Geochronology, Geology, and Listric Normal Faulting of the Vulture Mountains, Maricopa County, Arizona

by

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Abstract

Geologic mapping and geochronologic studies in the Vulture Mountains near Wickenburg, Arizona, have led to the recognition of a large, northeast-trending batholith of 68.4-m.y. age that intrudes complex gneissic and granitic rocks of probably Precambrian age. Overlying the denuded crystalline terrane is a sequence of late Oligocene to Miocene (∿26 to 16 m.y.) volcanic rocks (vitrophyres, ash-flow tuffs, welded tuffs, breccias, agglomerates, and lava flows) that vary locally. Nearby source areas are suggested. A swarm of north- to north-northwest-trending porphyritic dikes intrudes the volcanics and crystalline basement. Overlying this volcanic sequence in angular unconformity is a thin section of basal conglomerate and basalt lava flows dated at 13.5 m.y. B.P.

The older, tuffaceous sequence is generally calc-alkalic but with a high proportion of rhyolites that are exceptionally rich in potassium and silica. These silicic units are peralkaline or nearly so, and those with $K_2O/Na_2O > 3$ are ultrapotassic. Initial strontium ratios average 0.7081, whereas an initial ratio for the younger basalt sequence is significantly lower at 0.7054.

The silicic volcanics have been severely tilted on multiple, low-angle listric normal faults. The youngest basalt flows are relatively flat lying and postdate this deformation. By geologic and radiometric criteria, the transition from tilted silicic volcanics to untilted basalts occurred between about 16 and 14 m.y. B.P. This petrologic-tectonic boundary can be extended regionally in the southwestern United States and represents a fundamental change from laterally dominant "thin-skinned" extension to basin-range steep normal faulting, accompanied by a switch from calc-alkalic to basaltic volcanism.

The approximately 25- to 15-m.y. B.P. interval of north-northwest-oriented intrusion and listric normal faulting corresponds to a recently discovered period of intense northeast-southwest extensional phenomena in neighboring metamorphic core complexes. Using relationships in these complexes (particularly steeply tilted Tertiary rocks faulted on mylonite) and a broad, northwest-trending antiform of tilted rocks that incorporates the Vulture Mountains and adjacent ranges, a hypothesis for the development of listric faulting is suggested. This hypothesis calls for appreciable northeast-southwest spreading and extension at a shallow crustal level, perhaps facilitated by a concomitant burst of mid-Tertiary magmatism emplaced along north-northwest to northwest trends. After about 14 m.y. B.P., with the change to more primitive basalt volcanism, basin-range extension was significantly reduced by means of the shift from low-angle to high-angle normal faulting, suggesting cooling of crust and tapping of relatively uncontaminated subcrustal melts by deeper penetrating, high-angle structures.

Introduction

Intermittent geologic mapping during the past 10 years in the Vulture Mountains of west-central Arizona (Fig. 1) has led to a significant reinterpretation of the geology and tectonic history of the area. New insights are augmented by 12 potassium-argon age determinations, 18 chemical analyses, and Rb-Sr isotopic data. These discoveries initially provided for updating earlier concepts

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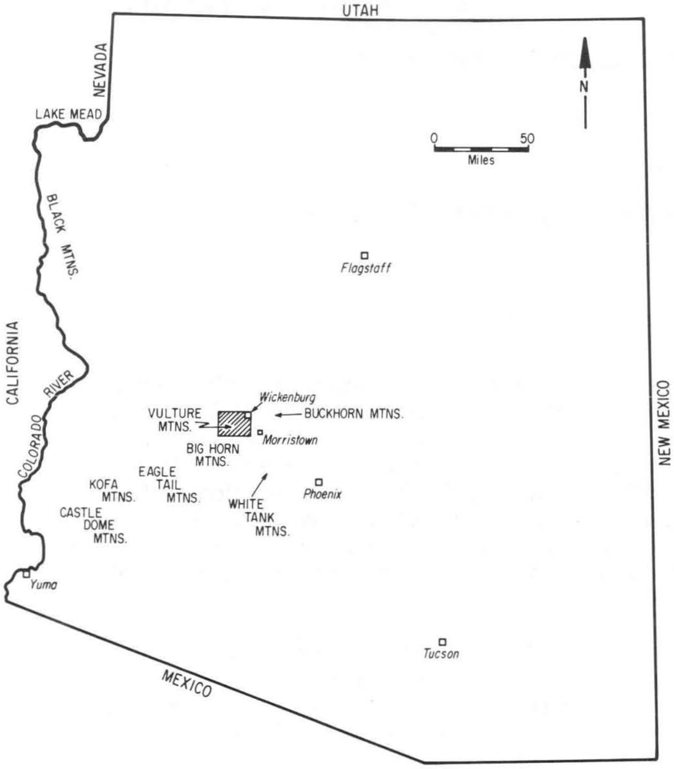


Fig. 1. Location index map of Vulture Mountains and surrounding mountain ranges

regarding chronology of volcanic rocks throughout extensive parts of southwestern Arizona. In addition, details of the structural habitat of these volcanics describe a fascinating tectonic disturbance in Tertiary time, which is becoming recognized as a profound and poorly understood, pre-basin and range event.

The Vulture Mountains are located immediately southwest of the town of Wickenburg, Arizona, in the northwest corner of Maricopa County (Fig. 1). The mountains form a series of elongate ridges and hummocky hills of relatively low relief. This landscape is interrupted by the prominent, sharp ridges of the Vulture and Caballeros Peaks.

Primary access to the area is via U.S. Highway 60-70 west from Wickenburg. Numerous dirt roads (e.g., Vulture Mine Road) and jeep trails lead south from the main highway into the region of study.

There are numerous early literature references to mining activity and specific mineral deposits in the Vulture Mountains, particularly to the gold deposits of the Vulture mine (Defty, 1912; Hutchinson, 1911; Purington, 1907; Metzger, 1938). There are, however, few descriptions of the broader aspects of geology and age relationships of rocks in the Wickenburg-Vulture region, other than those general features appearing on the Maricopa County geologic map (Wilson, Moore, and Peirce, 1957) and the Arizona Geologic Map (Wilson, Moore, and Cooper, 1969). On these maps the Vulture range is shown formed mainly by Cretaceous volcanics and Precambrian gneiss and granite intruded by late Mesozoic/Laramide dikes. Capping this complex are outlier mesas of Quaternary basalt.

In this paper, we will present data supporting a Miocene age for the "Cretaceous" volcanics, late Miocene ages for the basalts, and a Laramide age for part of the basement crystalline complex. The mid-Miocene volcanics are largely subalkaline and include an abundance of ultrapotassic rhyolites, among the first reported occurrences of such rocks in Arizona. Chemical and isotopic data on these tectonically disturbed rocks and the overlying, late Miocene, basic volcanics document a fundamental structural-petrologic transition, which occurred in this region between approximately 16 and 14 m.y. B.P.

General Geology

Regional Geology

The Vulture Mountains occur in the Basin and Range province within a north-northwest- to northwest-trending zone of intense normal faulting. The zone may be projected along strike some 20 miles to the south where it aligns with prominent north-northwest linear trends in granitic-gneissic rocks of the White Tank Mountains (Fig. 1). The faults in the Vulture range are of the listric normal type and have tilted Tertiary volcanic units that dip steeply northeast. This rotational faulting extends with progressively less effect toward the northeast into the Buckhorn Mountains north of Morristown. As a whole, the broad area of north-northwest- to northwest-trending faults represents a major structural transition between the Mountain and Desert subprovinces. Across this zone, crustal blocks have been repeatedly downdropped to the southwest and tilted northeast during the latter part of the Tertiary period.

Two separate volcanic sequences of Tertiary age occur in the Vulture Mountains: an earlier siliceous sequence of flows and tuffaceous rocks and a later series of basaltic flows. These same sequences crop out extensively in many of the surrounding mountain ranges. In particular, a nearly continuous northeast-southwest-trending area of these rocks occurs from the Buckhorn Mountains, across the Vulture, Big Horn, Eagle Tail, Kofa, and Castle Dome Mountains to the Colorado River (Fig. 1). Regional work by the authors indicates that the two volcanic series can be correlated in general temporal and petrologic senses throughout a large portion of western and central Arizona (Shafiqullah and others, this volume).

Rock Types

Pre-Tertiary rocks in the Vulture Mountains consist of a Precambrian metamorphic-igneous basement intruded by a composite Laramide batholith. Tertiary rocks include hypabyssal intrusive and volcanic rocks. Figure 2 is a generalized reconnaissance geologic map of a large portion of the Vulture Mountains. The map and accompanying cross section illustrate relationships between the various rock types described below.

Precambrian basement rocks exhibit a crude northeast-oriented zonal pattern of different lithologies. To the north (along U.S. 60-70), a coarse-grained, porphyritic granite is found in scattered outcrops between alluvial cover. A similar granite occurs to the south between the Vulture and Caballeros Peaks. This rock is mesoscopically similar to Precambrian granites in adjacent areas. Tertiary volcanic rocks rest depositionally on this granite, but its relationships with the other rock units have not been observed.

A 2-3-mile wide, northeast-striking zone of gneissic granite is found south of the granite. The gneissic granite is composed generally of fine- to medium-grained orthoclase and quartz with laminae and aligned crystals of biotite or muscovite. A granitic composition is most common; however, a rather broad compositional variation to granodiorite is noted locally. The zone of gneiss is cut by pegmatite and granitic dikes, and there is evidence of extensive quartz and potassium-feldspar metasomatism adjacent to many of these intrusions. Numerous lenses and bands of gneissic amphibolite and foliated diorite are found interlayered with the granitic gneisses.

Mafic schists are common in the southern part of the gneissic belt and crop out extensively around the Vulture mine (Fig. 2). One to 2 miles north-northwest of the mine the contact between gneiss and schist is marked by a northeast-trending fault. The mafic schists presumably continue southward beneath alluvial cover and reappear in scattered outcrops just north of Indian Buttes in the southeast corner of the Vulture Mountains quadrangle.

A large granodiorite pluton intrudes the core of the granitic gneiss belt. This pluton is highly elongate, with an average width of approximately 3 to 4 miles and a length that extends northeast and southwest beyond the limits of the Vulture Mountains quadrangle. Much of the town of Wickenburg is probably underlain by the pluton; therefore, the name *Wickenburg batholith* is proposed for this igneous body.

At least three intrusive phases are present in the batholith. Along the north contact, an early diorite phase occurs as a discontinuous border zone. It is intruded sharply by the main granodiorite phase, a light-gray, equigranular rock containing abundant biotite and minor hornblende. A porphyritic quartz monzonite phase with orthoclase phenocrysts up to 3 cm across has intruded between Precambrian gneiss and the main granodiorite phase at the southwestern edge of the Wickenburg batholith. Northeast-trending dikes of aplite and granodiorite porphyry cut all intrusive phases of the batholith.

Postbatholith rock units in the Vulture Mountains consist of tilted and downfaulted remnants of silicic tuffs, flows, and hypabyssal dikes overlain by basalt and basaltic andesite flows. The tuffaceous volcanics overlie a reddish-brown conglomerate, which was deposited on an erosion surface developed upon the Wickenburg batholith and Precambrian basement (Fig. 4). The conglomerate is of variable thickness, up to about 30 m. This unit is locally missing due either to erosion or nondeposition. Clasts in the conglomerate are predominantly of Precambrian(?) rock with lesser amounts of granodiorite from the underlying pluton. In places, the conglomerate is interbedded with thin mafic volcanic flows (Fig. 3B).

Volcanic rocks above the conglomerate consist generally of rhyolitic lava flows, welded tuffs, and pyroclastic-volcaniclastic rocks interbedded with minor basaltic andesite flows. The basal volcanic section in most areas is made up of a buff to yellowish ash-flow tuff, which exhibits volcaniclastic and agglomeratic facies in places. Pumice is abundant and vitrophyres occur locally. This tuff is partially interstratified with but generally overlain by sequences of rhyolitic lava flows and welded tuffs. The flows are gray to purple and usually exhibit marked flow banding. Commonly, flows have been extensively devitrified and zeolitized to a "punky" yellowish-buff rock. The welded tuffs show variable eutaxitic structure and lithophysae. There are local laharic volcaniclastic beds in the sequence.

The section of silicic volcanics displays marked changes in its thickness and facies over various portions of the Vulture Mountains. For example, an approximately 470-m-thick partial section (Fig. 3A), exposed along old Highway 60 (sec. 13, T. 7 N., R. 6 W.), consists of a relatively high proportion of basaltic andesite flows. These flows overlie a thick, dark-gray vitrophyre and basal yellowish ash-flow tuff and tuffaceous sandstone deposited on basement granite. Overlying the basaltic andesites is a light-gray unit of latite flows (Fig. 3A).

Several miles to the south-southeast, a 300-m-thick partial section exposed on Vulture Peak ridge (Fig. 2) consists predominantly of thick sequences of yellowish tuff and tuffaceous agglomerate rich in pumice. The agglomerates contain 7- to 40-m-thick beds of densely welded tuff and rhyolite flows (Fig. 3B).

These abrupt transitions to coarsely agglomeratic facies and increasing proportion of rhyolitic flows suggest proximity to vents and intrusive centers. These centers have not been identified within the mapped area (Fig. 2). Limited reconnaissance east of the Vulture quadrangle, however, suggests the presence of small domes, tuff vents, and a thickening of volcanic units.

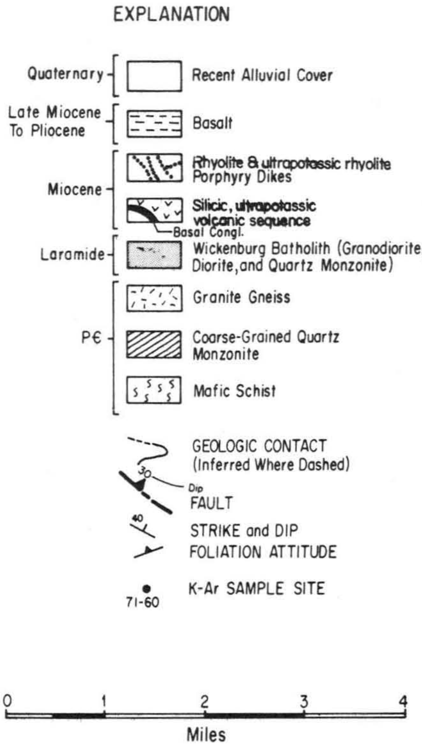
The yellowish, poorly welded, basal tuffaceous unit of the volcanic section is widespread throughout the Vulture Mountains. It is also found deposited on conglomerate and directly upon pre-Tertiary rocks in the nearby Big Horn, Eagle Tail, and Kofa Mountains, southwest of the Vulture Mountains (Fig. 1). Fresh biotite occurring locally in this unit yielded similar K-Ar ages in several of these localities and thus supports the correlation (Shafiqullah and others, this volume).

The silicic volcanic section is intruded by a swarm of north-trending, hypabyssal dikes. These silicic dikes are generally of two types: (1) dark-purplish-gray, ultrapotassic rhyolite porphyry and (2) gray, quartz-biotite alkali rhyolite porphyry. Dike thicknesses range from about 10 to 30 m. Their outcrop traces are often curvilinear, and individual dikes are commonly continuous for distances in excess of 2 km.

The siliceous volcanics and dike swarms are overlain in marked angular discordance by a sequence of blocky basalt flows, often with an underlying conglomerate or basal, reddish, oxidized zone. The basal conglomerate contains clasts of both pre-Tertiary basement and Tertiary volcanics. The basalts are highly vesicular in places and commonly contain iddingsite after olivine. These flows are relatively flat lying, with dips less than 10-15 degrees. The angular unconformity with the underlying rhyolitic sequence is best seen on Black Mountain just north of U.S. 60-70 and on Twin Peaks along the Vulture Mine Road, several miles to the south-southeast (Fig. 2).

Structure

Foliation dips in Precambrian gneisses, schists, and amphibolites are steeply inclined with strikes that vary from west-northwest to northeast (Fig. 2). These structural attitudes are similar to those in Precambrian terranes elsewhere in Arizona and are probably the result of Precambrian deformation. The coarse-grained, porphyritic granite is not foliated and if it is equivalent to 1.4 b.y.- to 1.7 b.y.-old plutons elsewhere, an older deformational event is further indicated.



Explanation for Figure 2 (facing page)

The intrusion of the Wickenburg batholith was strongly controlled along northeast to east-northeast structural alignments. This control is also indicated by the similar orientation for comagmatic dikes, veins, and sheeted joints within the pluton.

The most prominent structural grain in the mapped area (Fig. 2) strikes north to north-northwest. This grain is primarily represented by north-trending, postbatholith dike swarms, normal faults, and tilted elongated fault wedges of siliceous volcanic rocks.

Conglomerate and siliceous volcanic strata are severely fragmented and occur as steeply tilted and repeated sections separated by nortn-striking, west-dipping normal faults (Fig. 2).

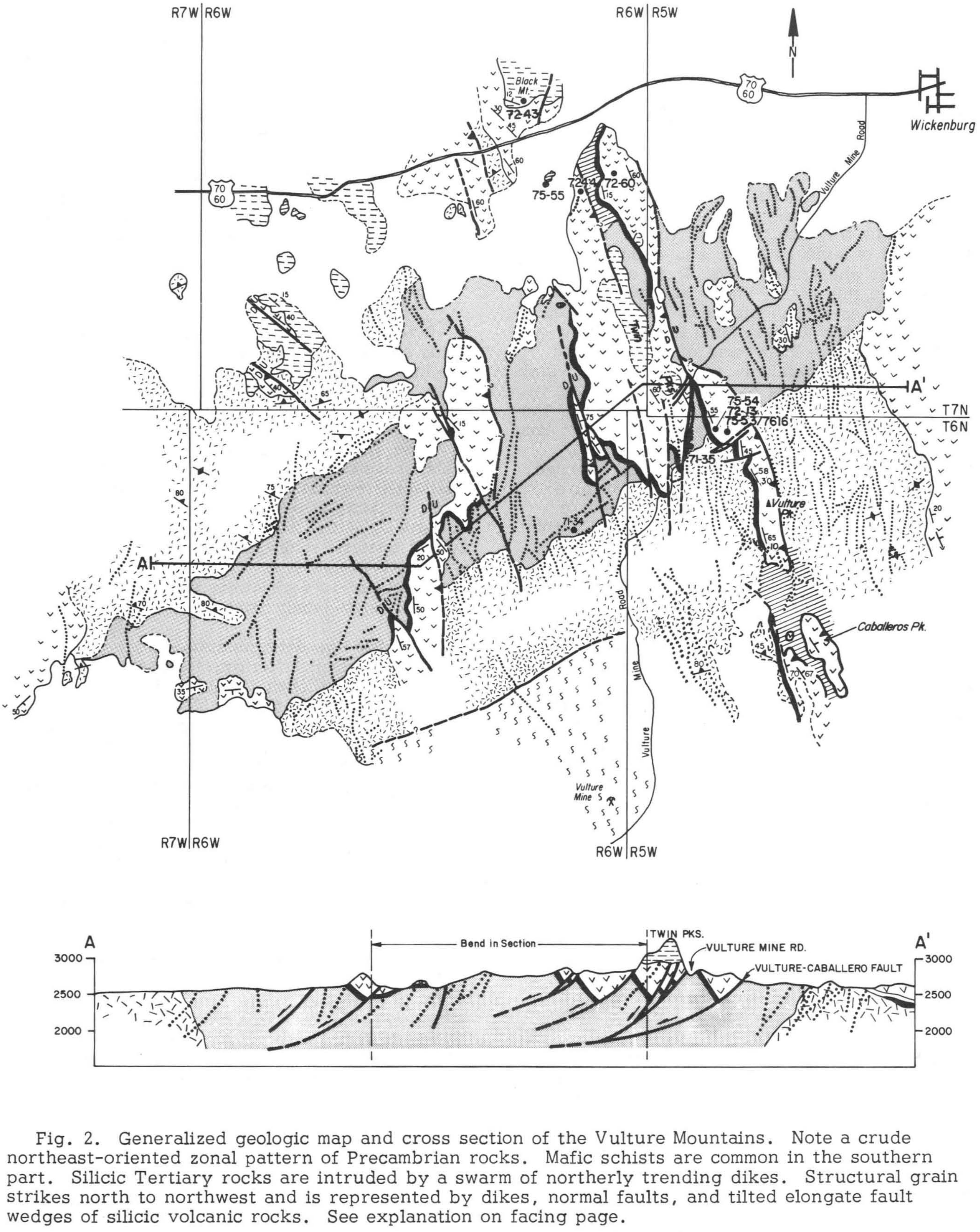


Fig. 2. Generalized geologic map and cross section of the Vulture Mountains. Note a crude northeast-oriented zonal pattern of Precambrian rocks. Mafic schists are common in the southern part. Silicic Tertiary rocks are intruded by a swarm of northerly trending dikes. Structural grain strikes north to northwest and is represented by dikes, normal faults, and tilted elongate fault wedges of silicic volcanic rocks. See explanation on facing page.

These faults often merge in a complex acute-angle fashion. They are most obvious in the layered Tertiary volcanics or at contacts between volcanics and older crystalline rocks.

Ubiquitous repetitions of volcanic rocks having dips up to 70 degrees indicate rotation of small structural blocks along normal faults that flatten at relatively shallow depth. These inferred structures, called listric normal faults, are only rarely exposed (e.g., on the ridge in the NW¼ sec. 5, T. 6 N., R. 5 W., south end of Vulture Peak, and Caballeros Peaks) but where seen (Fig. 4) do exhibit flat dips to the west. The most prominent of these faults is a branching pair of structures that crosses the Vulture Mine Road between Twin and Vulture Peaks and displaces silicic volcanics down against footwall rocks of crystalline "basement." One of these faults can be traced southward along the eastern flank of the prominent Vulture-Caballeros ridge. At the common corner of secs. 4, 5, 8, and 9, T. 6 N., R. 5 W., the actual fault plane is well exposed, dipping 30° W. At the south end of Vulture Peak ridge (sec. 16), the fault flattens to a 10° W. dip and is exposed on both sides of the ridge (Fig. 2). In like manner, the Vulture-Caballeros fault floors the volcanics of Caballeros Peaks as well as klippen of tilted volcanic rocks west of the peaks.

These outcropping examples reveal the following details about the fault. Rhyolites of the hanging wall are brecciated and silicified for 1 to 5 m above the slickensided shear surface. Slickensides and striations indicate approximate dip-slip movement. Granitic and gneissic rocks of the footwall show intense microbrecciation, brecciation, and shearing for distances up to 20 m below the fault. At the south end of Vulture Peak a quartz-biotite rhyolite porphyry dike appears cut by the fault. Dark-colored rhyolite porphyry dikes, however, cut both hanging and footwall rocks. Significantly, these dikes are not brecciated, intrude the fault plane, and thus clearly postdate rotational fault movements (Fig. 4). Equivalents of both pre- and postfault dikes have been dated by the potassium-argon method and the age of this unusual deformation will be discussed in a subsequent section.

Another characteristic of the listric normal faulting is its consistent rotation of blocks toward the east (west transport of hanging-wall blocks). This tilting appears to have affected volcanic dikes as well as the tuffs and flows they intrude, because these dikes exhibit moderate to steep westward dips. The eastward tilting in the Vulture Mountains is part of a more extensive terrane of faulted and variably tilted Tertiary volcanic flows that stretches from the Vulture Mountains northeast through the Buckhorn Mountains and Castle Hot Springs area nearly to the Bradshaw Mountains (Figs. 1 and 7). The overall sense of rotation through this region is northeastward.

In T. 6 N., R. 6 W., where volcanic dikes penetrate the Wickenburg batholith, many dikes veer to the northeast, departing from their more persistent north-northwest trend. In this area, the strong Laramide fracture fabric in the pluton appears to have exerted a local anisotropic control on the Tertiary dike emplacement.

Geochronology

Potassium-argon data for 12 Vulture Mountains samples are presented in Table 1. Sample locations are shown on Figure 2. Age results, from oldest to youngest, are discussed below.

A 68.4-m.y. age was determined for the main granodiorite phase of the Wickenburg batholith (Sample 71-34). This datum refines prior geologic knowledge concerning crystalline rocks of the Vulture Mountains. Previously, all granitic rocks in the range were considered Precambrian. Note that a biotite partially altered to vermiculite (Sample 71-14) gave an anomalously young age of 62.9 m.y.

A biotite age determination on the coarsely crystalline porphyritic granite north of the Wickenburg batholith (Sample UAKA-75-55) yielded a Laramide date of 65.6 m.y., which is similar to the age of the batholith itself. Geologic criteria can only establish that the porphyritic granite is older than the unconformably overlying volcanic strata. However, from compositional and textural similarities to the 1.7-b.y.-old granites in the nearby region, we would prefer tentatively to assign a Precambrian age to this granite. The 65.6 m.y. apparent age of the granite is thought to have been reset due to its proximity to the large Laramide pluton (Fig. 2).

Geochronologic data for the sequence of silicic volcanic rocks established an age range from 26 to 16 m.y. (late Oligocene to mid-Miocene). The range is particularly wide due to the 26.0-m.y. biotite date on Sample 75-54. This sample was taken from a rhyolite tuff just above the conglomerate overlying pre-Tertiary crystalline rocks.

Another rhyolite tuff, whole-rock Sample UAKA-72-13, had been dated during early reconnaissance, but this sample was altered and no attempt was made to remove glass and clay. The date of 16.3 m.y. B.P. gives a minimum age for this unit.

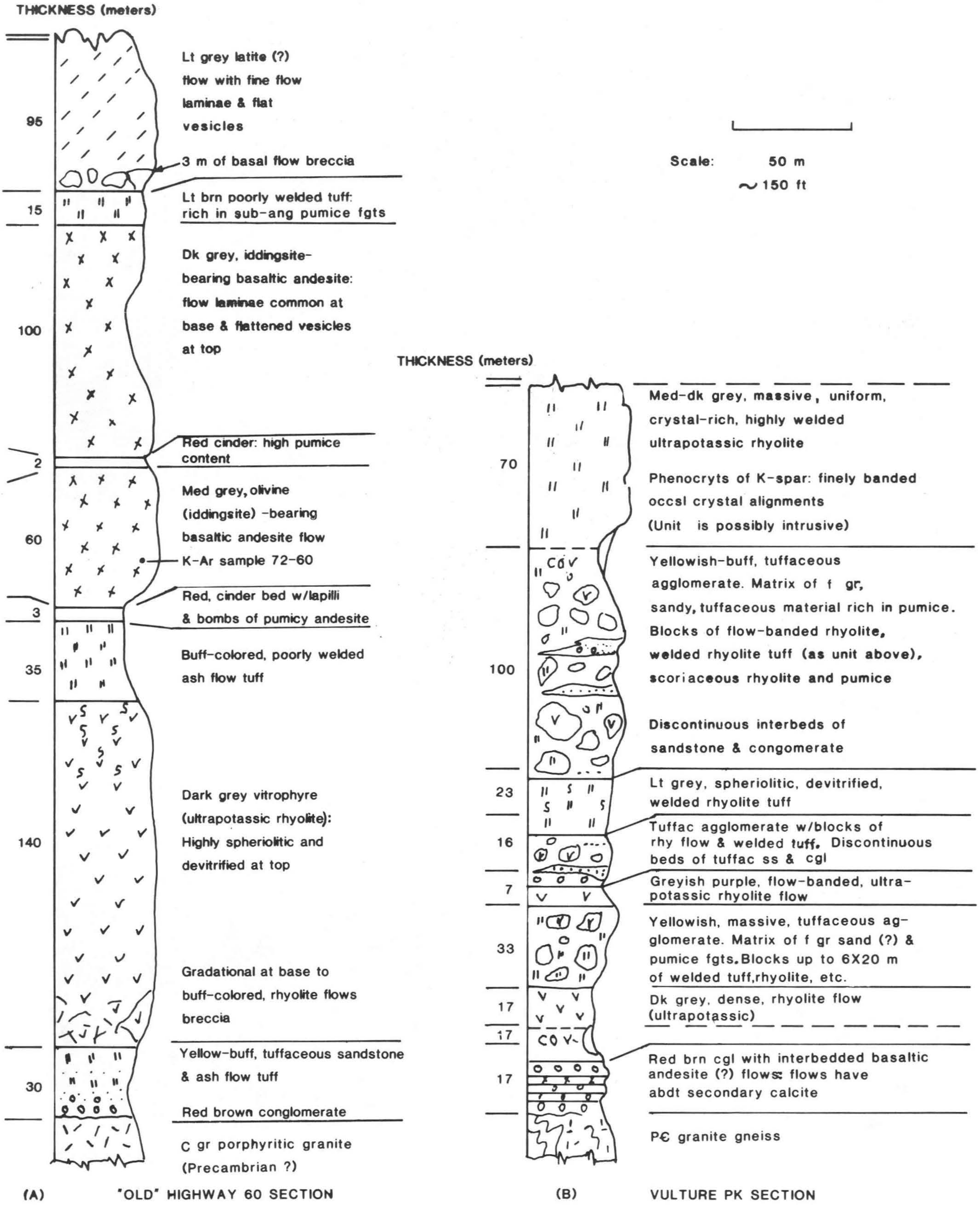
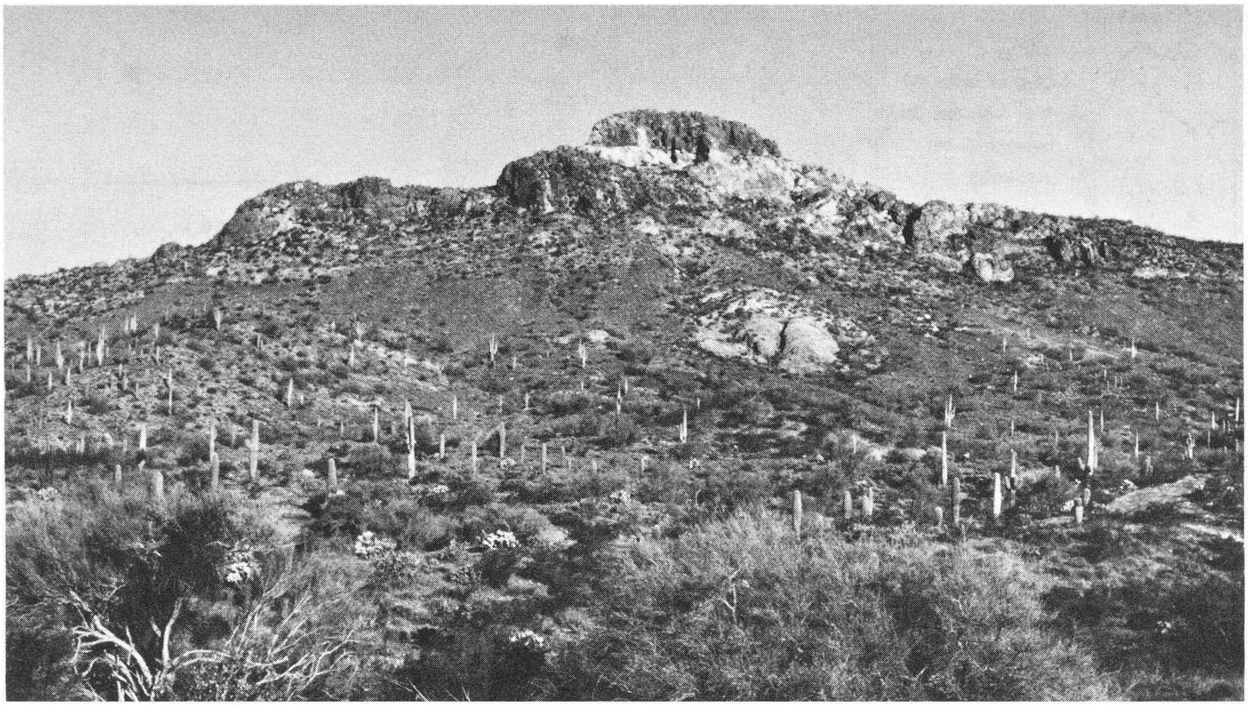


Fig. 3. Generalized stratigraphic sections: (a) east-dipping section exposed along old highway 60 in sec. 13, T. 7 N., R. 6 W.; (b) section of east-dipping volcanics exposed on west side of Vulture Peak. Sections rich in ultrapotassic rhyolite flows and tuffs but with marked changes in thickness and facies.

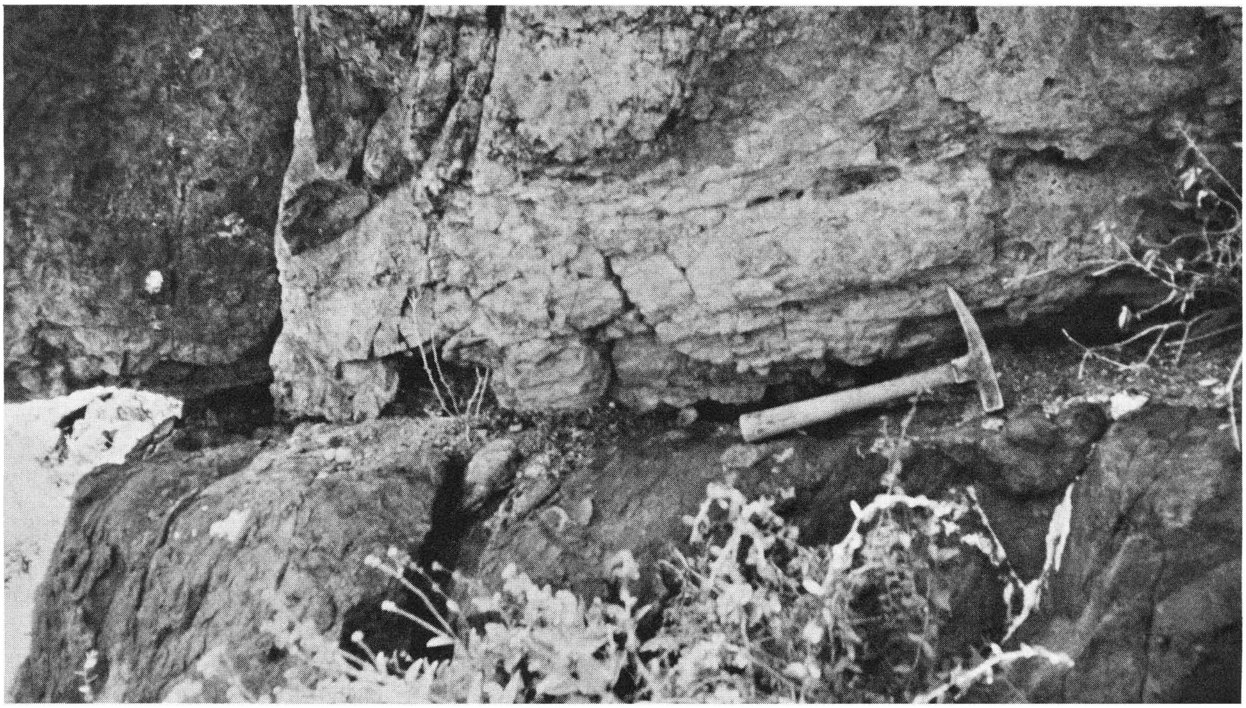


A. Ridge in NW¼ sec. 5, T. 6 N., R. 5 W. which exposes steeply tilted, red conglomerate at the base overlain by ultrapotassic rhyolite flows and tuffs. Just below highest crest of ridge outcrops trace of flat listric normal fault. This view looking east from Vulture Mine Road shows sites of K-Ar samples 72-13, 75-54 in lowermost tuffs, sample 75-53 from the fault, and sample 76-16 from above the fault.

B. View south of tilted (∿70° E. dip) basal conglomerate overlying Laramide granodiorite and Precambrian gneisses at base of ridge shown in A.

Fig. 4. Relevant structural and stratigraphic relationships in the Vulture Mountains

C. North-looking view of listric normal fault exposed near crest of ridge shown in A. Fault (center of photo) places ultrapotassic rhyolite flow upon similar rhyolite tuffs and flows. K-Ar sample 75-53 taken from fault zone; sample 76-16 is of rhyolite about 3 m above fault.



D. South end of Vulture Peak ridge (sec. 16, T. 6 N., R. 5 W.). View of west-dipping, low-angle, listric normal fault which places shattered, silicified, Tertiary rhyolite on intensely brecciated Precambrian(?) granite. Hammer rests on half-meter-thick ultrapotassic rhyolite dike intruding the fault plane.

Fig. 4. Continued

Table 1. K-Ar analytical data on Vulture Mountains samples, Vulture Mountains quadrangle, Maricopa County, Arizona

Sample No.	Sample description and location	K analyses	Percent K used	argon-40 x 10-12 mole/g	% atmospheric argon-40	Age in million years
UAKA-71-34	Biotite, granodiorite - Wickenburg Batholith Medium grained, equigranular, light grey in hand specimen. Intruded into Precambrian granite and gneisses, forms basement for Mid-Tertiary volcanic sequence. Lat. 33° 52.5'N., Long 112° 50.5'W.	5.723 5.701 5.587 5.652	5.67	684.2	53.6	68.4 ± 1.7
UAKA-71-14	Vermiculitized biotite, Granodiorite - Wickenburg Batholith Lat. 33° 56.8'N., Long. 112° 47.0'W.	4.804 4.796	4.80	532.5	38.4	62.9 ± 1.2
UAKA-75-55	Biotite, granite Granitic basement complex. Coarse grained-granite with quartz veins, probably Precambrian rock reset by Laramide intrusions. Lat. 33° 56.8'N., Long. 112° 50.8'W.	6.540 6.492	6.52 6.52	747.0 763.8	13.7 13.2	65.6 ± 1.4
UAKA-75-54	Biotite, rhyolite Sample from 15 meters above the contact with red-bed conglomerate that separates this unit from the Precambrian basement gneisses. Lat. 33° 53.8'N., Long. 112° 48.7'W.	6.594 6.634	6.61	298.4 302.5	11.0 11.1	26.0 ± 0.6
UAKA-72-44	Biotite, porphyritic rhyolite Dike cuts lowest basaltic andesite flows and the underlying Precambrian basement rocks. Lat. 33° 56.8'N., Long. 112° 50.4'W.	6.064 6.020	6.04	191.4	44.4	18.2 ± 0.4
UAKA-75-53	Whole rock, rhyolite cataclasite - Gouge zone at sole of low angle fault. Lat. 33° 53.8'N., Long. 112° 48.4'W.	5.778 5.772	5.78	170.3 170.4 172.1 173.4 173.3	13.4 11.5 13.6 11.6 11.9	17.1 ± 0.4
UAKA-72-60	Whole rock, basaltic andesite (Trachyandesite) Basal unit of andesitic volcanic sequence Lat. 33° 56.9'N., Long. 112° 50.0'W.	2.020 2.053	2.04	57.8 60.7	88.9 85.0	16.7 ± 1.1
UAKA-72-13	Whole rock, rhyolite Porphyritic, tuffaceous latite, slightly altered Minimum age for this unit. Lat. 33° 53.8'N., Long. 112° 48.4'W.	7.635 7.643	7.64	216.8	48.6	16.3 ± 0.3
UAKA-71-35a	Whole rock, rhyolite Trachyte contains small (1 mm) feldspar phenocrysts in a reddish-brown aphanitic matrix. Vertical dike intrudes tilted volcanic sequence. No acid leaching. Lat. 33° 53.4'N., Long. 112° 49.0'W.	8.642 8.666	8.65	241.1 243.8 248.0	68.5 70.0 68.6	16.2 ± 0.5
71-35b	Whole rock, rhyolite Same outcrop, acid leached. Lat. 33° 53.4'N., Long. 112° 49.0'W.	8.123 8.105	8.11	226.5 229.2	26.4 30.2	16.1 ± 0.4
UAKA-76-16	Whole rock, rhyolite Sample from 2m above the sole of the low-angle fault. Structurally above UAKA-72-53. Lat. 33° 53.8'N., Long. 112° 48.4'W.	8.080 8.024	8.05	223.5 227.4 225.8	39.4 39.7 40.2	16.1 ± 0.4
UAKA-72-43	Whole rock, olivine basalt Mesa-capping basalt rests on partially indurated gravel. Flow dips gently (13°) to the northeast and lies above steeply tilted older volcanics. Lat. 33° 58.0'N., Long. 112° 51.1'W.	0.860 0.860	0.860	19.54 20.87	60.7 59.4	13.5 ± 0.3

Constants used:

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

$\lambda_e = 0.581 \times 10^{-10}\ \mathrm{yr}^{-1}$

$\lambda = 5.544 \times 10^{-10}\ \mathrm{yr}^{-1}$

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

Two samples were collected at a listric fault zone in an attempt to date the fault movement. A cataclastically reconstituted rhyolite at the sole of the fault yielded an age of 17.1 m.y. (Sample UAKA-75-53), and another whole-rock rhyolite date on a unit above the fault yielded an age of 16.1 m.y. (Sample UAKA-76-16). From these dates alone, it can only be concluded that the listric fault is 16 to 17 m.y. old or younger. However, the age of listric faulting can be further constrained by considering geologic relationships at the south end of the Vulture Peak ridge. There a quartz-biotite rhyolite porphyry dike is apparently truncated by the flat Vulture-Caballeros listric fault, whereas dark, ultrapotassic rhyolite porphyry dikes intrude the fault plane and show no evidence of structural deformation. The truncated rhyolite dike is very similar to the biotite-bearing dike (Sample 72-44) that yielded a biotite age of 18.2 m.y. The postfaulting, dark dikes appear to correlate with similar dikes giving dates of approximately 16 m.y. (Sample 71-35). Two analyses were made on Sample 71-35 with and without removal of glass and clay. The results are identical. If the above correlations are valid, listric normal faulting occurred between approximately 18 and 16 m.y. B.P.

The age of postdeformational basalt volcanism is believe to be established by the 13.5-m.y. date of Sample 72-43. This sample came from the blocky basalt flows at Black Mountain just north of U.S. 60-70 (Fig. 2). At this locality the relatively flat-lying basalt flows unconformably overlie tilted silicic volcanics dipping 30-40° NE. This angular discordance is even greater in the Twin Peaks area a few miles to the south. The 13- to 14-m.y. age interval for the untilted basalts also places a minimum date on the interval of listric normal faulting. This interval would by these criteria fall between about 18 m.y. B.P. (age of truncated rhyolite dikes) and 14 m.y. B.P. (age of untilted basalt flows).

It is interesting that basaltic andesite volcanism (Sample 72-60, 16.7 m.y.) accompanied rhyolitic volcanism in the Vulture Mountains as it did elsewhere throughout the basin-range of Arizona (Damon and Shafiqullah, 1976). However, the ultrapotassic nature of the rhyolitic volcanism in the Vulture Mountains is a unique feature that warrants further discussion in the following section.

Chemistry of the Tertiary Volcanic Rocks

Major Oxides

Whole-rock chemical analyses of representative Vulture Mountains volcanic rocks (Table 2) show that most of the silicic flows and tuffs have SiO_2, Al_2O_3, and K_2O as major oxide constituents. These three oxides generally make up more than 90 weight percent of the total rock. Thus, quartz and orthoclase are the dominant normative minerals. Fifteen of the 18 analyzed samples have more than 69 weight percent SiO_2 and are therefore oversaturated with silica. The K_2O content of analyzed rocks is strikingly high, and for silicic samples averages 8.1 weight percent.

Using Streckeisen's (1973) classification, all but three of the Vulture rocks plot as alkali rhyolites. Because K_2O/Na_2O is greater than 3 for most of the silicic samples (Table 2), they can be defined as ultrapotassic rhyolites (Carmichael, Turner, and Verhoogen, 1974). Five of the ultrapotassic rhyolites are peralkaline with alkali-Al_2O_3 molecular ratios greater than 1 and normative acmite (Table 1). Several other samples are nearly peralkaline. With the exceptions of Samples VP-1-14, 75-54, and 76-16, the rocks sampled belong to the subalkaline series of Irvine and Baragar (1971).

Some rocks in the northern Vulture Mountains have less than 60% SiO_2, lower alkali contents, and significantly lower K_2O-Na_2O ratios than the ultrapotassic rhyolites. These flow rocks resemble the potassic basaltic andesites common to other parts of Arizona (Eastwood, 1970). They are also similar to the shoshonitic clan of Jakes and White (1972), although potassium in the samples is somewhat low.

If viewed in association with other mid-Tertiary volcanics in the southwestern Basin and Range province, the Vulture ultrapotassic rhyolites are unique due to their exceptionally high potassium and silica contents. This is, to our knowledge, the first reported occurrence of ultrapotassic alkali rhyolite in the basin-range of Arizona, although ultrapotassic trachytes have been reported from the Picacho Peak area, about 200 km southeast of the Vulture Mountains (Shafiqullah and others, 1976). The two ultrapotassic suites are similar in gross lithology and MgO, CaO, and Na_2O distribution patterns; however, the Picacho trachytes are lower in SiO_2, higher in K_2O, and higher in total iron than the Vulture rhyolites (Fig. 6).

The more basic flow rocks from the Vulture Mountains have compositions compatible with alkali basaltic andesites. As seen from Figures 5 and 6, these andesites are common to the mid-Tertiary volcanic episode of the Southwest.

In marked contrast to the sequence of rocks described above is the blocky basalt of Black Mountain (Sample 72-43) and Twin Peaks. Chemically this flow sequence is distinguished by relatively low alkali content (Na > K) and high CaO and MgO. Potash is especially low ($\sim$1%).

Table 2. Analyses and Barth-Niggli cation normative minerals of Vulture Mountains volcanic rock suite

	UAKA 75-54	UAKA 71-35	VP 3	VP 7	VP 5	VP 9	V1 17	UAKA 76-16	UAKA 75-53	V1 15
SiO_2	69.3	75.3	74.0	75.5	76.9	74.8	77.5	70.2	79.5	76.8
TiO_2	0.50	0.54	0.17	0.14	0.14	0.17	0.12	1.61	0.57	0.17
Al_2O_3	12.80	10.73	12.10	11.70	10.80	11.06	11.70	12.27	9.10	11.20
Fe_2O_3	1.54	0.92	0.71	0.48	0.48	0.71	0.10	1.57	0.93	0.79
FeO	0.93	0.56	0.53	0.34	0.34	0.51	0.35	0.90	0.68	0.55
MnO	0.63	0.48	0.05	0.02	0.02	0.10	0.01	0.83	0.48	0.07
MgO	0.55	0.26	0.36	0.12	0.12	0.12	0.33	0.12	0.32	0.12
CaO	0.18	0.15	0.14	0.20	0.70	3.43	0.67	0.17	0.07	0.53
Na_2O	0.28	0.27	0.36	0.47	0.47	0.46	0.47	0.99	0.65	0.86
K_2O	11.70	9.75	8.40	8.70	8.30	8.12	7.70	10.34	6.75	8.20
K_2O/Na_2O	41.8	36.1	23.3	20.7	17.7	17.7	16.4	10.5	10.5	9.5
S.I.	3.52	2.15	3.46	0.80	1.23	1.17	3.68	0.79	3.29	1.13
D.I.	93.68	95.83	94.47	96.50	95.63	88.81	93.41	93.53	95.78	95.73
Quartz	20.91	34.70	38.26	38.29	39.71	34.77	41.64	23.98	47.74	37.48
Orthoclase	71.98	60.14	52.77	54.24	51.49	49.76	47.37	64.00	41.94	50.25
Albite	0.79	0.99	3.44	3.98	4.43	4.28	4.39	5.55	6.10	8.01
Anorthite			0.74	1.05	3.00	4.28	3.46		0.36	2.58
Corundum			2.51	1.42			1.57		0.70	
Acmite	3.01	1.41						1.48		
Femic Minerals	5.23	3.10	2.28	1.03	1.37	6.91	1.57	3.74	3.17	1.69

Rubidium–Strontium Data

Rb-Sr analytical data on Vulture Mountain samples are presented in Table 3. The ultrapotassic rhyolites have low Sr and high Rb contents; K-Rb ratios of the two samples are 200 and 236, respectively. The 16.8-m.y.-old trachyandesite and 13.5-m.y.-old basalt contain high Sr and low Rb, Rb-Sr ratios smaller than 0.04, and K-Rb ratios greater than 1400. Thus, rubidium is preferentially enriched in the ultrapotassic rhyolites. Although both Ca and Sr are low in the ultrapotassic rhyolites, the Ca-Sr ratio is lower than in the trachyandesites, implying relative enrichment of Sr in the potassium-rich rocks.

The initial ^{87}Sr-^{86}Sr ratios of the pre-15-m.y.-old silicic and intermediate volcanic rocks range between 0.7071 and 0.7089, with a mean of 0.7081. These ratios are somewhat higher than the initial ratio of 0.7069 for the Laramide Wickenburg granodiorite but similar to that of the mid-Tertiary volcanics (0.7085 ± 0.006) in the 10,000-km^2 region surrounding Tucson (Damon and Shafiqullah, 1976; Shafiqullah and others, 1978).

The 13.5-m.y.-old Black Mountain basalt has an initial ^{87}Sr-^{86}Sr ratio of 0.7054, which is above the average of 0.7038 for Arizona basin-range basalts of similar age (Shafiqullah and others, 1978). This ratio is appreciably lower than the average value for the underlying siliceous volcanic sequence. The relatively high strontium, low Rb-Sr ratio, and initial ^{87}Sr-^{86}Sr ratio of the Black Mountain basalt are in line with similar data for other late Cenozoic alkali basalts in the southern Great Basin (Carmichael and others, 1974; Leeman, 1974; Scott and others, 1971).

Table 2. *Continued*

	UAKA 72-13	VP 1	VP 0	VP 1 12	UAKA 72-44	VP 1 14	UAKA 72-60	UAKA 72-43
SiO_2	73.6	76.1	74.3	72.0	72.4	57.5	59.8	53.6
TiO_2	0.37	0.19	0.15	0.19	0.68	1.20	0.80	1.35
Al_2O_3	12.43	11.20	12.10	12.70	13.60	15.30	14.30	14.20
Fe_2O_3	0.86	0.80	1.09	0.53	1.32	2.84	2.38	3.36
FeO	0.52	0.54	0.76	0.42	1.00	3.12	3.21	5.31
Mno	0.60	0.11	0.10	0.08	0.50	0.09	0.10	0.12
MgO	0.08	0.33	0.06	0.23	0.65	3.00	4.54	7.58
CaO	0.12	0.70	0.90	1.00	1.19	6.30	6.40	7.61
Na_2O	1.85	2.40	2.70	3.50	4.18	4.00	2.92	3.17
K_2O	8.91	7.10	6.80	4.90	4.60	3.50	1.84	1.02
K_2O/Na_2O	4.8	3.0	2.5	1.4	1.1	0.9	0.6	0.3
S.I.	0.61	2.93	0.52	2.38	5.31	18.13	30.29	36.87
D.I.	96.49	94.64	95.73	93.39	90.14	64.07	55.55	40.76
Quartz	26.87	32.08	29.61	29.71	25.11	5.69	17.28	5.78
Orthoclase	53.98	42.92	41.24	30.53	27.31	21.33	11.22	6.11
Albite	15.63	19.64	24.89	33.15	37.72	37.05	27.05	28.87
Anorthite			0.84	4.72	4.79	13.89	21.14	21.82
Corundum								
Acmite	1.28	0.36						
Ferric Minerals	2.55	3.48	3.43	1.89	5.07	22.04	23.31	37.42

1. H_2O, P_2O_5 and CO_2 were not determined for all samples, and are not reported for any.

Table 3. Rb-Sr analytical data on samples from the Vulture Mountains

UAKA Sample No.		K-Ar age	% K	Rb ppm	Sr ppm	$(^{87}Sr/^{86}Sr)_m$	$(^{87}Sr/^{86}Sr)_i$	K/Rb	Rb/Sr
71-34	Granodiorite	68.4		98.0 95.3	805.0 799.0	0.7073(1) 0.7072(2)	0.7069		0.121
72-60	Trachyandesite	16.8	3.15	19.6	1585.1	0.7071(2)	0.7071	1609	0.012
72-13	Ultrapotassic rhyolite	16.3	7.55	320.2	47.3	0.7130(2)	0.7083	236	6.770
71-35	Ultrapotassic rhyolite	16.2	8.30	421.0 406.0	72.5 69.8	0.7124(1) 0.7123(2)	0.7089	200	5.807
72-43	Olivine basalt	13.5	0.86	18.4 16.1	472.0 479.1	0.7055(1) 0.7054(2)	0.7054	1539	0.036

(1) Dr. Paul D. Pushkar, analyst

(2) Dr. Donald E. Livingston, analyst

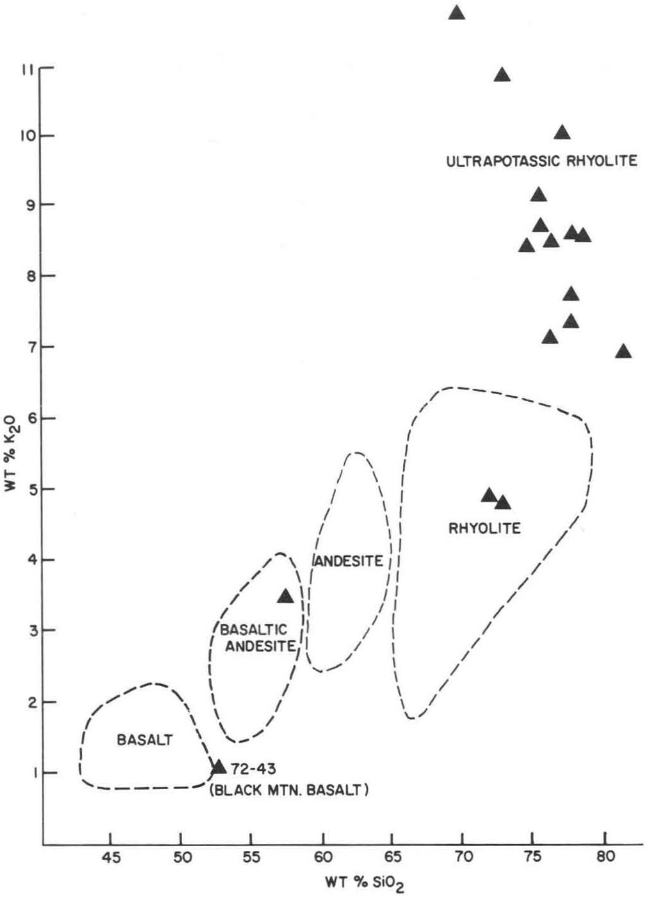


Fig. 5. Plot of K_2O versus SiO_2 for Vulture Mountains volcanic rocks. Areas covered by dashed lines represent compositional fields delineated by Damon for compiled populations of volcanic rocks from southern Arizona.

Petrogenesis

A definitive model for the genesis of the ultrapotassic rhyolites cannot be drawn from the available data. Major, minor, and trace element and isotopic studies on ultrapotassic rocks of Arizona are continuing.

One aspect warranting additional investigation is the possible influence of widespread deuteric potash metasomatism in these volcanics. These effects are often extremely subtle in such fine-grained siliceous rocks (even in thin section), but in some areas secondary alteration has greatly increased potassium at the expense of original plagioclase (Chapin and others, 1978). Analysis of unhydrated volcanic glasses would aid in evaluating this potential problem. In any case, the hypothesized potassium metasomatism must have affected some flows and not others, because not all flows in any one area are ultrapotassic (This study; Shafiqullah and others, 1976).

The solidification index, the ratio of residual melt to crystals in a differentiating magma (Kuno, 1954), for Vulture rocks is relatively low (Table 2). These low index values and high K_2O-Na_2O ratios suggest that the ultrapotassic alkali rhyolites are the residuum of a more basic magma. Compositionally, this residuum resembles orthoclase pegmatite, and it might have crystallized as such if allowed to cool slowly at depth with high water pressure.

The initial ^{87}Sr-^{86}Sr ratios rule out derivation of the Vulture rocks by partial or complete melting of Precambrian basement, which would yield ratios greater than 0.71. Likewise, the magmas are not strictly isotopically linked to mantle material, which would yield much lower ratios. A working hypothesis requiring further testing is that the siliceous, potassic, Vulture Mountains assemblage represents a late melt of the residuum of protracted fractional crystallization of a more basic magma (trachyandesite?) during mid-Tertiary time. Physical separation of the residuum from early crystallized, more mafic constituents is required. The consistency of regional 0.708 $^{87}Sr/^{86}Sr$ values for mid-Ter-

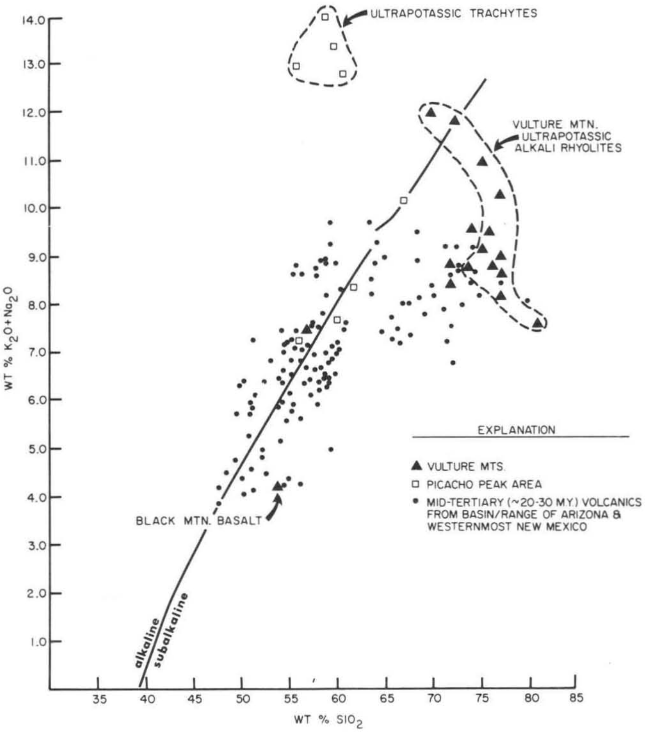


Fig. 6. Plot of alkalis versus SiO_2 for Vulture Mountains volcanic rocks and other mid-Tertiary volcanics from the basin-range of Arizona and westernmost New Mexico. Regional data compiled by Rehrig. Data for Picacho Peak samples from Shafiqullah and others (1976). Alkaline-subalkaline boundary is from Irving and Baragar (1971).

tiary volcanics, which incorporate the Vulture Mountains values, suggests that the fundamental source for the volcanism is a remarkably uniform material probably from the lower crust. The ascent and differentiation of such primary melts apparently did not allow for variable processes of upper crustal contamination. The significantly more primitive Black Mountain basalt is believed to be derived from subcrustal sources.

Tectonic Considerations

Certain geologic features in the Vulture Mountains are exemplary of important tectonic relationships in the southwestern United States. These features are: (1) northeast structural control of Laramide plutonism, (2) north-northwest control of mid-Tertiary plutonism, (3) listric normal faulting associated with mid-Tertiary silicic and potassium-rich volcanic rocks, and (4) the fundamental change in tectonic style and volcanic petrology that took place between about 16 and 14 m.y. B.P.

The northeast trends of Laramide plutonic features in the Wickenburg region are a further example of a widespread tendency for the 50-75-m.y.-old stocks, dikes, veins, and fractures to have northeast to east strike trends. This systematic pattern has been documented by numerous workers in Arizona geology (e.g., Schmidt, 1971; Balla, 1972) and has been summarized on a regional scale by Rehrig and Heidrick (1972, 1976).

Similarly, north-northwest dike trends in the Vultures exemplify a regional phenomenon (Rehrig and Heidrick, 1976), where mid-Tertiary elongate stocks, dikes, and veins trend north to northwest, orthogonal to Laramide trends. At first glance, north-northwest-oriented mid-Tertiary intrusion might appear tectonically related to basin-range, high-angle faulting. However, as discussed further in this section, there is a much closer genetic relationship (in terms of direction and age) between this north-northwest-directed intrusion and low-angle listric faulting. Both these events *preceded* the high-angle normal faulting which helped sculpture the present physiography of the Basin and Range province.

Rotational fault displacements on downward-flattening shear planes (listric faults) are widely characteristic of the Basin and Range province. Only recently is the importance of this phenomenon becoming recognized (Stewart, 1978). This unusual style of extensional faulting has been described at many localities by numerous geologists (Longwell, 1945; Anderson, 1971; Proffett, 1977; Armstrong, 1972; Ashley, 1974; Stewart, 1971; Wright, 1976).

As previously mentioned, the Vulture Mountains occupy part of a broad belt of listric-faulted Tertiary volcanic rocks (Fig. 7). To the northwest, examples of intense rotational faulting are found scattered through the Harcuvar, Buckskin, and Rawhide ranges (Rehrig and Reynolds, n.d.) and onward into the Whipple Mountains of California (Davis and others, n.d.). Anderson (1971) described a northerly trending belt of steeply tilted to overturned Tertiary volcanics rotated on a myriad of shingled listric normal faults northward from the Whipple Mountains along the east flank of the El Dorado Mountains (Nevada) and in adjacent terrane in Arizona (Black Mountains). These strata generally dip westward and indicate surficial lateral transport to the east. Southeast of the Vulture Mountains, rotational faulting has severely affected mid-Tertiary volcanic and clastic rocks in the Tempe Buttes area and at Picacho Peak.

The transition that occurred 16 to 14 m.y. B.P. from silicic tilted volcanics to relatively flat-lying basalts in the Vulture Mountains also has regional correlations (Damon, Shafiqullah, and Lynch, 1973; Shafiqullah and others, 1978; Shafiqullah and others, this volume). Apparently, this tectonic boundary varies in age from place to place (i.e., ∿18 to 10 m.y. B.P.), but the general interval from about 16 to 14 m.y. B.P. is most common.

One correlative example of the tectonic boundary is found along the Colorado River between Davis Dam and Lake Mead. In this region, volcanic geochronology has been particularly well established (Anderson and others, 1972). Highly tilted rocks include the early part of the Mount Davis volcanics (Bridge Spring tuff, Patsy Mine volcanics) of intermediate to acidic compositions. These mid-Tertiary formations are pre-15 m.y. Younger volcanic rocks are flat lying and consist of uppermost Mt. Davis andesitic basalts (∿15 to 12 m.y. B.P.) and the thick fanglomerate-basalt sequence of the Muddy Creek Formation (∿11 to 4 m.y. B.P.). The structural-petrologic boundary here falls at about 14 to 13 m.y. B.P., correlative with its timing in the Vulture Mountains.

In a reappraisal of time of basin-range extension and change from calc-alkalic to basaltic magmatism, McKee (1974) suggested that the petrologic switch occurred between 17 and 15 m.y. B.P. throughout a large portion of the Great Basin. The inception of basaltic extrusion was accompanied by a great increase in continental sedimentation, suggesting a dramatic transition to dominantly vertical tectonics. We see exactly these characteristics in and around the Vulture Mountains.

Having established the above setting for the Vulture Mountains, a tectonic synthesis for the Vulture range is now possible. Laramide deformation was superimposed on a metamorphosed, intruded, and structurally complex terrane of probably Precambrian derivation. Laramide tectonic stress is deciphered from an analysis of structural patterns of or in crystalline rocks. The highly dominant northeast-east-northeast direction of tensional or extensional dikes, elongate batholiths, and veins indicates that Laramide compression was horizontally directed in the northeast-east-northeast direction. Because the northeast tensional pattern persists regionally (see Rehrig and Heidrick, 1976), it is believed that Laramide compression resulted from interplate tectonics, likely the rapid northeast-southwest-directed convergence between the North American and Farallon plates from 80 to 40 m.y. B.P. (Coney, 1976, 1977). In the Wickenburg area, this northeast—east-northeast-directed compession "opened" extensional zones into which were emplaced the Laramide magmatic and hydrothermal products now manifest as the Wickenburg batholith and consanguinous dikes and veins.

Some 40 m.y. later the direction of regional crustal extension rotated 90 degrees, resulting in 18- to 16-m.y.-old dikes oriented north-northwest (east-northeast—west-southwest crustal expansion). Dike intrusion acccompanied and shortly followed a period of even greater extension toward the west-southwest by means of repetitive listric normal faulting in 26- to ∿16-m.y.-old silicic volcanics.

Although the extensional phenomenon of listric normal faulting has been frequently described over increasingly widespread areas of the Basin and Range province, its origin is poorly understood. As concluded by Anderson (1972), zones in which this structural style is accentuated represent belts of shallow, low-angle detachment where near-surface rocks are highly distended laterally like a deck of cards. Anderson and Longwell (1945) suggested that such thin-skinned deformation develops marginal to rising, spreading domes such as might result from upwelling plutonic masses. Wright (1978) suggested a relationship of rotational faulting with severe extension at deeper crustal levels accompanied by emplacement of plutons. Proffett (1977) explained listric faulting as a response to subjacent convective, laminar flow in the mantle. This faulting would in his opinion involve the entire crust.

A fascinating new aspect of the listric fault puzzle has come from recent studies of metamorphic core complexes in western Arizona and southeastern California. Although details remain outside the scope of this paper, severely tilted volcanic and clastic assemblages similar in age to the Vulture Mountains rocks are found in extraordinary detachment upon gently arched mylonitic rocks in these complexes (Davis and others, n.d.; Rehrig and Reynolds, n.d.). Structural and geochronological studies (Reynolds and Rehrig, 1978; G. H. Davis, n.d.) suggest that the mylonites were formed by extreme flattening and extension of the rock mass in a northeast-southwest direction during Tertiary time. The age of detachment and rotation of the volcanic cover (also northeast-southwest directed) postdates the underlying cataclasis and correlates temporally with tilting in the Vulture Mountains (i.e., ∿18-16 m.y. B.P.).

There thus seems to be an inescapable genetic link between the pervasive northeast-southwest extension of the rock mass in parts of the Arizona crust and superimposed listric faulting. In the metamorphic core complexes where listric rotation seems greatest, the rigid fault blocks have extended on curviplanar faults that appear to merge into a single flat detachment surface above the zone of lineated mylonite. The mylonites exhibit extension (parallel to that in the faulted blocks above) by means of pervasive intergranular strain. In this sense the detached listric fault blocks appear to have extended "piggy-back" style upon the underlying ductilely extended layer. Such would be the case for the Harcuvar metamorphic core complex immediately northwest of the Vulture and Big Horn Mountains, as shown by Figures 7 and 8.

The Vulture Mountains occur on the northeast side of a broad antiformal feature whose northwest-trending axis runs through the adjacent Big Horn Mountains (Rehrig and Heidrick, 1976). Mid-Tertiary volcanic rocks in ranges northeast of the Big Horn Mountains are tilted to the northeast, while similar volcanics to the southwest have been rotated toward the southwest (Fig. 7). Some explanation for the origin of this pseudo-arch should have important relevance to the origin of listric normal faulting in the Vulture Mountains.

Unusual aspects of this archlike feature are its breadth (∿100 miles) and apparent lack of structural relief. For example, the unconformity between Tertiary volcanic rocks and pre-Tertiary basement is found at similar elevations across the entire structure. This characteristic would make it highly unlikely that the antiformal feature formed in response to arching or uplift. A more plausible working hypothesis may be a variation of that postulated for crustal spreading in the metamorphic core complexes. This model involves bilateral extension beneath the surficial rigid plate of Tertiary volcanics, as shown in Figure 8. This spreading or extension would not be as

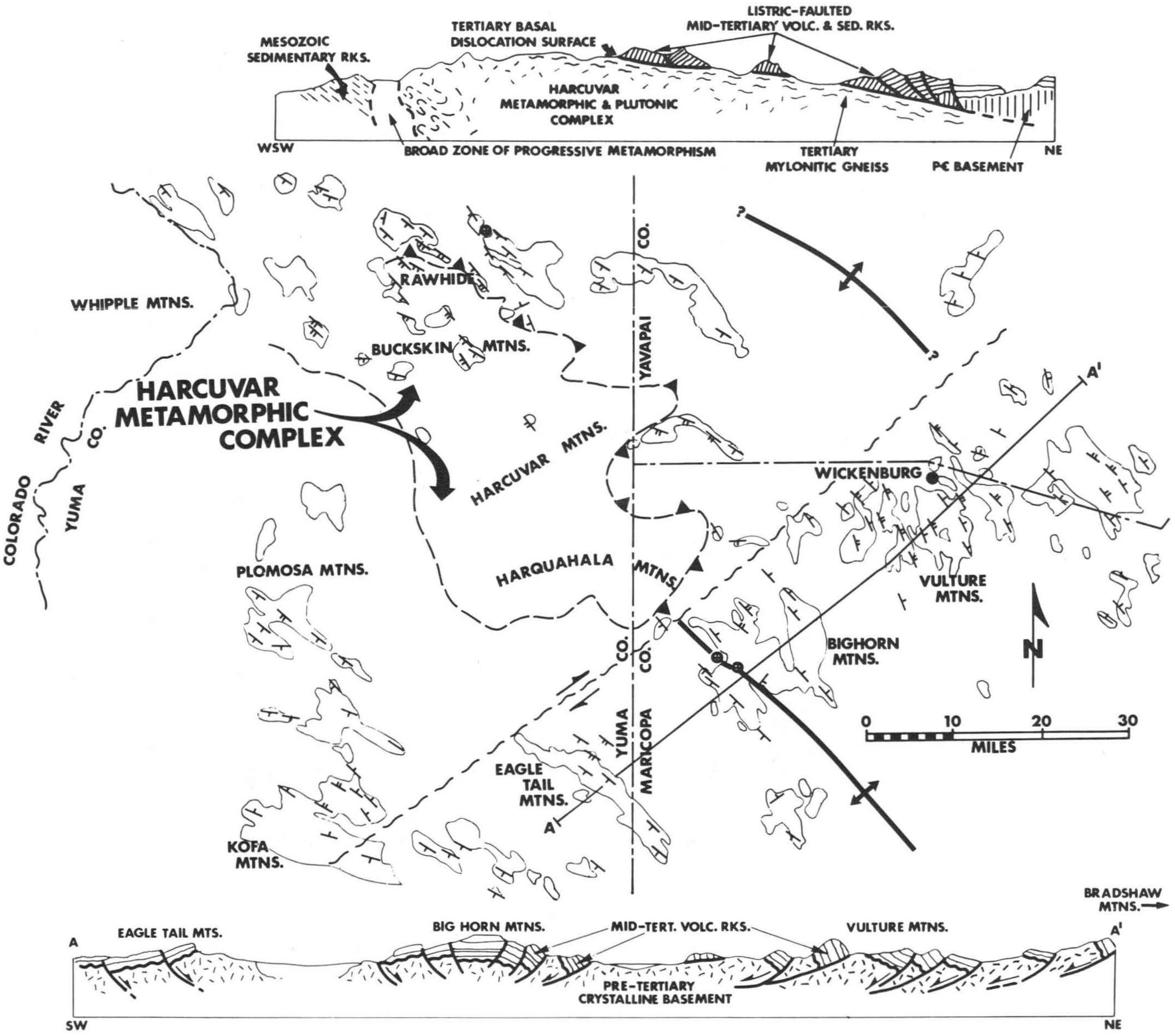


Fig. 7. Regional tectonic setting of the Vulture Mountains. Map shows outcropping areas of Oligocene-Miocene volcanic rocks (outlined areas) and their tilted attitudes. Double-bar dip symbols indicate dips > 45°. Sources for structural data include: Arizona county geologic maps; unpublished tectonic map (Cooley and others, n.d.); Rehrig and Heidrick (1976, p. 218); and first author's more recent field observations. Information (map and section) on Harcuvar metamorphic complex is from Rehrig and Reynolds (n.d.). Barbs along eastern front of Harcuvar complex indicate general trace of northeast-dipping, Tertiary dislocation surface. Heavy-lined, anticlinal symbols indicate axial position of regional antiform (i.e., Big Horn–Vulture antiform) of Tertiary tilting. Wavy-lined, northeast-trending lineament may displace antiformal axis as shown (Stewart, n.d.). This transform(?) boundary possibly allowed differential northeast crustal expansion between the highly extended Harcuvar metamorphic complex (upper cross section) and the Big Horn–Vulture antiform (lower section).

Cross sections are highly schematic and not to scale. The Harcuvar section represents an idealized composite impression from the Granite Wash Mountains on the west through the Harcuvar Mountains.

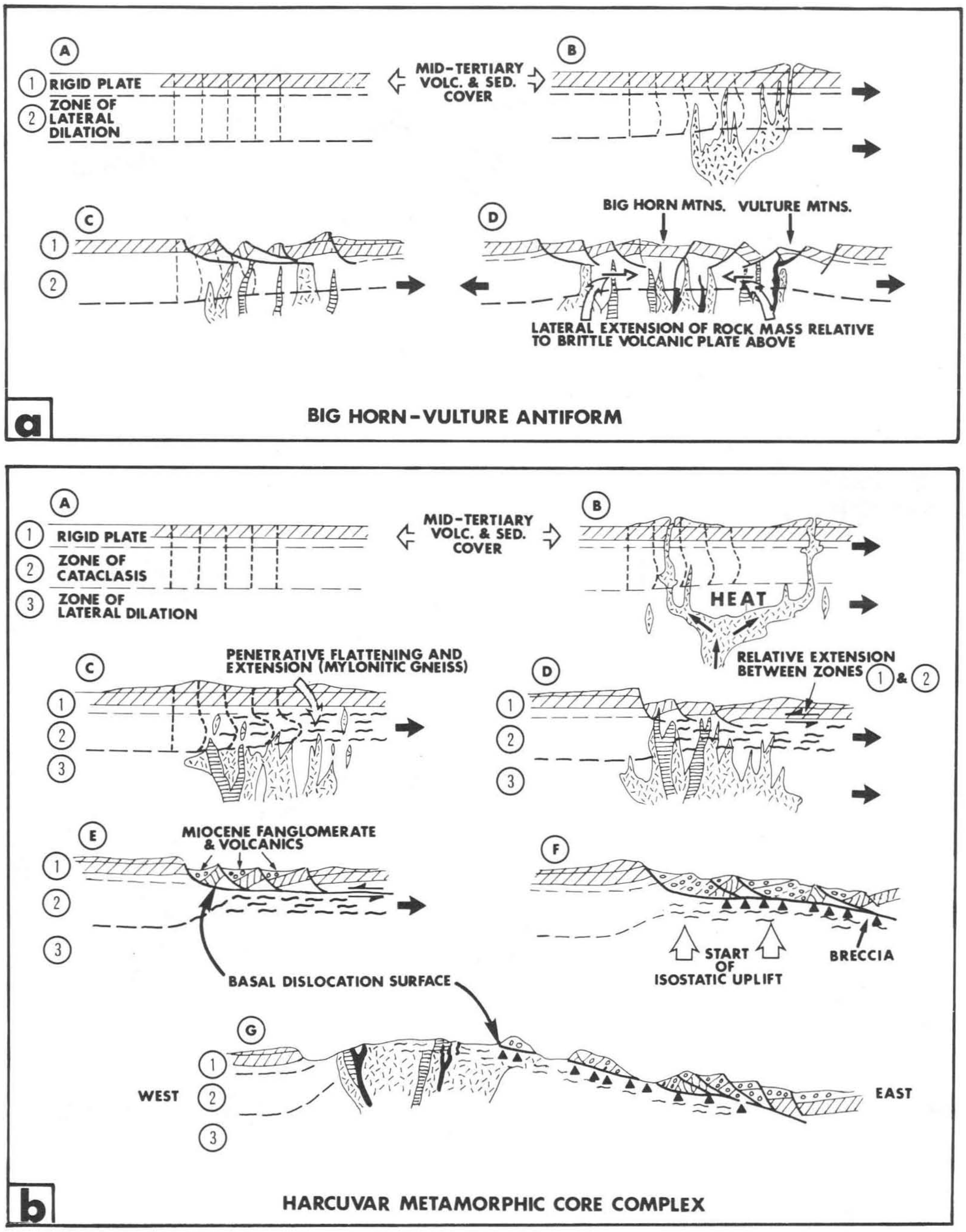


Fig. 8. Working hypothesis for development of listric faulting in the Big Horn-Vulture antiform (a) and Harcuvar metamorphic core complex (b). Large black arrows represent lateral extensional stress toward the northeast or southwest. Vertical dashed lines through plates 1 and 2 show extensional strain.

(a) Active lateral crustal extension combined with north-northwest-northwest-trending, mid-Tertiary dike swarms (B) allow zone 2 to expand past zone 1. This differential extensional strain is taken up by listric normal faults inclined in direction of greatest expansion below (C). Section (D) shows symmetrical bilateral development of stages (A) through (C) forming regional antiform.

(b) More intense intrusive activity (dikes, stocks, sills) and heat generation in active tensional stress field forms flattened and northeast-extended, mylonitic fabrics in subvolcanic, crystalline rocks (C). Continued stretching and dilation in zones 2 and 3 result in listric faulting and differential shear (dislocation surface) between ductile plate 2 and rigid plate 1 (D) (E). Severe thinning in plate 2 and tectonic removal of plate 1 initiate isostatic uplift (F) and lead to present configuration of metamorphic core complex (G). Figure 8b is based on text and figure 8 of Rehrig and Reynolds (n.d.).

intense as that in the Harcuvar core complex, thus explaining the lack of cataclastic textures in crystalline rocks beneath the tilted Vulture Mountain fault blocks. Crustal spreading beneath the Big Horn–Vulture antiform may have been facilitated by a combination of lateral dilation and dike or pluton emplacement along north-northwest to northwest trends. Many such linear intrusive swarms cut pre-Tertiary crystalline rocks in the Vulture, White Tank, Eagle Tail, and Big Horn–Belmont Mountains areas.

This deformation, which persisted from approximately 20 to 15 m.y. B.P., was dominantly laterally rather than vertically directed. The disturbance was profound and closely associated with two important events: (1) maximum extension in the Basin and Range province and (2) a major mid-Tertiary pulse of magmatic activity (Damon and others, 1973; Damon and Mauger, 1966).

As shown on Figure 6, the late Oligocene to Miocene magmatic pulse in the Southwest is generally calc-alkalic but with commonly occurring suites of unusually high potassium and silica. The Vulture Mountains rhyolites, for example, are ultrapotassic with peralkaline affinities. The tectonic significance of such potassium-rich rocks is perplexing. As reviewed by Shafiqullah and others (1976), these rocks have been linked to large-scale rifting tectonics in Africa and Europe. Certainly the similarities between tensional rifting in the African sense and east-northeast crustal extension in the southwestern United States is obvious. Major differences, however, are seen in the importance of listric faulting and horizontally directed translations in the North American examples. Furthermore, the 0.708 ^{87}Sr-^{86}Sr ratios of the Vulture Mountains rocks suggest that rift faults did not tap mantle-derived material directly. Such ratios are indistinguishable from those of Laramide magmatic rocks, which are considered by many to be subduction related.

Coney and Reynolds (1977) presented evidence for a progressively steepening subduction zone under Arizona during mid-Tertiary time. Keith (1978), using independent evidence, confirmed their conclusions and utilized the deeper level of subduction-generated magmatism to explain potassium enrichment in the approximately 24- to 15-m.y.-old volcanic rocks of the Southwest. However, his hypothesis does not account for the high initial ^{87}Sr-^{86}Sr ratios.

At first glance profound and extensive east-northeast- to northeast-directed crustal extension may seem inexplicable in a subduction regimen also directed northeasterly. However, as discussed by Coney and Reynolds, the steepening of the subducting plate was primarily the result of a dramatic decrease in convergence rates of the Farallon and North American plates. Another major result of such slowed convergence would have been severely reduced compressional effects transmitted to the continental plate. Furthermore, Karig (1970, 1971) has demonstrated that tensional tectonics are possible in back-arc areas even during subduction, the postulated active agent for extension being mantle diapirism. Back-arc spreading has been applied to the Basin and Range province by numerous authors as summarized by Stewart (1978, p. 24).

It is thus difficult to assign a specific origin to the Vulture Mountains potassium-rich volcanics. They originated in an environment perhaps characterized by both subduction and rifting. The consistency of $\sim$0.708 strontium isotope ratios for these mid-Tertiary rocks is not typical of either upper crustal- or mantle-derived magmas but does suggest derivation from a uniform lower crustal level. The bimodal tendency of Vulture rocks (i.e., ultrapotassic rhyolites and basaltic andesites) further implies that originally calc-alkalic magmas became highly differentiated near the surface with the silica- and potassium-enriched residues becoming separated in some manner from the more mafic portions.

By approximately 14 m.y. B.P., the shift to basaltic magmatism had occurred both in the Vulture Mountains and regionally. Strontium isotope ratios ($\sim$0.705+) of these basic rocks are significantly lower than those of older siliceous volcanics. This petrologic change also had its tectonic counterpart. Basin-range extension was reduced by means of a shift from low-angle to high-angle normal faulting. The tectonics thus became predominantly vertically directed. Ramifications of this petrologic-tectonic change are that the crust had cooled and become more brittle and that relatively uncontaminated subcrustal melts were tapped by deeper penetrating, high-angle structures.

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