphic test hole #. 14-1. The lava flow lies beneath 150 m of unconsolidated sediments, mostly gravel. Hyder NE Quad., Yuma Co., AZ Lat 33° 08.'N, Long 113° 21'W	0.814 0.818	0.816	34.0 33.7 33.7 33.5	20.6 20.9 16.7 16.6	23.7 ± 0.6
74	UAKA-73-18	Biotite, rhyolite ash-flow tuff The flow is tilted, striking northwest, dipping 40°-50° northeast. Unconsolidated gravel above this flow is tilted also. Sample (#19,UAKA-73-19) from this site is a flat-lying lava flow. The flow predates deformation, a limiting older age for the mid-Tertiary unconformity. Kofa Butte Quad., Yuma Co., AZ Lat 33° 27.97'N, Long 113° 57.20'W	6.976 7.045	7.011	298.0 279.6	38.4 39.2	23.6 ± 0.62

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
75	UAKA-70-05	Whole rock, basalt Overlies oreodont mammal site at Cave Creek (#PED-5-70) New River Mesa Quad., Maricopa Co., AZ Lat 33° 53.50'N, Long 111° 57.33'W	0.892 0.888	0.890	29.07 44.01 35.66	89.4 87.1 90.2	23.3 ± 2.7
76	UAKA-75-21	Biotite, granite Coarse-grained biotite granite collected from southeast of the junction of Black Rock Canyon and Goat Canyon, Santa Teresa Mountains. Klondyke Quad., Graham Co., AZ Lat 32° 54.8'N, Long 110° 16.1'W	8.019 7.901 8.001	7.974	318.1 316.1	17.3 17.2	22.80 ± 0.55
77	UAKA-74-148	Whole rock, trachyte - drill chips Sample from 1420-1440 meter depth. The flow overlies consolidated red beds and underlies coarse clastic deposits with intercalated evaporite beds in the Paradise basin between the Phoenix and McDowell Mtns. Curry's Corner Quad., Maricopa Co., AZ Lat 33° 42.3'N, Long 111° 58.0'W	6.254 6.158	6.206	246.5 243.9	11.7 11.8	22.65 ± 0.54
78	UAKA-67-23	Biotite, rhyolite tuff Unit interbedded with reddish-brown arkosic sandstone, about 120 m stratigraphically below the mammal fossil locality of Lance and Wood (1958), Muggins Mountains. May be part of Kinter Formation (#PED-23-67) Lat 32° 45.28'N, Long 114° 07.90'W	6.88 6.90	6.89	270.0	56.8	22.5 ± 0.7
79	UAKA-73-19	Whole rock, basalt Olivine basalt flow dips 30° southwest, overlies gravel above flow # 74 and is unconformably beneath #105. Kofa Butte Quad., Yuma Co., AZ Lat 33° 27.50'N, Long 113° 54.08'W	1.086 1.083	1.085	39.8 41.3 41.8	73.5 73.1 73.3	21.68 ± 0.57
80	UAKA-75-04	Whole rock, basalt Flow about 50 m above the base of the basalt sequence from a relatively massive flow unit. The flow dips WSW about 25° ; overlies Precambrian Apache Group and unconsolidated alluvium near crest of Table Top Mtn. Vekol Mtns. Quad., Pinal Co., AZ Lat 32° 44.51'N, Long 112° 07.36'W	0.827 0.827	0.827	30.85 30.79	24.5 24.3	21.37 ± 0.53
81	UAKA-76-90	Whole rock, trachyandesite Forms rounded hills north of Granite Creek on the east side of Chino Valley, host rock for eclogite and pyroxenite nodules, Granite Creek Hills, Chino Valley. Paulden Quad., Yavapai Co., Lat 34° 46.40'N, Long 112° 20.41'W	3.743 3.764	3.754	138.1 140.6	10.1 10.5	21.28 ± 0.51
82	UAKA-72-48	Whole rock, trachyte (ultrapotassic) Flow unit tilted 45° to the northwest on Turtleback Mountain. Turtleback Mountain Quad., Yuma Co., AZ Lat 33° 08.18'N, Long 113° 23.87'W	7.764 7.790	7.777	285.2 285.3	35.0 35.0	21.03 ± 0.54
83	UAKA-73-107	Whole rock, basalt Flat lying basalt flow remnant overlies tilted dacite and trachyandesite flow in the Eagle Tail Mtns. Lone Mtn. Quad., Yuma Co., AZ Lat 33° 32.92'N, Long 113° 26.50'W	0.987 1.002	0.994	36.45 36.02	32.9 33.0	20.90 ± 0.53

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
84	UAKA-75-06	Biotite, andesitic basalt tuff of Rox Conglomerate Rox Quad., Lincoln Co., NEV Lat 36° 53'N, Long 114° 40'W	6.902 6.847	6.875	247.6 248.2	28.6 28.6	20.70 ± 0.5
85	UAKA-73-33	Whole rock, basalt Lowermost flow in a sequence of basalt lava flows in Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 23.3'N, Long 112° 48.8'W	0.578 0.573	0.575	20.8	63.1	20.70 ± 0.5
86	UAKA-68-16	Biotite, dacite Superstition Mountains, near Willow Springs caldera (#PED-16-68) Mormon Flat Dam Quad., Maricopa Co., AZ Lat 33° 31.18'N, Long 111° 27.42'W	7.183 7.176	7.180	257.9	31.1	20.60 ± 0.62
87	UAKA-74-39	Whole rock, basalt Olivine basalt lava flow caps an alluvial surface developed on fanglomerate which extends southward from the Maricopa Mountains. Estrella Quad., Maricopa Co., AZ Lat 32° 50.51'N, Long 112° 18.38'W	0.509 0.507 0.503 0.501	0.505	18.25 17.74	32.1 33.4	20.44 ± 0.45
88	UAKA-73-08	Whole rock, andesitic basalt This lava flow is exposed in a small hill adjacent to the west abutment of Gillespie Dam and is tilted 35 to 40° to the west. The hill is surrounded by a 2.7 m.y. lava flow from the nearby Gillespie Lava Cone (#154, UAKA-73-4). Woolsey Peak Quad., Maricopa Co., AZ Lat 33° 13.70'N, Long 112° 46.30'W	1.233 1.345	1.239	44.1 44.1	35.2 34.4	20.41 ± 0.52
89	UAKA-73-31	Whole rock, andesite This 1.3 m thick dike intrudes volcanic units in the Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 23.9'N, Long 112° 55.0'W	3.265 3.260	3.263	116.2 115.2	34.7 35.3	20.36 ± 0.40
90	UAKA-73-29	Whole rock, basaltic andesite This faulted lava flow overlies a reworked tuff unit in the southern part of the Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 24'N, Long 112° 56'W	1.915 1.921	1.918	67.4 68.9	55.9 55.3	20.35 ± .63
91	UAKA-64-21	Biotite, volcanic ash Layer between Overton fanglomerate and Horse Spring Formation, North Muddy Mountains, (#PED-21-64) Moapa Quad., Clark Co., NEV Lat 36° 38.50'N, Long 114° 31.67'W	7.07 7.13	7.10	247.9	36.8	20.0 ± 0.8
92	UAKA-73-27	Whole rock, basaltic andesite Rock of the sharply eroded and high-standing dark-colored hills which lie between the Gila Bend Mountains and Buckeye Hills in the vicinity of Gillespie dam. Spring Mtn. Quad., Maricopa Co., AZ Lat 33° 12.7'N, Long 112° 48.2'W	1.599 1.572	1.585	55.22 55.37	24.8 24.9	20.00 ± .49
93	UAKA-72-72	Biotite, latite intrusion Latite porphyry dike cuts Precambrian basement rock and overlying volcanic tuffs and vitrophyres. Minimum age of intruded volcanic units. Courthouse rock, Eagle Tail Mtn. Quad., Yuma Co., AZ Lat 33° 27.80'N, Long 113° 21.35'W	7.144 7.120	7.132	251.7 245.3	33.4 32.1	19.98 ± 0.58

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
94	UAKA-73-22	Whole rock, This rock unit may be a flow dipping southwest or a source vent for the local lava flows, the base is hidden in debris. Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 20.3'N, Long 112° 47.5'W	1.324 1.290	1.307	45.96 44.76	51.0 51.8	19.91 ± 0.58
95	UAKA-73-30	Whole rock, basaltic andesite Andesite dike in mid-Tertiary volcanic rocks, Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 26.8'N, Long 112° 52.6'W	2.083 2.095	2.089	72.5 70.1	72.5 73.6	19.58 ± 0.88
96	UAKA-73-14	Biotite, granodiorite Collected from the west end of the White Tank Mtns. White Tank Mtns. Quad., Maricopa Co., AZ Lat 33° 36.9'N, Long 112° 37.6'W	6.618 6.614	6.616	220.7 230.9	43.5 45.0	19.58 ± 0.53
97	UAKA-73-21	Whole rock, andesite Lava flow tilted 50° to 70° in the Palo Verde Hills, Arlington Quad., Maricopa Co., AZ Lat 33° 26'N, Long 112° 57'W	2.241 2.267	2.254	77.04 76.30	49.1 49.3	19.52 ± 0.56
98	UAKA-74-38	Biotite, rhyolite tuff-vitrophyre breccia The tilted and apparently deformed rhyolite sequence underlies unconsolidated gravel and basalt at Black Mesa. Provides an older age for deformation in this area. See Figure 10 Quartzsite Quad., Yuma Co., AZ Lat 33° 35.16'N, Long 114° 02.49'W	7.387 7.386	7.386	247.4 252.5	17.6 17.5	19.41 ± 0.47
99	UAKA-74-130	Biotite, poorly welded pyroclastic rock - drill core From 2400 - 2420 meter depth, geothermal kinetics drill hole, Higley Basin. Flow probably correlates with the rhyolite volcanism in the Superstition-Superior area. Maximum age for the Higley Basin. Higley Quad., Maricopa Co., AZ Lat 33° 17.0'N, Long 111° 41.3'W, Head Alt. 1338 ft.	6.918 6.922	6.920	234.1 233.9	16.1 15.7	19.40 ± .47
100	UAKA-74-149	Whole rock, basalt Lowermost, flow near the summit of Lookout Mountain. Sunnyslope Quad., Maricopa Co., AZ Lat 33° 37.4'N, Long 112° 02.7'W	1.332 1.331	1.332	45.07 44.05	24.4 25.0	19.20 ± .47
101	UAKA-77-147	Whole rock, trachyte (ultrapotassic) Boulder of autobrecciated, purple-red trachyte contained within a red bed fanglomerate unit that underlies flow breccia # 107 (UAKA-77-148). The fanglomerate also contains cobbles and boulders of older crystalline rock and unmetamorphosed pyroxene andesite. Granite Reef Dam Quad., Maricopa Co., AZ Lat 33° 32.43'N, Long 111° 41.24'W	9.330 9.299 9.328	9.319	302.3 304.5 304.0	4.0 3.6 3.7	18.70 ± 0.44
102	UAKA-65-11	Biotite, dacite	7.16	7.16	229.0 230.0	31.9 22.3	18.40 ± 0.50
		Plagioclase, dacite Coexisting minerals from the dacite flow that forms the top of Picketpost Mountain in the Superior area. Related to the Superior cauldron complex, (#PED-11-65) Picketpost Mtn. Quad., Pinal Co., AZ Lat 33° 15.3'N, Long 111° 09.4'W	0.52	0.52	17	85.6	18.8 ± 1.5

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
103	UAKA-73-109	Biotite, aplitic granite Associated with disseminated pyrite in the Woodcamp Canyon stock and in adjacent wall rocks. Reevis Canyon, Picket Post, Pinal Co., AZ Lat 33° 21.75'N, Long 111° 07.67'W	7.583 7.635	7.609	242.8 243.7	22.8 23.2	18.35 ± 0.38
104	UAKA-77-145	Whole rock, basalt This flow, from the north end of Saguaro Lake, is overlain by a poorly welded ash-flow tuff unit that contains pumice and rhyolite chips. Gross lithology is similar to # 106 (UAKA-77-144) Stewart Mtn. Quad., Maricopa Co., AZ Lat 33° 34.53'N, Long 111° 31.54'W, Alt. 1590 ft.	1.067 1.068 1.080	1.072	33.89 34.24 34.49	38.2 38.7 36.9	18.31 ± 0.46
105	UAKA-73-108	Whole rock, basaltic andesite Highest, mesa-forming lava flow from the Kofa Mtns. This flow is flat lying and records the minimum age of tilting. Kofa Butte Quad., Yuma Co., AZ Lat 33° 29'N, Long 113° 53'W	1.785 1.803	1.794	58.30 56.22	38.69 39.92	18.31 ± 0.42
106	UAKA-77-144	Whole rock, basalt This flow unit is part of a fractured and disturbed volcanic sequence overlying a tilted fanglomerate-conglomerate unit. The clastic unit strikes N 30°W, dip 20°SW. Stewart Mtn. Quad., Maricopa Co., AZ Lat 33° 33.54'N, Long 111° 34.78'W, Alt. 1440 ft.	0.987 0.987	0.987	31.18 31.22	17.3 17.6	18.15 ± 0.44
107	UAKA-77-148	Whole rock, trachyte (ultrapotassic) Autobrecciated, purple-red flow unit overlies red bed fanglomerates. #101 (UAKA-77-147). Granite Reef Dam Quad., Maricopa Co., AZ Lat 33° 32.18'N, Long 111° 41.12'W	10.715 10.634 10.676	10.675	329.2 336.7 339.1	6.5 6.3 6.8	18.01 ± 0.43
108	UAKA-72-71	Biotite, latite porphyry Porphyry that overlies basement rocks in the Buckhorn Mtns. The rocks are hydrothermally altered and sulfide bearing in several areas. Copperoplis Quad., Yavapai Co., AZ Lat 34° 01.17'N, Long 112° 26.13'W	7.282 7.336 7.350	7.323	229.5	44.6	17.98 ± 0.43
109	UAKA-73-32	Whole rock, basalt Porphyritic basalt flow from the uppermost unit of the volcanic sequence in the Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 21.2'N, Long 112° 51.1'W, Alt. 1230 ft.	1.345 1.345	1.345	41.9	70.4	17.9 ± 0.7
110	UAKA-76-41	Hornblende, andesite intrusion North end of a-1.5 km long vertical dike that strikes N 60°E, cutting the Gunnery Range Granite in the southern Cabeza Prieta Mountains. Three circular pipes of similar rock have been found in nearby hills. The dike and pipes were probably conduits for some Cabeza Prieta lava flows. Tule Mtn. Quad., Yuma Co., AZ Lat 32° 14.71'N, Long 113° 50.66'W, Alt. 1250 ft.	0.370 0.366	0.368	11.23 11.60	52.7 50.8	17.81 ± 0.52
111	UAKA-77-149	Sanidine, rhyolite ash-flow This flow unit overlies trachyte breccia # 107 (UAKA-77-148) and the red bed fanglomerate in places. Granite Reef Dam Quad., Maricopa Co., AZ Lat 33° 32.15'N, Long 111° 41.12'W	9.237 9.280 9.284	9.267	285.8 286.0 286.1 286.2	15.7 15.5 15.7 15.5	17.71 ± 0.43

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
112	UAKA-72-42	Whole rock, rhyolite Flow-banded rhyolite unit overlies Childs Latite in the Organ Pipe Cactus National Monument. Mt. Ajo Quad., Pima Co., AZ Lat 32° 04.03'N, Long 112° 42.53'W	6.51	6.51	198.4 196.7	58.0 17.5	17.4 ± 0.5
113	UAKA-74-37	Whole rock, basalt Mesa-Capping olivine basalt flow that dips 5° south, overlies unconsolidated gravel on erosion surface cut on rhyolite breccia # 98 (UAKA-74-38). Lower limit on age of deformation. Fig. 10. Quartzite Quad., Black Mesa, Yuma Co., AZ Lat 33° 35.27'N, Long 114° 02.01'W	1.345 1.350	1.347	40.17 40.75	27.8 26.6	17.24 ± 0.43
114	UAKA-73-94	Whole rock, basaltic andesite Lava flow encountered at 100 meter depth in a drill hole east of the Palo Verde Hills. Arlington Quad., Maricopa Co., AZ Lat 33° 21.77'N, Long 112° 51.99'W. Head Alt. 912 ft.	1.542 1.542	1.542	45.3	28.3	16.87 ± 0.42
115	UAKA-73-127	Biotite, granodiorite Granodiorite stock at Bouse, cooling age. Utting Quad., Yuma Co., AZ Lat 33° 58.1'N, Long 113° 49.8'W	6.216 6.258	6.237	178.1 179.5	54.8 54.4	16.46 ± 0.50
116	UAKA-74-04	Whole rock, basalt Lava flow lies beneath a Miocene dislocation surface where Precambrian gneiss has over-ridden the basalt and associated coarse clastic sediments. Minimum age for deformation in the Artillery Mountains. Artillery Peak Quad., Mohave Co., AZ Lat 34° 21'N, Long 113° 37'W	1.127 1.124	1.126	32.00 31.83	18.4 18.4	16.28 ± 0.40
117	UAKA-68-06	Whole rock, basaltic andesite Interbedded with fanglomerate of Miocene age near Parker (#PED-6-68) Black Peak Quad., Yuma Co., AZ Lat 34° 10.64'N, Long 114° 13.15'W	1.726 1.773	1.750	50.92 47.61	74.9 76.0	16.16 ± 0.95
118	UAKA-68-07	Whole rock, basaltic andesite Uppermost flow at top of Black Peak at Parker. 200 m of flow is exposed. (#PED-7-68) Parker SE Quad., Yuma Co., Lat 34° 07.20'N, Long 114° 13.28'W	1.678 1.660	1.669	48.82 45.01	92.6 62.0	16.14 ± 0.75
119	UAKA-74-122	Whole rock, Cabeza Prieta Volcanics andesite Lowest agglomeratic flow unit on Cabeza Prieta peak. Clasts over 1 m diameter are common in this 40 m thick unit. It rests on a steep erosion surface cut in Gunnery Range granite, preserving a fossil desert topography. Same volcanic sequence as # 110 (UAKA-76-41), Fig. 5. Cabeza Prieta Peak Quad., Yuma Co., AZ Lat 32° 17.19'N, Long 113° 48.61'W	1.278 1.294	1.286	36.35 35.84	29.9 30.3	16.12 ± 0.41
120	UAKA-72-40	Whole rock, rhyolite Uppermost rhyolite flow in the Gu Vo Hills, Organ Pipe Cactus National Monument. Overlies Childs Latite - minimum age for the latite. Diaz Peak Quad., Pima Co., AZ Lat 31° 57.30'N, Long 112° 33.08'W	4.037 4.068 4.068	4.058	111.0	34.7	15.71 ± 0.40

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
121	UAKA-72-64	Whole rock, Batamote andesite Fine grained basaltic andesite that overlies Childs Latite in the Batamote Hills northeast of Ajo. (See # 112) Ajo Quad., Pima Co., AZ Lat 32° 25.63'N, Long 112° 48.25'W	2.182 2.192	2.187	60.79 59.05 57.32	62.3 64.2 64.0	15.52 ± 0.54
122	UAKA-77-146	Whole rock, basaltic andesite The hill of basaltic andesite is flanked by flat-lying gravel containing mid-Tertiary volcanic rocks, metamorphic and granitic cobbles. Stewart Mtn. Quad., Maricopa Co., Lat 33° 36.68'N, Long 111° 33.27'W, Alt. 2040 ft.	1.102 1.113	1.108	29.48 30.40	31.1 30.0	15.53 ± 0.39
123	UAKA-72-41	Whole rock, basalt Nearly horizontal lava flow in sequence which overlies rhyolitic flows of Organ Pipe Cactus National Monument sample from the Gu Vo Hills, Papago Indian Reservation. Diaz Peak Quad., Pima Co., AZ Lat 31° 55.35'N, Long 112° 32.84'W, Alt. 2000 ft.	1.450 1.466	1.458	39.06	52.6	15.39 ± 0.45
124	UAKA-73-10	Whole rock, basalt Lowermost lava flow in Hot Rock Hill, overlies unconsolidated gravel beds. Gravel dips 10-25°SE. Palo Verde Hills area Belmont Mtns. Quad., Maricopa Co., AZ Lat 33° 35.14'N, Long 112° 52.83'W	0.571 0.577	0.574	15.00	47.2	15.01 ± 0.42
125	UAKA-77-151	Whole rock, pyroxene andesite This lava flow caps unconsolidated clastic sediments that contain intercalated ash flows. The entire section strikes N 30°W, dips 35°SE. Sample from the north side of the Verde River near Bartlett Dam. Bartlett Dam Quad., Maricopa Co., AZ Lat 33° 48.54'N, Long 111° 39.50'W, Alt. 1630 ft.	1.404 1.409 1.414	1.409	36.23 36.27	42.4 42.3	14.78 ± 0.40
126	UAKA-73-11	Whole rock, basaltic andesite Flow overlies volcaniclastic conglomerate. Bedding and contact dip 20° southeastward. South end of Vulture Mountains Wickenburg SW Quad., Maricopa Co., AZ 33° 48.2'N, Long 112° 44.8'W	2.196 2.203	2.200	54.8 55.4 55.8 56.2	21.3 19.8 19.5 25.1	14.51 ± 0.2
127	UAKA 79-55	Whole rock, basalt Lava flows cap a broad mesa at the north end of the Aguila Mountains that dips about 10° to the north. The mesa is cut by several vertical faults that strike N 35° W and the surface is stepped in a "piano key" fashion. Beneath the lava is a massive bedded, weakly indurated volcani-clastic unit. Arroyos cut in the surface of this unit are preserved at the contact. Aguila Mtn. Quad., Yuma Co., AZ Lat 32° 38.45'N, Long 113° 20.57'W	1.359 1.352 1.357	1.356	33.48 32.77 32.90	23.6 23.4 24.9	14.00 ± .32
128	UAKA-66-55	Whole rock, basalt Lava flow overlies unconsolidated gravels, 0.4 km west of a tributary to Dry Beaver Creek. (#PED-55-66) Lake Montezuma Quad., Yavapai Co., AZ Lat 34° 44.10'N, Long 111° 47.01'W, Alt. 4250 ft.	0.730 0.729	0.730	17.6	83.3	13.9 ± 1.6
129	UAKA-74-118	Whole rock, trachyte (potassic) - drill chips From 675 to 690 m level, Exxon Arizona 14-1 drill hole near Hyder. Unit is 20 m above the crystalline basement rocks and presumably represents a sill or dike. Hyder Quad N.E., Yuma Co., AZ Lat 33° 08'N, Long 113° 21'W	5.65 5.60	5.62	135.6 135.7	22.7 22.7	13.9 ± 0.3

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
130	UAKA-65-10	Whole rock, basaltic andesite Flow contained within the Thumb Formation (#PED-10-65) Henderson Quad., Clark Co., NEV Lat 36° 09'N, Long 114° 46'W	1.82 1.83	1.82	43.06	29.8	13.56 ± .50
131	UAKA-76-123	Whole rock, andesite Faulted and tilted lava flow strikes N 20° W dips 15°W faults strike N 30°W. Sample from roadcut 3 km east of Los Vidrios on Highway 2. Sonoyta Ams 1°x 2° Quad., Sonora, MEX Lat 32° 01.0'N, Long 113° 23.1'W, Alt. 240 m.	2.864 2.893	2.878	66.65 66.97 66.91	9.7 9.8	13.35 ± .32
132	UAKA-67-09	Whole rock, Flow contained within the Hickey Formation. Sample from Mingus Mountain road above Haywood Spring. (#PED-9-67) Hickey Mtn. Quad., Yavapai Co., AZ Lat 34° 42'N, Long 112° 08.4'W, Alt. 7400 ft.	0.630 0.635	0.632	14.56	70.5	13.2 ± 0.8
133	UAKA-66-28	Whole rock, Lava flow caps Government Hill and Black Hills, resting upon Hickey formation. (#PED-28-66) Middle Verde Quad., Yavapai Co., AZ Lat 34° 32.11'N, Long 111° 56.23'W, Alt. 4700 ft.	1.55 1.53	1.54	35.01	88.6	13.1 ± 1.6
134	UAKA-65-01	Whole rock, trachyte Sill in thick section of Thumb Formation in the Frenchman Mountains (#PED-1-65) Henderson Quad., Clark Co., NEV Lat 36° 07.6'N, Long 114° 57.1'W	5.65	5.65	117.4	70.4	11.9 ± 0.7
135	UAKA-66-05	Whole rock, Sill in Thumb Formation, Frenchman Mountains (#PED-5-66) Henderson Quad., Clark Co., NEV Lat 36° 07.9'N, Long 114° 57.0'W	7.41	7.41	144.0	81.0	11.2 ± 0.9
136	UAKA-73-139	Whole rock, basalt - drill chips Flow encountered at 315 m depth, Goodyear Farms drill hole # 1729. The lava occurs near the top of a thick evaporite deposit (bottom not penetrated) in the Luke Basin. Waddell Quad., Maricopa Co., AZ Lat 33° 30.5'N, Long 112° 22.0'W	0.917 0.903	0.909	17.10 16.18	79.0 80.2	10.52 ± 0.61
137	UAKA-76-100	Whole rock, basalt Lava flow caps westernmost of the Mesas de Malpais. The basalt preserves a "fossil desert" surface on unconsolidated alluvium which fills a steep topography cut on Precambrian gneiss. Stream channels are superposed on both the basalt and the gneiss. This extensive lava flow has been offset by normal faults. Ajo AMS 1 x 2 Quad., Sonora, MEX Lat 32° 10.0'N, Long 113° 56.5'W, Alt 510 m	0.203 0.202 0.203	0.203	3.723 3.819 3.566	67.4 65.7 68.8	10.49 ± 0.41
138	UAKA-74-36	Whole rock, olivine basalt Resting on horizontal fluvio-lacustrine silts, mudstones, marls and tuffaceous sandstone. North end of Malpais Mesa near the Santa Maria River. Malpais Mesa Quad., Yavapai Co., AZ Lat 34° 19.41'N, Long 113° 05.90'W	0.484 0.488	0.486	8.414 8.534	63.0 63.0	10.02 ± 0.35
139	UAKA-70-13	Whole rock, basalt Interbedded with late Miocene sediments near horizon of fossil locality, Frick Museum collection, (#PED-13-70), Big Sandy Fm. Dutch Flat, SW Quad., Mojave Co., AZ Lat 34° 34.32'N, Long 113° 23.58'W	1.386 1.386 1.416 1.417	1.401	23.21 23.63	60.7 59.9	9.62 ± 0.38

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	^{40}Ar$_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
140	UAKA-75-62	Whole rock, basalt Flow overlies the Chapin Wash Formation in the Rawhide Mountains. Manganese Mesa. Artillery Peak Quad., Mohave Co., AZ Lat 34° 22.0'N, Long 113° 42.1'W	1.336 1.321	1.328	22.51 22.03 22.00 21.70	67.7 70.2 70.5 69.0	9.55 ± 0.38
141	UAKA-76-89	Whole rock, basalt Lava flow remnant 300 m south of Gila River Channel 7 km east of Florence. 3-6 m displacement on high angle fault. Lies on fine grained basin fill sediments overlain by patches of Gila River (?) gravel up to 20 m thick. Flow possibly predates Gila River to Florence. China Draw Florence SE Quad., Pinal Co., AZ Lat 33° 05.14'N, Long 111° 17.15'W	1.164 1.150	1.157	17.84 17.85	51.5 51.5	8.87 ± 0.26
142	UAKA-74-82	Whole rock, basalt Lowest exposed lava flow, Burro Canyon, beneath highway bridge.	0.658 0.658	0.658	10.19 9.94	68.3 69.1	8.80 ± 0.36
	UAKA-74-81	Whole rock, basalt Flow at base of relay tower. Part of a thick sequence of lava flows exposed in Burro Canyon southwest of Aquarius Mountains. Prescott AMS 1°x2° Quad., Yavapai Co., AZ Lat 34° 32.4'N, Long 113° 26.4'W	0.414 0.412 0.406 0.415	0.412	5.87 5.92	29.4 30.2	8.24 ± 0.21
143	UAKA-75-57	Whole rock, basalt Flow caps "The Tablelands" of the northern Galiuro Mountains, unconformably overlying Apsey conglomerate on a surface of low relief. Predates 150m downcutting of Gila River and tributaries. Jerusalem Mtn. Quad., Pinal Co., AZ Lat 33° 00.96'N, Long 110° 36.34'W	0.811 0.816	0.813	12.0 11.9	40.6 40.6	8.46 ± 0.22
144	UAKA-72-20	Whole rock, basalt Poston Butte olivine basalt, intruded in or extruded within Gila-type gravels and conglomerates Florence Quad., Pinal Co., AZ Lat 33° 03.3'N, Long 111° 24.5'W	1.25	1.25	17.26 17.70 17.94	79.8 85.8 85.4	8.12 ± .64
145	UAKA-76-130	Whole rock, basalt Middle of three flows at top of Bucket Mountain, southwest of San Carlos, 1 km south of highway 70. Flows cap a pediment cut on Santa Teresa Granite. The modern alluvial surface is 90 m below this pediment. Bucket Mountain Quad., Gila Co., AZ Lat 33° 19.03'N, Long 110° 33.99'W, Alt 4140 ft.	0.889 0.881	0.885	11.51 11.45 11.44	84.6 84.7 87.2	7.46 ± 0.59
146	UAKA-74-138	Whole rock, basalt Lowermost flow of the Fortification Hill sequence. Overlies Muddy Creek Formation. Predates downcutting by Colorado River Hoover Dam Quad., Mohave Co., AZ Lat 36° 02.8'N, Long 114° 39.6'W, Alt 3560 ft.	0.909 0.916 0.908	0.911	9.35 9.37 9.18 9.03	59.2 59.2 61.6 62.2	5.84 ± 0.18
147	UAKA-69-04	Glass, vitric tuff	2.06 1.91	2.06 1.91	21.58 17.69	78.9 90.3	5.47 ± 0.20
		Glass vitric tuff	2.094	2.094	19.55	72.2	
		Glass vitric tuff			18.66	72.1	
		These three samples are from the same site, a Tributary to Milpitas Wash, and represent a vitric tuff in the basal limestone of the estuarine Bouse Formation Quartz Peak Quad., Imperial Co., CA Lat 33° 06.5'N, Long 114° 52.4'W					

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
148	UAKA-74-120	Whole rock, basalt - drill chips Sample from 3120 to 3130 m interval, Exxon Yuma drill hole Nr. 1. Possible intrusion. South of Yuma Quad., Yuma Co., AZ Lat 32° 29'N, Long 114° 44'W	0.320 0.322	0.321	3.01 3.01 3.09	94.9 94.9 94.1	5.4 ± 1.0
149	UAKA-75-30	Anorthoclase megacryst, mugearite Sample from volcanic plug at Soda Springs south of Peridot Cove, San Carlos Indian Reservation-Coolidge Dam Quad., Gila Co., AZ Lat 33° 14.9'N, Long 110° 32.4'W	1.218 1.197 1.20 1.24	1.21	11.4 11.5	39.2 39.1	5.28 ± 0.13
150	UAKA-65-09	Whole rock, basalt Columnar basalt flow in Grand Wash Bay, rests on eroded Muddy Creek Formation and fluviatile gravels deposited by the Colorado River. Post dates major downcutting of 810 m Iceburg Canyon Quad., Mohave Co., AZ Lat 36° 12.3'N, Long 114° 01.0'W	1.27	1.27	8.316 8.440	61.3 60.0	380 ± 0.11
151	UAKA-64-08	Whole rock, basalt Sandy Point, the flow rests on Colorado River gravels, Iceburg Canyon Quad., Mohave Co., AZ Lat 36° 06.54'N, Long 114° 06.44'W	1.260 1.260	1.260	7.941 8.648	90.7 90.2	3.79 ± 0.46
152	UAKA-77-04	Whole rock, basalt Southernmost flow edge of agglutinate cone at Warford Ranch, northeastern part of Sentinel Plain volcanic field. Flow rests on Gila River Gravels 30 m above the modern Gila River flood plain. North end, Painted Rock Mountains. Woolsley Peak Quad., Maricopa Co., AZ Lat 33° 01.10'N, Long 112° 59.89'W, Alt 680 ft.	0.683 0.688 0.687	0.686	3.69 3.91	71.0 69.0	3.19 ± 0.11
153	UAKA-73-03	Whole rock, basalt of Arlington cone-SW flow Lat 33° 19.67'N, Long 112° 45.60'W, Alt 840 ft.	0.648 0.647	0.648	3.73 3.71 3.61	85.5 85.4 85.7	3.28 ± 0.27
	UAKA-73-151	Whole rock, basalt of Arlington Cone-West flow Lat 33° 20.96'N, Long 112° 45.98'W, Alt 870 ft.	0.526 0.536	0.531	2.14 2.06	86.4 87.0	2.28 ± 0.21
	UAKA-73-152	Whole rock, basalt of Arlington Cone-West flow Lat 33° 20.03'N, Long 112° 43.80'W, Alt 840 ft.	0.613 0.611	0.612	2.31 2.28	88.6 89.0	2.17 ± 0.25
	UAKA-73-149	Whole rock, basalt of Arlington Cone-West flow Lat 33° 20.73'N, Long 112° 46.14'W, Alt 840 ft.	0.534 0.535	0.535	1.88 1.96	85.2 83.0	2.08 ± 0.18
	UAKA-73-09	Whole rock, basalt of Arlington Cone-South summit Lat 33° 20.77'N, Long 112° 44.62'W, Alt 1080 ft.	0.880 0.894	0.887	2.953	94.5	1.92 ± 0.42
	UAKA-73-150	Whole rock, basalt of Arlington Cone-North summit Lat 33° 20.94, Long 112° 45.02'W, Alt 1020 ft.	0.742 0.736	0.739	1.62 1.66	94.0 93.8	1.28 ± 0.26
		Arlington cone is northeastern most volcano of the Sentinel Plain - Arlington volcanic field. It has the shape and lava flow distribution of a monogenetic basalt volcano. (Fig. 12) Arlington, and Buckeye Quads., Maricopa Co., AZ					
154	UAKA-73-04	Whole rock, basalt of Gillespie Cone-East side Lat 33° 14.15'N, Long 112° 46.96'W, Alt 800 ft.	0.537 0.539 0.524 0.519	0.538	2.54 2.44	78.9 98.3	2.67 ± 0.20

Ser. No.	Sample No.	Sample description and location	K Analysis	% K Used	$^{40}Ar_{rad}$ x10-12 mole/g	% air argon-40	Age in m.y.
154	UAKA-73-07	Whole rock, basalt of Gillespie Cone-near summit Lat 33° 13.79-N, Long 112° 48.02'W, Alt 1310 ft. Gillespie cone is third of four cones on the N 45 E extension of the Sentinel Plain-Arlington volcanic field (Fig. 12) Woolsey Peak Quad., Maricopa Co., AZ	0.774 0.783	0.779	1.63 2.01	97.0 96.4	1.35 ± 0.55
155	UAKA-73-05	Whole rock, basalt of Midway cone Sample from first road cut west of the Painted Rock Mountains on Interstate 8. Sentinel Plain - Arlington Volcanic Field (Fig. 12). Sentinel Quad., Maricopa Co., AZ Lat 32° 53.4'N, Long 113° 04.1'W, Alt 800 ft.	0.899 0.901	0.900	2.77 2.59	92.6 98.3	1.72 ± 0.46
156	UAKA-77-33	Whole rock, basalt of Peridot Mesa Xenolith-bearing basalt flow. Predates 50 to 100 m downcutting of modern Gila River. San Carlos Quad., Gila Co., AZ Lat 33° 20.57'N, Long 110° 28.12'W, Alt 2840 ft.	0.738 0.234	0.736	1.22 1.20 1.15	87.4 88.4 88.1	0.93 ± 0.08