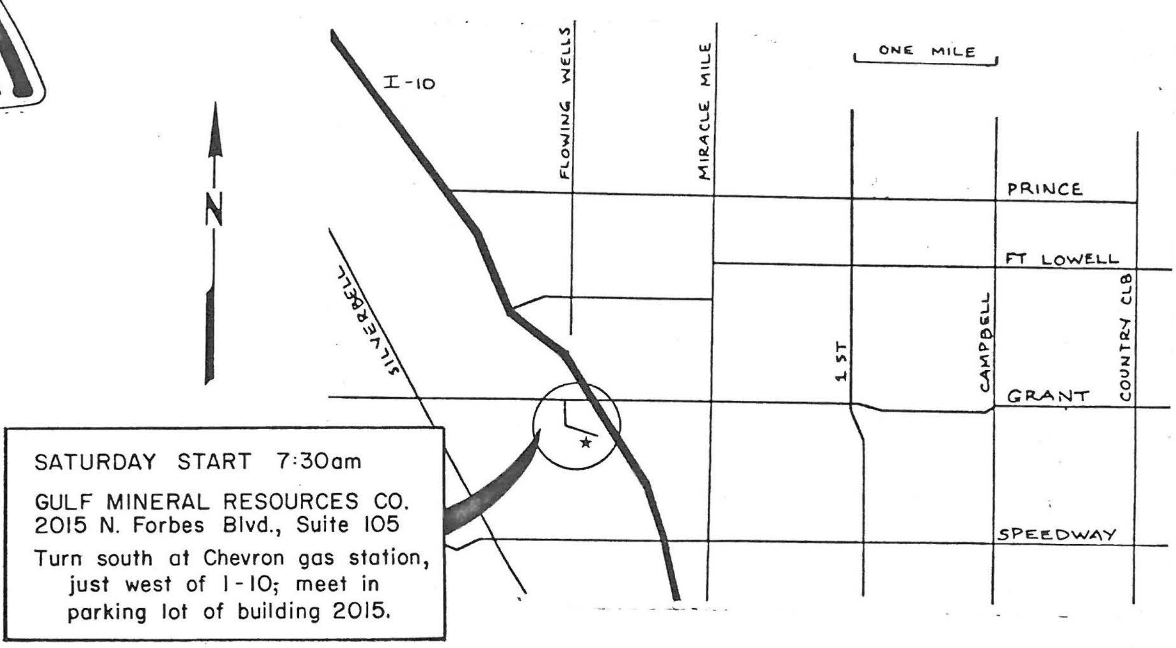
ARIZONA GEOLOGICAL SOCIETY
1980 Fall Field Trip

LOW-ANGLE TECTONIC PHENOMENA
BETWEEN TUCSON AND SALOME, ARIZONA

LEADERS: S. Keith, S. Reynolds,
W. Rehrig, and S. Richard

COORDINATOR: Tom L. Heidrick

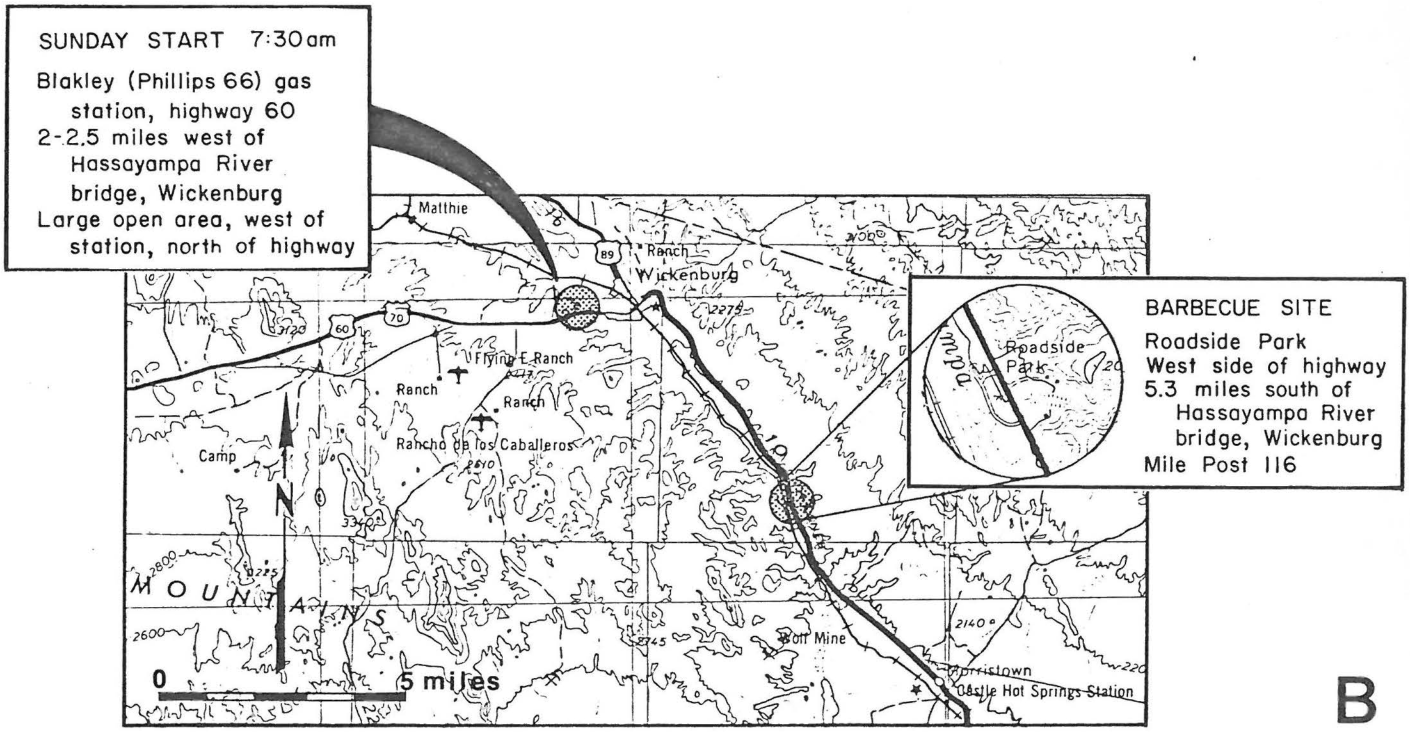


SATURDAY START 7:30am

GULF MINERAL RESOURCES CO.
2015 N. Forbes Blvd., Suite 105

Turn south at Chevron gas station, just west of I-10; meet in parking lot of building 2015.

A



SUNDAY START 7:30am

Blakley (Phillips 66) gas station, highway 60
2-2.5 miles west of Hassayampa River bridge, Wickenburg
Large open area, west of station, north of highway

BARBECUE SITE

Roadside Park
West side of highway
5.3 miles south of Hassayampa River bridge, Wickenburg
Mile Post 116

B

Location maps showing the starting points for the 1980 Fall AGS field trip: A, Saturday morning, Tucson, Arizona; and B, Sunday morning, Wickenburg, Arizona. The insert on B shows the campground reserved for the Saturday evening outdoor steak fry and beer bust.

PICACHO STOP

by

Stanley B. Keith

Introduction

Picacho Pass is a familiar landmark in Arizona's cultural history as well as its geologic history. Near here Arizona's only Civil War Battle was fought in 1862. According to Barnes (1960), the following events took place:

> On April 15, 1862, sixteen Confederate cavalrymen of Capt. Sherod Hunter's command were with Lt. Jack Swilling when they were overtaken by Lt. James Barrett and a dozen soldiers. During the skirmish Barrett was killed, as were Pvt. George Johnson and Pvt. William S. Leonard of the Union forces. Two Confederates, whose names are not known, were killed and two others taken prisoner. (Not all accounts agree concerning the Confederates.)

In recent years major new insights into the geology of the Picacho Mountains have been obtained by a number of workers. On the Arizona State Geologic map (Wilson and others, 1969), the Picacho Mountains (in view to your north) are shown as Precambrian gneisses, whereas Pichacho Peak, the prominent Peak to the south of Interstate 10, is depicted as a Cretaceous-Tertiary intrusion. In recent years work by numerous workers has vastly changed that interpretation. Undoubtedly that interpretation will continue to evolve significantly.

Geology

The present geologic interpretation as we can piece it together, is as follows. The northern Picacho Mountains (north of I-10) is divisible into two major terranes. These terranes are separated by a major WNW-striking fault. The terrane north of this fault (not in view) consists mostly of a schist that strongly resembles Pinal Schist. The schist is intruded to the east by a porphyritic granite that strongly resembles Oracle Granite (Yeend, 1976; Banks; 1980). A more gneissic rock locally occurs between the gneiss and the schist. The above assemblage is cut by a series of WNW-trending shear zones that locally contain dikes of probable Precambrian-aged diabase that are lithologically similar to the classic younger 1200-1100 m.y. diabase in the Sierra Ancha Mountains thirty-five miles north of Globe, Arizona. The extreme north end of this terrane contains a diorite to granodiorite pluton of early Tertiary age that intrudes the above rocks (Johnson, Masters thesis, in preparation). All of the above rocks are intruded by an impressive NW-striking swarm (especially in western exposures) of intermediate to silicic dikes. The probable age of this dike swarm is middle Tertiary. Copper mineralization at the North Star Mine may be related to this intrusive event.

South of the WNW-striking fault a much different terrain is present. Several low north-trending and northwest-trending, rounded, low ridges (not viewable from this stop) occur immediately south of the fault. This area of subdued relief is underlain by a granodiorite pluton of middle Tertiary age referred to as the North Star stock. Biotite from the North Star pluton has yielded a K-Ar age of 24.35 ± 0.73 m.y. (Shafiquallah and others, 1978). The North Star intrusion is cut by numerous northwest to west-northwest trending dikes of intermediate composition. These dikes exibit differnt lighologies than those that intrude the northern terrane.

About three miles south of the WNW-trending faults the low-relief topography gives way to a dramatically rugged, high relief topography that comprises the main topographic mass of the Picacho Mountains. This is the topography that dominates our view to the north. The high point in this topography is Newman Peak at the 1:00 position (use I-10 NW-bound as the 12:00 reference position). The majority of this high relief terrane is underlain by a foliated mylonitic, muscovite granite pluton. The mylonitic muscovite granite pluton is intruded by the generally non-foliated, mid-Tertiary Lone Star pluton near the topographic break mentioned above. The light colored cliffy outcrops and rubble that occupy the exposures to our north are of the muscovite granite. Biotite-rich phases (presumably of the muscovite pluton) are locally observed (for example, the outcrops under the low ledges at 1:30). Their relationship to the main phase must still be rigorously determined and awaits someone's mapping. Muscovite extracted from this pluton has yielded a late Oligocene cooling age (Gary Johnson, Master thesis in preparation). This age is similar to numerous late Oligocene ages reported on the Wilderness Granite in the Santa Catalina Mountains (see Keith et al., 1980, for a review of these apparent ages). The muscovite granite of the Pichacho Mountains is presumably a member of Late Cretaceous to Eocene peraluminous granitoid suite that has now been recognized as a major new magma type throughout southern Arizona (Keith and Reynolds, in press).

Another mylonitic lithology common in the southern part of the main Picacho Mountains (for example, the inselberg outliers at 3:00) is a porphyritic augen gneiss. This lithology was intruded by the muscovite granite. Yeend (1976) and Banks (1980) believe the protolith for the mylonitic porphyritic, augen gneiss is the Oracle Granite dated at about 1400 m.y. We see no reason to doubt this suposition. Nearly all of the mylonitic foliation is low-angle and is responsible for the layered aspect of the rocks. One hundred seventy-one lineations measured by George Davis, all fall in the NE-SW quadrant and average about N 50^{o} E.

Near Newman Peak these mylonitic gneisses are intruded by a non-mylonitic, north-trending dike that resembles the Tortolita quartz monzonite in the Tortolita Mountains to the southeast. A date on this dike could provide a minimum age for the mylonitic deformation.

The mylonitic granitoid rocks are overlain by a curious slope- and ledge-forming mylonitic schist that caps the high ridges of the Picacho Mountains (for example, Newman Peak and the table-like hill @ 1:30). At Newman Peak the schistose rock were abundantly intruded by pegmatites and aplites; some of these intrusion are folded. Exposures of the mylonitic schist in the hill at 1:30, and nearby hills, locally contain box-fold structures. Geometric data for 14 box-folds yield an ENE-WSW axis of shortening. These folds fold the older, above mentioned, lineation. Within the same zone reverse faults are locally numerous. Geometric data for 25 of these faults yield an average strike of N 37^{o} W at a dip of about 30^{o} SW. Hence, the faults show a marked preference for northeast transport or vergence. The axis of shortening for these faults is S 53^{o} W. These faults are late and cut the mylonitic schist. It is interesting that the axis of shortening for the reverse faults is parallel to lineation phenomena in the same rocks. The data seems to indicate that an event of NE-SW shortening occurred late in the history of, or post-dates the mylonite formation, if the muscovite granite in the Picacho Mountains correlates wih similar granitoids in the Tortolita and Santa Catalina Mountains, mylonitic deformation in the Picacho Mountains is syn- to post-middle Eocene and predates emplacement of the 24 m.y. North Star pluton.

Close inspection of the conical hill at 2:00 will reveal a small dark outcrop that caps the very top of the hill. This outcrop is a volcanic rock that closely resembles the ultrapotassic trachytes in the small outlier at 2:00 and the extensive exposures at Picacho Peak south of I-10. The volcanic rock on this hill rests tectonically on a highly fractured and somewhat chloritic, coarse-grained, biotite granite which in turn rests tectonically on mylonitic schist ledges at the mid-point on the hill. These ledges also contain folds (see previous discussion). The low-angle tectonic contact between the volcanics and the underlying crystalline rocks probably represent a low-angle normal fault or dislocation surface (in the sense of Rehrig and Reynolds, 1980) of mid-Miocene age. The age of the trachyte is about 22 m.y. (Shafiquallah and others, 1976). The exposure of this fault occurs only on the small hill at 2:00. However, the northeast-dipping volcanic section of Picacho Peak may rest as an allochthon on this low angle surface. If so, the trace of this fault would pass between the outlier of trachyte at 1:00 low and the crystalline mylonitc rocks underneath Newman Peak at 1:00 high. If the NE dip of the volcanic section is related to movement on this dislocation surface, then the volcanic section at Picacho Peak (which dominates our view from 8:00 to 11:00) was transported SW above this surface. As previously mentioned, Picacho Peak was formerly thought to represent a Tertiary intrusion. Work by Briscoe (1967) and Shafiqullah and others (1976) has shown that Picacho Peak predominantly consists of a 23-21 m.y. pile of northeast-dipping, high-K andesites and ultrapostassic trachytes. The volcanic section is intercalated with conglomeratic clastic rocks (the Wyomola conglomerate by Briscoe, 1967) in the lower part of the section. Base and precious metal mineralization is locally present in northwest-striking fractures that cut this early Miocene section.

FIELD GUIDE TO THE SOUTH MOUNTAINS, CENTRAL ARIZONA

by

Stephen J. Reynolds

GEOLOGICAL OVERVIEW

Introduction

The South Mountains are located immediately south of Phoenix in central Arizona. They are a northeast-trending range approximately 20 km long and 4 km wide with about 500 meters of topographic relief. The range is isolated from other bedrock exposures, being surrounded by a low-relief surface underlain by late Tertiary-Quarternary surficial deposits.

Although the South Mountains were briefly mentioned by several early geologists, they were first reconnaissance mapped by Wilson (in Wilson and others, 1957; Wilson, 1969). Avedisian (1966) studied petrology of selected rocks in the western half of the range. The first detailed map and discussion of the geology of the range was done by Reynolds and colleagues (Reynolds and others, 1978; Reynolds and Rehrig, 1980; Reynolds, in progress). They recognized that the South Mountains have many characteristics similar to metamorphic core complexes (see Reynolds and Rehrig, 1980). The following discussion of geology of the area is extracted from published and ongoing studies of Reynolds and others.

General Geology

Precambrian rocks exposed in the western half of the South Mountains consist of amphibolite-grade gneiss and schist with local intrusive masses. Almost the entire eastern half of the range is underlain by mid-Tertiary granodiorite which generally displays a weakly to strongly developed mylonitic foliation. In the center of the range a locally foliated mid-Tertiary granite intrudes between the Precambrian amphibolite gneiss and the granodiorite. Throughout most of the area, Precambrian rocks and the two mid-Tertiary plutons are intruded by numerous northwest-trending mid-Tertiary dikes which are, in many places, mylonitically foliated. In the northeastern portion of the mountains, the mylonitic granodiorite becomes progressively jointed, brecciated, chloritic, and hematitic up structural section until it is converted into chloritic breccia. In the southern foothills of the mountins, the chloritic breccia is overlain by a low-angle dislocation surface above which lie Precambrian metamorphic rocks similar to those exposed further to the west.

Structural Relationships

Most rocks in the range exhibit a gently dipping mylonitic foliation which contains a pervasive N60E-trending lineation. The foliation is defined by planar mineral aggregates and thin bands of intensely granulated and recyrstallized rock. Mylonitically foliated rocks contain joints, quartz-filled tension fractures, and "ductile normal faults" which mostly strike NNW, perpendicular to lineation. Inclusions in deformed plutonic rocks are elongated parallel to lineation and flattened perpendicular to foliation. Folds are rare in mylonitic plutonic rocks, but are more abundant in mylonitically deformed Precambrian amphibolite gneiss.

Gently dipping mylonitic foliation defines an asymmetrical northeast-trending, double-plunging arch or dome. The foliation generally dips less than 20° where it is contained within plutonic rocks, but is more steeply dipping where it affects Precambrian amphibolite gneiss. The simple pattern of the arch is interrupted on its northeast end where southwest-dipping foliation is present. This attitude of foliation is restricted to structurally high rocks which are chloritic, jointed, and brecciated.

Excellent exposures in the range display the three dimensional distribution of mylonitic fabric and variations in its intensity. Both the granite and granodiorite are undeformed in the core of the arch except for jointing and minor faulting. However, both plutons exhibit a gradual increase in intensity of mylonitic fabric toward the top and margins of the arch (up structural section). A similar distribution of mylonitic fabric is revealed where mylonitization affects Precambrian amphibolite gneiss. In the core of the range near the granite contact, the amphibolites possess a Precambrian foliation which is generally nonmylonitic, northeast-striking, and steeply dipping. The intensity of mylonitic deformation increases upward from the core to several 15 m-thick zones of northeast-lineated, mylonitic gneiss that cut equally thick zones of much less mylonitic amphibolite. Importantly, the mylonitic fabric also decreases in intensity upward from the main zones of mylonitic rock. At high structural levels in the western parts of the range, foliation in the amphibolite gneiss is again nonmylonitic, generally east- to northeast-striking, and steeply dipping.

NNW-striking dikes are likewise undeformed in the core of the arch. They are also generally undeformed where they intrude rocks with moderately well-developed mylonitic fabric. However, in structurally high parts of the range where adjacent rocks are intensely deformed, the dikes locally exhibit a gently inclined mylonitic foliation and ENE-trending lineation. Undeformed dikes are commonly near well-foliated dikes of similar lithology and strike.

Another important lithological and structural transition is exposed along the northeast end of the range where mylonitic granodiorite grades upward into chloritic breccia. Structurally lowest exposures of the granodiorite in this area are nonchloritic and well foliated. Up section, chlorite and anastomosing, curvi-planar joints are present in the granodiorite. The rocks are progressively more jointed and brecciated higher in the section where they ultimately grade into chloritic breccia. Remnants of mylonitic foliation in the granodiorite are preserved in the breccia. Relict mylonitic foliation in the breccia generally dips to the southwest, indicating that total disorientation and random rotation of the foliation did not occur, except locally. Joints, breccia zones, and normal faults (northeast side down) have variable northwest strikes. Slickensides in the breccia have scattered, but dominantly northeast trends. In the southern foothills of the range, the chloritic breccia is overlain by a dislocation surface which dips gently to the northeast. Upper plate rocks above the dislocation surface are Precambrian metamorphic rocks which locally have a mylonitic fabric.

Geological Evolution

Reynolds and Rehrig (1980) have discussed geological evolution of the South Mountains. Around 1.7 b.y. ago Precambrian sediments and volcanics were deposited and subsequently metamorphosed and deformed into a steep northeast-striking foliation. Granitic rocks in the westernmost parts of the range may be representatives of the 1.45 b. y. old suite of granites which are common in

Arizona. There are no Paleozoic or Mesozoic rocks in the range. Around 25 m.y. ago, the Precambrian rocks were successively intruded by the granodiorite and granite. At this time the plutons and the Precambrian metamorphics were subjected to deformation which formed a low-angle mylonitic foliation containing a northeast-trending lineation. NNW-striking dikes were intruded both during and after mylonitization. Strain indicators in the mylonitic rocks require that during mylonitization, the rocks were vertically flattened and extended parallel to the lineation. After mylonitization, the chloritic breccia was formed in the response to northeast movement of rocks above the dislocation surface. Normal, dip-slip movement is suggested by structures in the upper plate rocks and underlying chlorite breccia. Arching of the mylonitic foliation and chloritic breccia is probably one of the last events in the range. It was followed by the Basin and Range disturbance in which steep normal faults down-dropped the adjacent Phoenix basin around 14 to 8 m.y. ago. Since 8 m.y., the area has been tectonically quiet and geological developments have been dominated by erosion and deposition.

SOUTH MOUNTAIN ROAD LOG

EXIT 162 - Maricopa Road

Exit and turn west (left) on Maricopa Road which passes over the Interstate. Proceed west for 0.5 miles and park in wide areas on either north or south side of the road.

STOP 2

The main features of the geology of the South Mountains to the north can be seen from this vantage point. The range has a broad arch-like profile with a prominent notch or saddle near the center of the range. West of the central notch are Precambrian metamorphic and igneous rocks. The rocks exhibit two distinct foliations: a northeast-striking, steeply dipping Precambrian foliation and a younger (middle-Teriary) mylonitic foliation which dips moderately to the west.

The central notch is underlain by easily eroded, Oligocene granite. Along its western contact, the granite intrudes the Precambrian metamorphic rocks. Along its eastern contact, the granite grades into and locally intrudes an Oligocene granodiorite (25 m.y. old) which occupies most of the range east of the notch. The television and radio towers are built upon a subhorizontal tabular body of alaskite which overlies and intrudes the granodiorite. The pronounced gentle topographic profile of the eastern half of the range is controlled by a gently inclined mylonitic foliation in the granodiorite. The slope loses its planar profile where the granodiorite has been brecciated in the northeastern end of the range. The topography of the range is controlled by an east-northeast-trending arch in the mylonitic foliation of all rock units.

The geology of the main range extends into the southern foothills which are composed of the same three major rock units (Precambrian metamorphics, Oligocene granodiorite, and Oligocene granite). The numerous man-made cuts in the southern foothills are part of an International Harvester proving grounds.

Turn around and head east on Maricopa Road for 0.5 miles. Return to the north-bound lane of the Interstate.

M.P. 156

Road cut on west side of road exposes chloritic and brecciated Oligocene granodiorite

EXIT 155 - Baseline Road.

Exit and turn east (right) on Baseline Road.

Cumulative Mileage	
0.2	56th St. - Turn right and proceed south through town of Guadalupe. 56th St. becomes Avenida del Yaqui.
1.2	Calle Guadalupe - turn right and proceed west on road over Interstate.
1.8	Pavement ends - continue straight on main gravel road.
2.5	Parking area to right. Park and lock cars for short hike.

STOP 3

Walk approximately 0.4 miles up the road to the west and then slowly climb slopes of small ridge south of the road. In this slope is the upwards transition from nonchloritic, mylonitic, Oligocene granodiorite to chloritic breccia-microbreccia derived from the granodiorite. As one proceeds up the slope, the granodiorite becomes progressively more chloritic, brecciated and jointed. The cliffy exposures are composed of chloritic breccia. They are capped by a meter-thick ledge of microbreccia that was also derived from the granodiorite. The microbreccia weathers tan but exhibits a characteristically gray, flinty or resinous appearance on fresh surfaces. Although not preserved here, Precambrian metamorphic rocks overlie the microbreccia in low-angle fault contact in the southern foothills.

Structures within the chloritic breccia are upon first inspection, chaotic. However, hundreds of measurements of joints and slickensides reveal the structures to be systematic. The predominant strike direction of joints is NNW and the modal trend of slickensides is ENE, perpendicular to the joints. Normal faults which dip gently to the northeast are locally present.

After inspecting the complete traverse, carefully return to the cars.

Turn around and proceed east on the gravel road upon which we entered the park.

Cumulative Mileage	
3.8	Avenida del Yaqui (56th St.). Turn left (north).
4.8	Baseline Road - Turn left (west) and proceed west on Baseline road.

5.0	Underpass beneath Interstate 10.
5.8	Note destruction of landscape of hills to the south by off-road vehicles.
7.8	After 32nd St., note two hills on top of range at 10:00. They are composed of chloritic breccia. The rest of the rounded outcrops are Oligocene granodiorite which possesses a mylonitic foliation which dips gently to the north. The topography of this area mimics the north flank of a major foliation arch that parallels the range.
11.0	Central Avenue - Turn left and proceed south on Central Avenue.
12.5	Stay on Central Avenue which curves to the right.
12.8	Small hills to the right (north) are composed of Precambrian metamorphic and Oligocene granitic rocks.
13.3	Park entrance - Granodiorite dikes have intruded Oligocene granodiorite to the right.
13.4	Road junction after dip in road. Turn right toward Las Ramada picnic area.
13.8	Lower ramadas, continue up road to west.
13.9	Upper ramadas, park cars for lunch and an orientation talk.

STOP 4

After lunch and the talk, walk a short distance up trail west of the ramada. Exposed in this area is the contact between Oligocene granite and Precambrian gneiss. The granite is medium-grained, light-colored and contains approximately 3 percent biotite (locally altered to sericite). In this hill, the granite is undeformed except for some exposures near its contact with the Precambrian gneiss where the granite is mylonitic. A white, fine-grained aplitic phase is locally present along the contact. The Precambrian rocks are quartzofeldspathic gneiss with some amphibolite and deformed porphyritic granite. The Precambrian rocks exhibit a steep, northeast-striking foliation which is cut by the younger mylonitic foliation. The mylonitic foliation dips gently to the north-northeast and contains a conspicuous east-northeast-trending lineation. This mylonitic fabric is also present within several Tertiary alaskitic dikes.

After inspecting the exposures, return to the cars. Proceed back to the road junction near park entrance.

Cumulative Mileage	
14.4	Raod junction. Turn right towards Summit Lookout.
14.9	Hill to left of road contains the contact between Precambrian metamorphic rocks and the Oligocene granite.
15.1	Soap Box Derby track to left of road.

15.3 Mile-post 1.

15.7 Junction. Bear left towards Summit Lookout. Exposures along next mile are of Precambrian metamorphic rocks. Both the older (steep dipping) and younger (gently dipping) foliations are present. Ridge south of road is composed of Precambrian metamorphic rocks and Oligocene-Miocene dikes.

16.4 Mylonitic, Oligocene-Miocene alaskite sill in Precambrian gneiss.

16.6 Note steep foliation in Precambrian gneiss.

16.7 Granite-Precambrian contact to right, small parking area to left, continue straight on road.

16.8 Andesitic dikes have intruded into the Oligocene granite.

16.9 North-northwest-striking fractures in granite contain limonite, sericite and very minor amounts of copper. Dark coloration to hill is due to a fairly recent grass fire.

17.4 Switchback.

17.5 Contact between Oligocene granite and granodiorite.

17.8 Microdioritic dikes in granodiorite. Road curves to the left.

18.1 Road junction. Turn left toward Holbert Lookout.

18.4 Parking loop.

STOP 5

Exposed in this area is the contact between Oligocene granodiorite and Oligocene granite. The contact here is mappable, but gradational. The granite is more leucocratic while the granodiorite has a higher percentage of biotite. Exposures of the gradational contact such as those present downstream (to the north) indicate that the granite and granodiorite are nearly contemporaneous and are phases of the same pluton. The contact between the two rocks is commonly gently to moderately inclined, with the granite on top. In some exposures the granite clearly intrudes the granodiorite. Rb-Sr whole rock isochrons on both plutons indicate an emplacement age of approximately 25 m.y. ago.

Return to cars and proceed back to road junction.

Cumulative
Mileage

18.7 Road junction. Turn left. Road traverses through hills of foliated granodiorite. Radio and T.V. towers are built upon a subhorizontal, tabular exposure of alaskite. The alaskite is most likely a phase of the granite.

18.8 Mile-post 4.

19.5 Road junction. Bear left to Dobbins Lookout.

19.8 Parking area at Dobbins Lookout. Park and lock car.

STOP 6

The lookout provides a good view of the entire range. The lookout is built on a hill of mylonitically foliated alaskite sills that overlie mylonitic granodiorite. Precambrian rocks are also locally present. Lineation in both rock types trends east-northeast. After examining both rock types and their contact relationships return to the cars.

Cumulative
Mileage

20.1 Road junction. Turn left toward Hidden Valley.

20.3 Mile-post 5. This area of the range is composed of a mylonitic Oligocene granodiorite and a swarm of north-northwest-trending dikes. The dikes are commonly mylonitic and exhibit the east-northeast lineation that characterizes mylonitic rocks throughout the range.

20.9 Road junction. Turn right toward T.V. towers.

21.8 Foliated dike north of road.

22.1 Road cuts of alaskite injected into granodiorite. Both rock types are mylonitic.

22.3 End of road. Park and lock car.

STOP 7

Exposed in this area are complex relationships between mylonitic Oligocene granodiorite, overlying Oligocene alaskite, and a small area of Precambrian metamorphic rocks that locally occurs as a subhorizontal pendant above the granodiorite and below the alaskite. All three rocks are extremely mylonitic. Exposures of all three rocks can be seen by walking west of the loop for approximately 0.3 miles. Be careful of the cliff that is formed by the granodiorite. Return to the cars and exit the park the way we came in.

Cumulative
Mileage

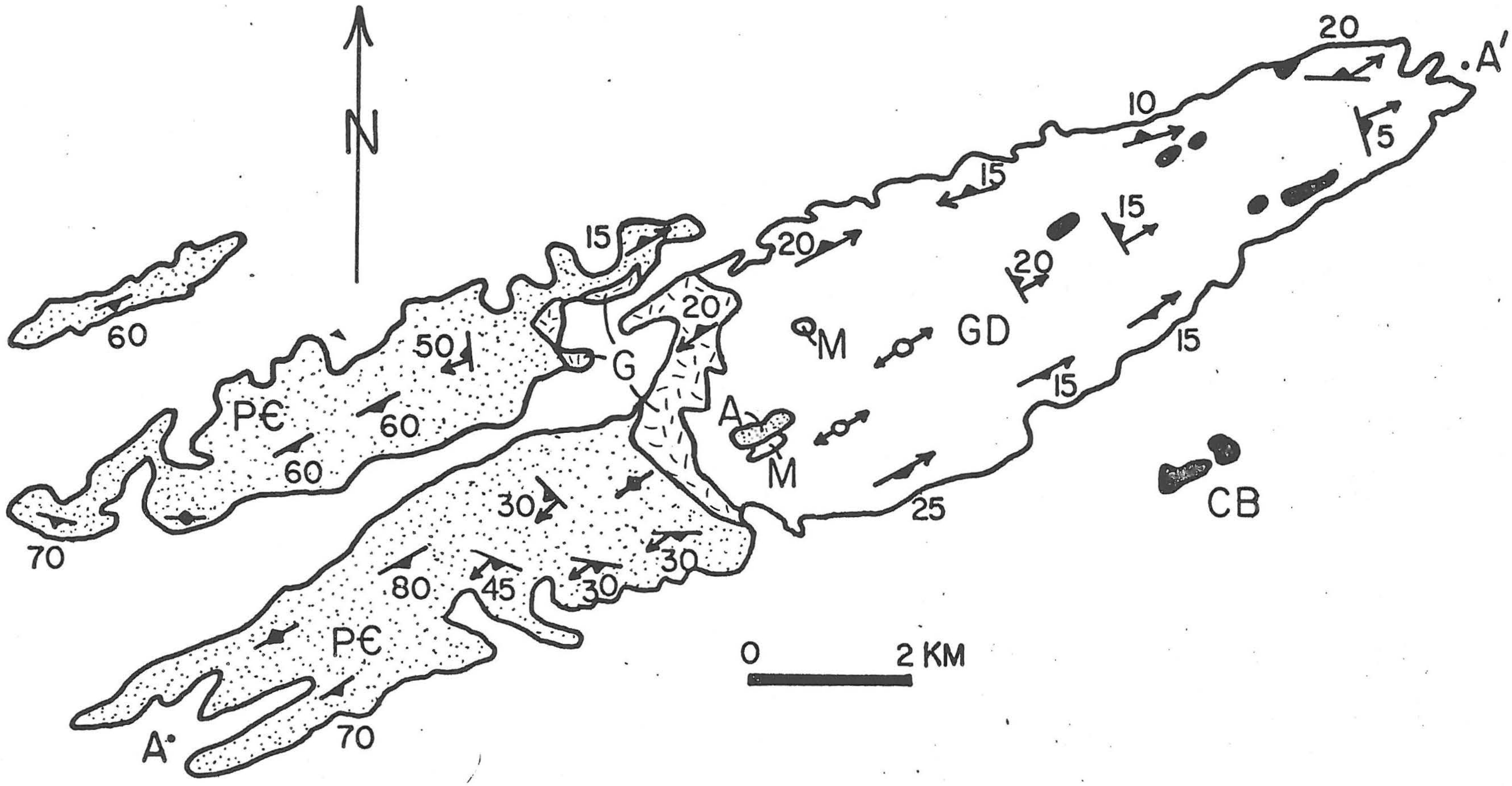
23.7 Road junction. Turn left.

24.5 Road junction. Turn left. Road to the right leads to Dobbins Lookout

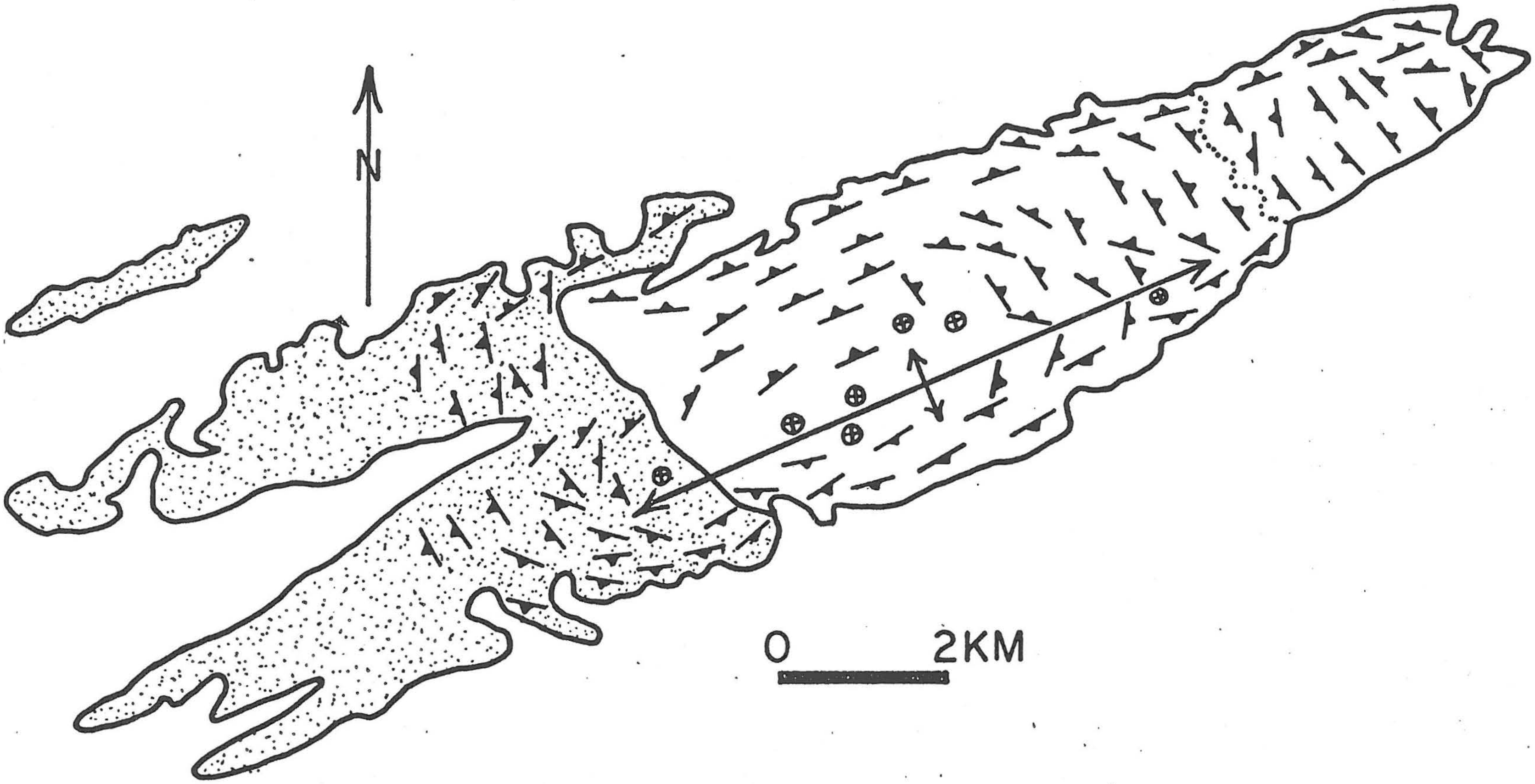
25.3 Rod junction. Bear left.

27.7 Road junction. Bear right.

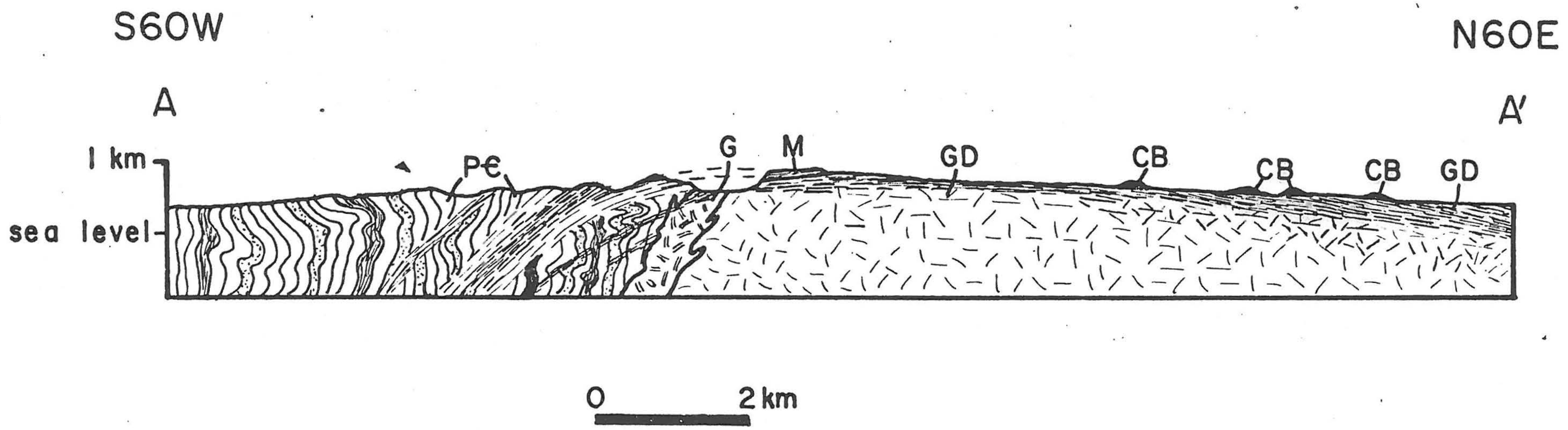
29.1 Park entrance.



Generalized geologic map of the South Mountains, exclusive of the southern foothills. P€ : Precambrian metamorphic and igneous rocks; GD : Oligocene granodiorite; G : Oligocene granite; A : Oligocene alaskite; M : mylonitic rocks; CB : chloritic breccia.



Orientation of mylonitic foliation where it is present in the South Mountains.



Cross-section of the South Mountians.

VULTURE MOUNTAINS ROAD LOG (Vulture Mine Road)

Cumulative Mileage From U.S. 60 and Vulture mine road junction	
0 - 1.6	Mainly alluvial cover
1.6	To the southeast is the Vulture Moutain Guest Ranch, temporary home for many a Snow-bird. To the west, occupying the low ground and thinly mantled by alluvium, are rare exposures of the 68 m.y. Wickenburg batholith, which forms bedrock in this area and probably underlies the town of Wickenburg. A quarry several hundred feet west of road exposes unaltered granodiorite and evidence of weak copper mineralization.
1.6 - 4.6	Traversing poorly outcropping Wickenburg batholith cut by swarms of northerly-trending Miocene dikes of ultrapotassic rhyolite forming low, elongate hills. Higher hills straight ahead are Twin Peaks capped by 13-14 m.y. olivine basalt flows resting in marked angular discordance upon severely tilted 20-26 m.y. silicic tuffs and flows.
4.6	Here we cross the unexposed trace of the Vulture Peak listric fault, upon which lie the tilted volcanic sections of Vulture and Caballeros Peaks. The ridge immediately southwest of this mileage locality is composed of these volcanics which dip steeply eastward into the shallow, west-dipping Vulture Peak fault.
4.8	At low topographic pass, reddish colored ditch cuts expose conglomerate unit forming base of silicic, tuffaceous volcanic section.
4.8 - 5.6	Road proceeds south along trace of another NS-striking listric fault which places volcanics west of road against Laramide granodiorite east of road. To the east (left) the ridge exposes scattered outcrops of tilted red conglomerate (at base of ridge) and overlying volcanics.
5.6	STOP (short jeep trail leading to base of ridge east of Vulture mine road) Park vehicles along Vulture mine road and proceed eastward on foot. In this area, several key contacts are accessible: (1) partially covered by alluvial debris, a NE-trending intrusive contact between the Wickenburg batholith on the north and Precambrian (?) gneisses on the south (2) At the base of the ridge,

the Tertiary conglomerate unit unconformably overlaps both Laramide granodiorite and gneisses. Clasts in the conglomerate are mainly Precambrian (?) metamorphic rocks although granitic clasts of undetermined age are present; (3) the upper contact of the conglomerate is made with the overlying silicic volcanics, the lower units of which are well-stratified, thin, welded tuffs and/or base surge deposits. Volcanics farther up-section consist of more tuffs, a grey dacitic flow and, on the steep part of the west-facing ridge, a thick, massive obsidian flow which contains extensive devitrification and zeolitization. Potassium-argon dates of 26 m.y. (biotite) and 16 m.y. (whole rock) were analyzed from near the base of the volcanic section.

The section of volcanics and conglomerate dips up to 70° east toward the flat Vulture Peak normal fault. The lower part of the section, with its unconformity and crystalline basement, is repeated just west of the Vulture mine road by another west-dipping listric fault.

Capping the ridge is a tectonic contact of special interest. A flat-lying listric fault and klippe of ultrapotassic rhyolite rest on the obsidian flow. Whole-rock K-Ar dates of 16 and 17 m.y. have come from the hangingwall rhyolite. The fault is beautifully exposed for detail study.

From the ridge top, a view northwest shows the faulted and tilted silicic volcanics overlain by relatively flat-lying basalt flows on Twin Peaks. Toward the south-southeast, the imposing Vulture Peak is seen with its tilted volcanic section rich in rhyolitic agglomerate and flows. This section dips 50-70° east. The Vulture Peak fault, along the eastern side of the peak is so flat that it outcrops on both east and west sides of the ridge, south of Vulture Peak.

GEOLOGY GEOCHRONOLOGY AND LISTRIC NORMAL FAULTING OF THE VULTURE MOUNTAINS MARICOPA COUNTY, ARIZONA

The Vulture Mountains, located near Wickenburg, about 50 miles northwest of Phoenix, consists principally of a faulted and tilted series of volcanic rocks surrounded and underlain by a plutonic and metamorphic basement. Intermittant geologic work during the past 10 years supported by chemical, isotopic and radiometric age analyses has led to a new appreciation of Miocene-Oligene volcanism and a fascinating period of extensional tectonism earlier and more profound than the traditional basin and range disturbance.

Regional Setting

The Vulture Mountains are located in the Basin and Range Desert province within a north-northwest to northwest zone of severe normal faulting. Many of these faults are of the listric normal type. In the Vulture Mountains, tilting on these faults is toward the northeast. These rotations extend with progressively less effect to the northeast into the Bradshaw Mountains. This broad, northeast-tilted zone represents a major structural transition between the Mountain and Desert subprovinces. Rotational normal faulting surrounds the Vulture Mountains on other sides as well. Taken collectively, the geometry and displacements of this fault system form an intriguing picture of northeast-directed crustal extension.

Two distinct volcanic sequences are found in the Vulture Mountains: an earlier silicious sequence of flows and tuffs and a later series of basalts. These same sequences crop out in surrounding mountain ranges across a broad, southwest-trending area from the Bradshaw Mountains to the Colorado River.

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 extrusive rocks (Figure 1).

Precambrian rock types exhibit a crude northeast-oriented outcrop pattern across the range (Figure 1). To the north (and between Vulture and Caballeros Peaks) a coarse-grained, porphyritic granite occurs which resembles 1400 or 1700 m.y. granites in adjacent areas. A 2-3 mile wide, northeast-striking zone of gneissic granite to granodiorite with minor amphibolite and pegmatite is found south of the porphyritic granite. Mafic schist lies south of the gneiss belt partly in fault contact with the gneiss (Figure 1).

A large, composite granodiorite pluton intrudes the core of the granitic gneiss belt. The pluton is dated at 68.4 m.y. It forms a highly elongate, dike-like mass extending well beyond the margins of the Vulture Quadrangle. The batholith is known as the Wickenburg batholith.

Postbatholith rocks include silicic and basic volcanic sequences--the former is tilted on listric faults. Above a reddish-colored basal conglomerate rest the silicic volcanics consisting of rhyolitic lava flows, welded tuffs and pyroclastic-volcaniclastic rocks interbedded with minor basaltic andesite to rhyodacitic lava flows. The basal volcanic unit is a buff to yellowish ash-flow which exhibits volcaniclastic and agglomeratic facies and commonly is intensely zeolitized. This unit is widespread in the Vulture Mountains and has been recognized (and dated) in the nearby Big Horn, Eagle Tail and Kofa Mountains. A biotite age of 26 m.y. and whole rock age of 16 m.y. has been established for this interval. The basal unit dates (biotite) at about 23 m.y. in other ranges.

The silicic volcanic rocks display rapid, short-distance changes in thickness and character suggestive of nearby source areas. For example, the section on Vulture Peak consists largely of proximal vent facies of very coarse, tuffaceous, pumice-rich, aggolomerate and thick rhyolite flows, whereas, the section near Highway 60 is rich in basaltic andesite flows and vitrophyres.

Chemically, the silicic volcanics are characterized by ultrapotassic rhyolite with SiO_2, Al_2O_3 and $K_2O > 90\%$. The K_2O content of these rocks is exceedingly high and for silicic samples averages 8.1 weight percent. Diagenetic or autoalteration potash metasomatism is suspected in part for the high K_2O contents. Some of the units are peralkaline with alkali-Al_2O_3 molecular rations > 1. Some more basic flow rocks sandwiched between the rhyolites have $< 60\%$ SiO_2, lower alkali contents and are basaltic andesites.

In contrast to the silicic sequence are the blocky basalt flows outcropping on Black Mountain and on Twin Peaks (Figure 1). Chemically this flow sequence is distinguished by relatively low alkali content ($Na > K$), high CaO, NaO and low potash ($\sim 1\%$). Olivine occurs in the basalts. A K-Ar date of 13.5 m.y. was secured from a sample on Black Mountain.

Tectonic Considerations

Certain geologic features in the Vulture Mountains exemplify important tectonic relationships in the southwestern U.S. These features are: (1) NE structural control of Laramide plutonism, (2) NNW control of mid-Tertiary plutonism, (3) listric normal faulting associated with mid-Tertiary silicic/potash-rich volcanic rocks, and (4) a fundamental change in tectonic style and volcanic petrology that took place between about 16 and 14 m.y. B.P.

Relationships (1) and (2) have been discussed by Rehrig and

Heidrick (1976). In close association with the NNW aligned dike swarms of mid-Tertiary (~20-30 m.y. B.P.) age is the period of intense listric faulting which tilted shallow crustal rocks and extended them NE to E, in a direction approximately normal to the strike of the dike swarms. Silicic volcanics in the Vulture Mountains have been strongly affected by this style of deformation (Figure 1). The flat-lying Black Mountain and related basalts post-date the deformation, thus, bracketing the listric faulting event to the broad interval 26 to 13.5 m.y. Undeformed ultrapotassic rhyolite dikes intruding the flat listric faults and correlated with dated 16 m.y. dikes, further narrows the main extensional faulting to the period from 26 to 16 m.y., or regionally from about 20 to 16 m.y. B.P.

From about 16 to 14 m.y. B.P. a fundamental tectonic change occurred which yielded the following results: (1) transition from low-angle to high-angle normal faulting (really a change from horizontal-to-vertical-directed tectonics), (2) a major petrologic change from silicic, calc-alkaline volcanism ($Sr^{87}/ Sr^{86} \approx 0.708$) to more primative basalt magmatism ($Sr^{87}/Sr^{86} \approx 0.705$). These litho-tectonic changes show a similar timing regionally.

The regional setting of the Vulture Mountains on the northeast flank of a broad antiformal feature (Big Horn - Vulture Antiform) and presence of the adjacent Harcuvar Metamorphic Core Complex (See Figure 2) suggest a causal relationship between antiform (listric faulting) and core complex. The basic factor common to both is ductile or penetrative shallow crustal stretching below a relative thin, brittle, surficial layer (Figure 3). Stretching in the ductile layer (mylonite formation?) and listric fault extension in the brittle layer are colinear in an ENE-WSW direction.

During the 16 to 14 m.y. litho-tectonic transition, magmatism waned and changed from calc-alkaline to basaltic. Tectonics became vertically directed, faults penetrated deeper through a cooling and more rigid crust and allowed relatively uncontaminated sub-crustal melts access to the surface.

W. A. Rehrig

M. Shafiqullah

P. E. Damon

October, 1980

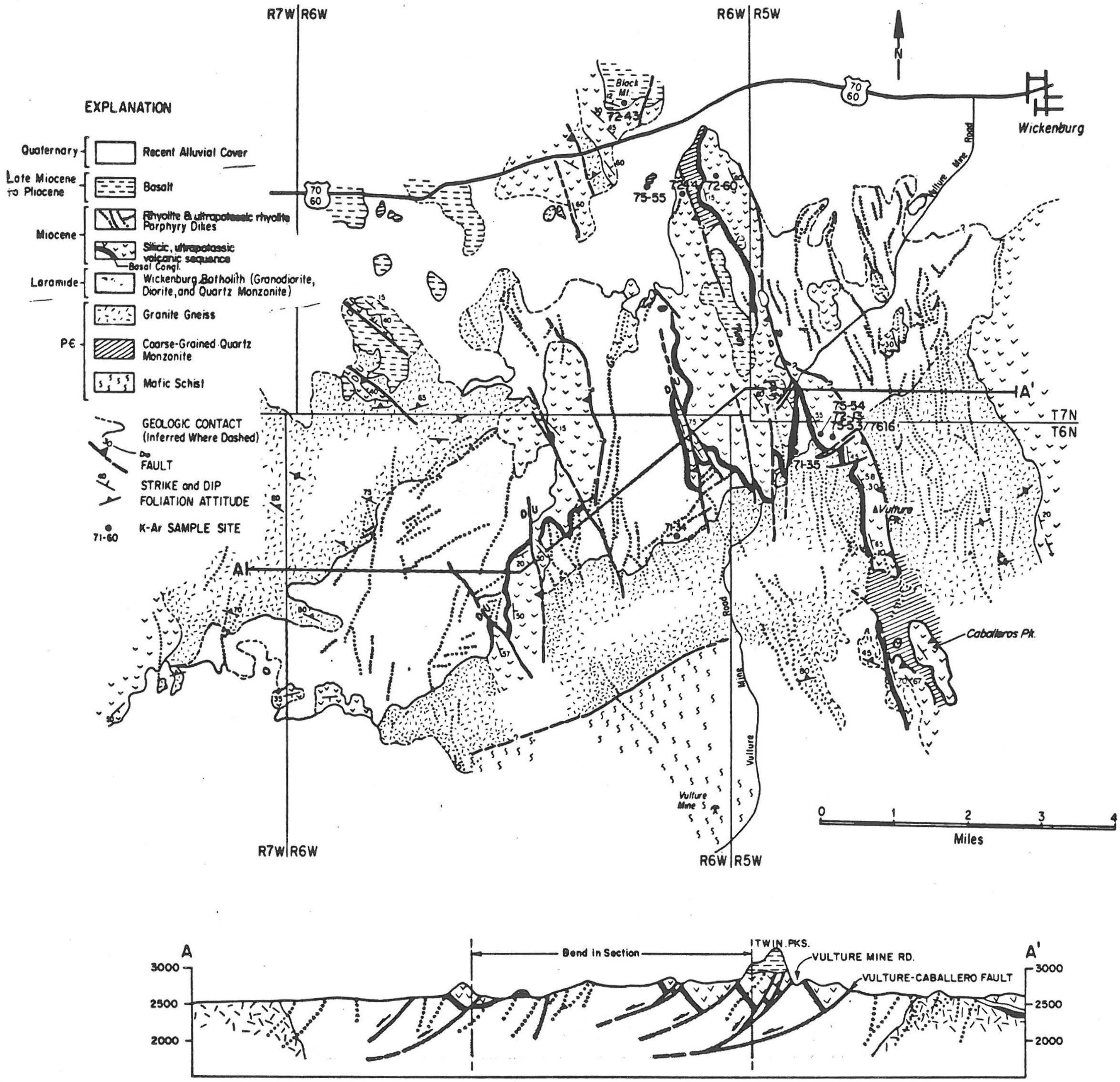


Fig. 1. Generalized geologic map and cross section of the Vulture Mountains. Note a crude northeast-oriented zonal pattern of Precambrian rocks. Mafic schists are common in the southern part. Silicic Tertiary rocks are intruded by a swarm of northerly trending dikes. Structural grain strikes north to northwest and is represented by dikes, normal faults, and tilted elongate fault wedges of silicic volcanic rocks. See explanation on facing page.

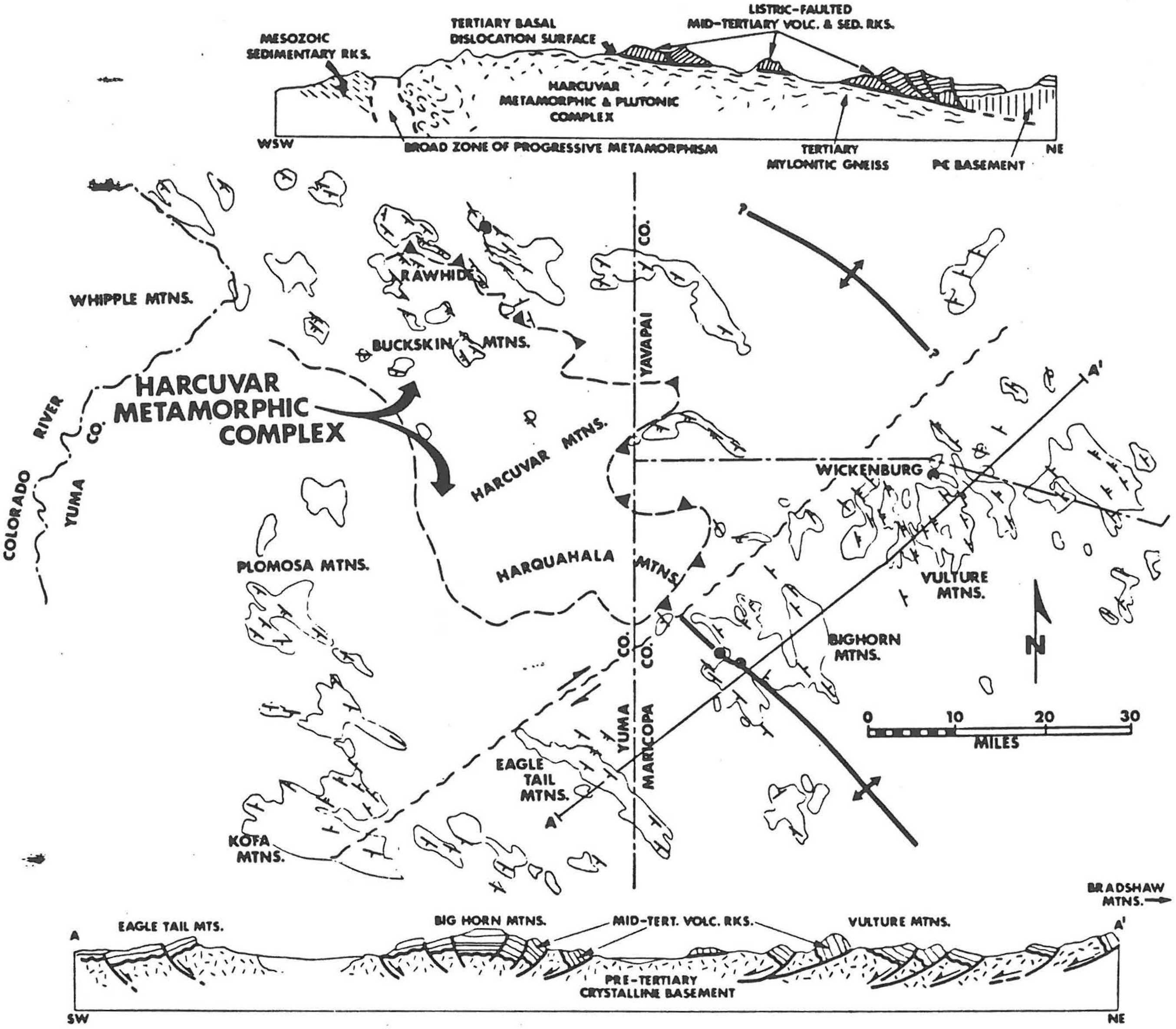
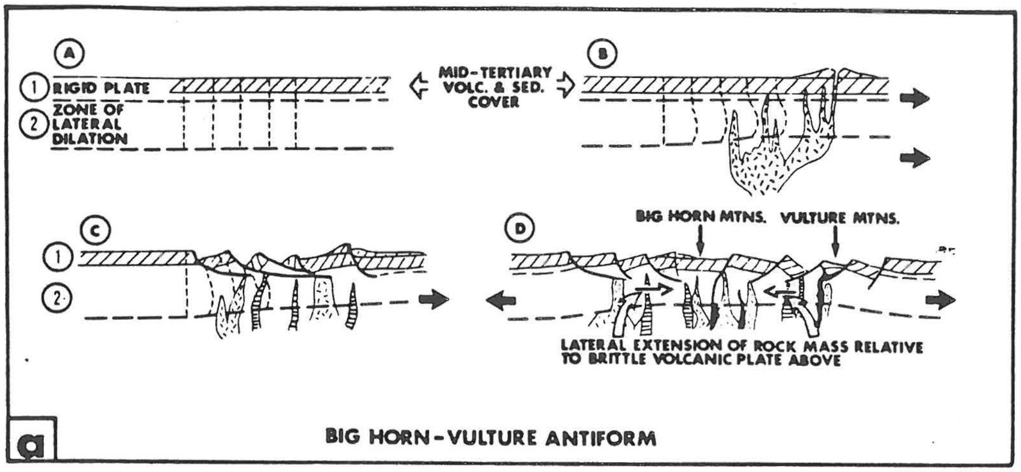


Fig. 2. Regional tectonic setting of the Vulture Mountains. Map shows outcropping areas of Oligocene-Miocene volcanic rocks (outlined areas) and their tilted attitudes. Double-bar dip symbols indicate dips > 45°. Sources for structural data include: Arizona county geologic maps; unpublished tectonic 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.



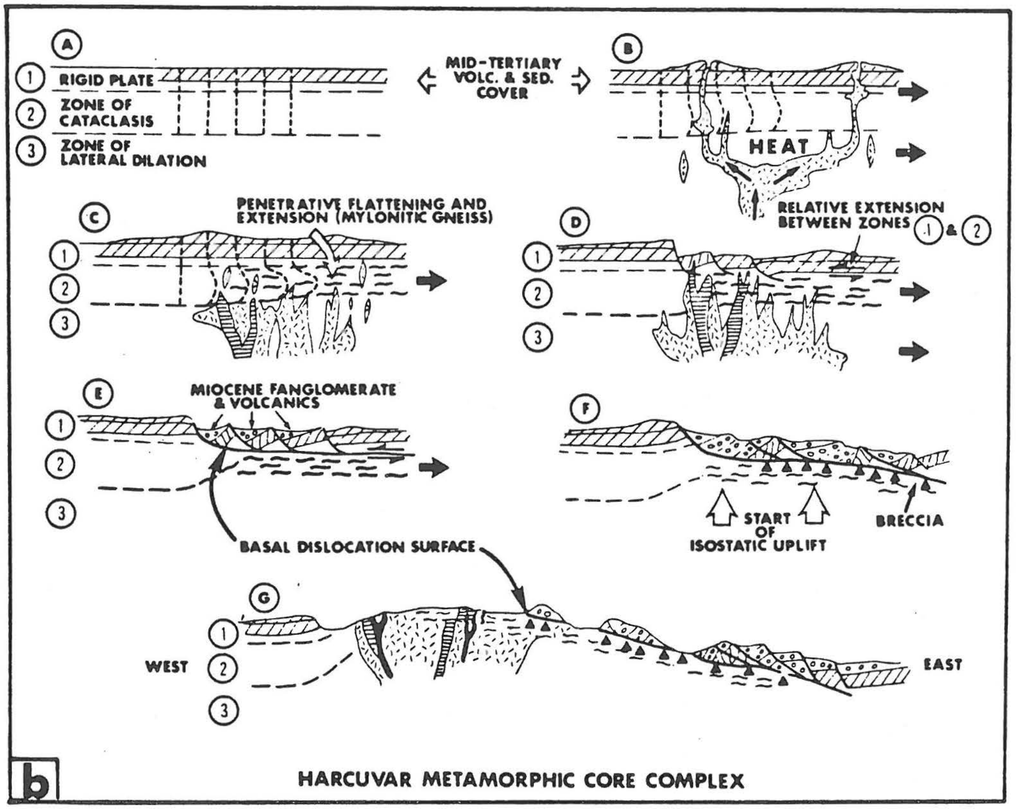


Fig. 3. Working hypothesis for development of listric faulting in the Big Horn-Vulture antiform (a) and Harcuvar metamorphic core complex (b). Large black arrows represent lateral extensional stress toward the northeast or southwest. Vertical dashed lines through plates 1 and 2 show extensional strain.

(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 3b is based on text and figure 8 of Rehrig and Reynolds (n.d.).

WICKENBURG TO EAGLE EYE PEAK

Mileage	
107.7	Vulture Mine road intersection
107	Black Mountain at 12:00.
106.2	Historical marker.
105.9	Wickenburg municipal airport. Turnoff to right.
105.4	Roadcut here and roadcuts for next several miles on south side of road are in terrace or basin fill gravels.
103	Roadcut on left is in Precambrian crystalline rocks of amphibolite grade.
102.9	Black Mountain on right.
102.4	Roadcuts in amphibolite-grade Precambrian crystalline rocks with steeply inclined northeast trending foliation.
102.1	Roadcuts on both sides of road expose a spectacular example of a low-angle normal fault placing mid-Miocene age rhyolitic volcanics on Precambrian amphilolite-grade crystalline basement. Foliation in the dark-colored biotite-feldspar gneissic basement strikes N60E, is near vertical, and is cut by granitic dikes and a chlorite-biotite lamprophyre dike (strike N80W, dip 75° NE).
	The fault strikes N20W, dips 15° SW and contains near dip-slip slickensides that trend S70° W. Precambrian crystallines immediately below fault are highly chloritic and epidotized and contains several shears parallel to the main fault. Tuffaceous rhyolites in the upper plate hanging wall strike N85W and dip 70° N.
101.7	This roadcut and the next several roadcuts (mainly on left) expose mid-Miocene rhyodacitic volcanics and water-lain tuffs.
100.8	Roadcuts here and next half mile expose northeast tilted andesitic volcanics.
100.2	Enigmatic roadcuts.
	Biotite granite of presumed Precambrian age crops out in the roadcut on left. Near the west end of the cut the granite is cut by N60W striking rhyodacitic dikes. In contrast, the roadcut on the right (north) side of the highway contains highly broken conglomerate with clasts of the biotite granite and Precambrian amphibolite grade clasts. This conglomerate is also cut by a N65W striking rhyodacite dike. The two roadcuts may be separated by a N80E striking high angle fault that dips steeply SSW and contains shallow east plunging slickensides.
99.9	Roadcut and hill right contain biotite granite?

WICKENBURG TO EAGLE EYE PEAK
(continued)

Mileage	
99	Middle Mountains are in middle distance at 2:00 to 3:00. The Weaver Mountains are in distance at 3:30. Inclined scar on south facing slope of Weaver Mountains is State Highway 71 to Prescott.
98.5	Roadcuts on both sides of highway are in highly broken granite. Low hills to right are also underlain by the granite.
98.2	Roadside rest on left.
98	East end Harquahala Mountains now easily viewable to the left at 11:30.
97	Black Butte in the west Vulture Mountains appears at 9:30. Black Mountain is capped by a dipping basalt dated at 15 m.y. (Scarborough and Wilt, 1979).
96	Harcuvar Mountains pierce skyline at 12:00 to 1:30.
93	East end of Harcuvar Mountains are at 1:30 and offer an excellent view of southwest-dipping volcanics that form well-developed hogback landforms. The volcanic pile is dominated by high potassium trachytes. One of these trachytes has been dated at 17 m.y. (Scarborough and Wilt, 1979)
93	Small buttes appear at 9:00 to 11:30.
87	Eagle Eye Peak in probable mid-Miocene age volcanics appears at 10:00. Watch for the eagle eye which will become more obvious as you travel west. Eagle Eye Peak will be Day 2's first stop.
86	Junction on right with Arizona State Highway 71 to Prescott, Arizona. Continue west on U. S. 60.
85	Metropolis of Aguila ahead. Prepare to make left turn onto Eagle Eye Road in downtown Aguila.
84.4	Turn left onto Eagle Eye road.
0.00	Cumulative mileage begins.
1.0	Eagle Roost suburban airport on left. Unnamed peak in eastern Harquahala Mountains is at 1:00. The eagle Eye is now at 11:45.

The unnamed peak is probably in equigranular banded leucocratic gneiss (ledge formers) interlayered with mafic, mesocratic, amphibolitic gneiss. These rocks are of probably Precambrian age. The foliation is generally non-mylonitic and no lineation was observed in exposures two miles east of the unnamed peak. The amphibolitic-grade rocks, on the unnamed peak and south facing slopes of the mountain, are separated from a mylonitically-foliated, biotite quartz monzonite by a zone of ultramylonite. This zone trends east-west across the map and dips about 15 to 20° south. The ultramylonite zone is expressed as a slope former between the amphibolite grade rocks and the underlying foliated biotite granite which forms rugged cliffs and bold outcrops below the ultramylonite zone.

Mileage

Locally a porphyritic mylonitic granite occurs between the amphibolite grade rocks and the biotite granite. All of the mylonitic rocks contain a pronounced N50 to 65E-trending lineation on foliation surfaces. The ultramylonite zone could be the eastern extension of the Harquahala Thrust, a regional thrust fault we have been mapping throughout the Harquahala Mountains. However, the northeast-trending lineation may be a younger lineation superimposed on the thrust which contains a differently oriented, older fabric in the western Harquahala Mountains. We will see this fabric at the White Marble Mine later on.

3.1 Road to left. Continue straight.

3.5 Materials pit sign and road on left. Prepare to park for STOP 1 at Eagle Eye Peak.

STOP 1 Eagle Eye Peak STOP

Eagle Eye Peak contains the best exposures of the low-angle fault between the mylonitic basement of the Harquahala Mountains and an upper plate of tilted Tertiary sedimentary and volcanic rocks. A majority of mylonitic rocks in this area have been derived from a granitic protolith. Foliation is gently dipping and defines a broad N60E-trending arch. Eagle Eye Peak is slightly southeast of the axis of the arch. Dioritic rocks are exposed in the footwall of the fault where they are highly brecciated. The low-angle fault dips gently to the east and is immediately underlain by a chloritic breccia. Tertiary rocks above the fault include reddish sandstone - siltstone, conglomerate, sedimentary and volcanic breccia and volcanic units. The Tertiary rocks dip to the southwest.

In this area, examine the lower-place mylonitic rocks, the dioritic rocks, the low-angle fault and the upper-plate Tertiary rocks. The peak also provides an excellent opportunity to observe the geology of the surrounding region 'S' Mountain window.

At 'S' Mountain window, the Hercules thrust is well exposed, placing Precambrian metamorphic and granitic rocks over Mesozoic strata. Mesozoic rocks below the thrust consist of (in order of increasing stratigraphic level): 1) feldspathic sandstone and gritty arkose; 2) calc-silicate beds interbedded with quartzitic and argillitic units; 3) a ledge-forming quartzite that is capped by a quartz-pebble conglomerate; and 4) quartzitic and argillitic strata. The Mesozoic rocks are locally highly deformed and exhibit a northerly trending lineation. Pebbles in the conglomerate are elongate parallel to the lineation. Precambrian rocks immediately above the thrust fault share the same lineation direction.

From the cars, walk east and examine the Mesozoic rocks below the thrust. Climb up to the quartzite ledge and examine the thrust which overlies the ledge. Above the thrust in this locality are a light-colored granitic rock and foliated quartz-diorite to quartz dioritic gneiss.

GEOLOGIC OVERVIEW OF THE HARQUAHALA, HARCUVAR, BUCKSKIN AND RAWHIDE MOUNTAINS, WEST-CENTRAL ARIZONA

Introduction

A northwest-trending zone of metamorphic core complexes in west-central Arizona is composed of (from southeast to northwest) the Harquahala, Harcuvar, Buckskin, and Rawhide Mountains. These four ranges have a pronounced northeast trend or physiographic grain, in contrast to the north or northwest trends of most mountain ranges in western Arizona. The Harcuvar and Harquahala Mountains are especially prominent in the region because they are relatively high (elevations above sea level of over 5,000 feet compared to valley elevations of 2,000 feet), northeast-trending ranges. The large northeast-trending McMullen and Butler Valleys bound the Harcuvar Mountains on the south and north sides, respectively. The Buckskin and Rawhide Mountains lie to the northwest and are parts of a single relatively low relief mountain range. They are separated by the Bill Williams River (the Rawhide Mountains are situated on the north side of the river).

Early geologic works in the area were of a reconnaissance nature or were concerned with the detailed geology of small mining areas (see references cited in Stanton B. Keith, (1978) and Reynolds, (1980). Lasky and Webber (1947) mapped the geology of the Artillery Mountains (located immediately east of the Rawhide Mountains) and described two important Tertiary sedimentary units: the Artillery and Chapin Wash Formations. Wilson (1960; see also Wilson and Moore, 1959; Wilson and others, 1969) mapped the reconnaissance geology of the entire west-central Arizona region. Shackelford (1976, 1977, 1980) and Gassaway (1972) describe the geology of the Rawhide and Buckskin Mountains, respectively. Rehrig and Reynolds (1977, 1980) discuss results of their reconnaissance geologic and geochronologic studies of the region. They recognize that the Harquahala, Harcuvar, Buckskin and Rawhide Mountains are metamorphic core complexes. Davis and others (1977, 1979, 1980) integrated the geology of the Rawhide and Buckskin Mountains with that of adjacent areas. Suneson and Lucchitta (1979) determined the ages of volcanic units and tilting in rocks north of the Bill Williams River. Reynolds (1980) synthesized results of unpublished detailed and reconnaissance geologic mapping with that of previous workers, and presented a summary of the geologic framework of west-central Arizona. Reynolds and others (1980) documented major Laramide thrust faults in the Harquahala Mountains, adjacent to an area mapped by Varga (1976, 1977). Geologic research and mineral exploration in the area are continuing at an accelerated pace.

General Geology

The Harquahala, Harcuvar, Buckskin and Rawhide Mountains have essentially all the characteristics that typify Cordilleran metamorphic core complexes. All four ranges are composed of a basement terrane of quartzo-feldspathic gneiss and micaceous schist interlayered with amphibolite, underformed to well-foliated granitic rocks, and local marble and quartzite. Foliation in the metamorphic rocks is gently dipping and defines large northeast-trending arches which parallel and control the topographic axis of each range. Field and isotopic studies define a major Late Cretaceous to early Tertiary metamorphic event which is probably spatially and temporally associated with plutons of the same age. The metamorphic rocks are most likely derived from Precambrian protoliths, although Paleozoic and Mesozoic sedimentary rocks are also locally incorporated into the basement terrane. Granitic rocks that are interlayered with the metamorphic rocks have Precambrian, Mesozoic and Cenozoic ages.

The metamorphic fabric and associated granites are overprinted by a gently inclined mylonitic foliation that contains a conspicuous northeast- to east-trending lineation. Mylonitic fabric is best developed in structurally high exposures and conforms to the arch defined by the non-mylonitic, metamorphic foliation. The mylonitic fabric is probably early to middle Tertiary in age because it clearly postdates Late Cretaceous - early Tertiary plutons and metamorphic fabric. In addition, mylonitic rocks in the ranges have so far yielded early and middle Tertiary K-Ar biotite and hornblende ages.

The metamorphic - plutonic basement of the Harquahala Mountains has additional structural complexities that have not been described for the other three ranges. For example, much of the range is composed of foliated, porphyritic Precambrian granite which is successively overlain by thrust slices of inverted Paleozoic rocks and Precambrian metamorphic and granitic rocks (Reynolds and others, 1980). A mylonitic zone associated with one of the thrusts is disconcordantly intruded by early Tertiary muscovite-bearing pegmatites. Elsewhere, these pegmatites exhibit a younger mylonitic foliation that contains the familiar east-northeast-trending lineation. It is uncertain whether basement terranes of the other three ranges were also subjected to such complex structural histories.

In all four ranges, structurally high exposures of mylonitic rocks have been brecciated, jointed, faulted, and affected by retrograde metamorphism or hydrothermal alteration which has formed chlorite, hematite, epidote, sulfides and copper minerals. This assemblage of rocks and minerals is best termed a chloritic breccia. The chloritic breccia is overlain by a thin (approximately one meter thick) ledge of microbreccia. A dislocation surface is well exposed above the microbreccia throughout much of the Rawhide and Buckskin Mountains and in more isolated exposures along the northeastern ends of the Harcuvar and Harquahala Mountains. The most common allochthonous rocks above the dislocation surface are Oligocene (?) - Miocene conglomerate, sandstone, siltstone and volcanic rocks. However, Precambrian metamorphic and granitic rocks, Paleozoic carbonate and clastic rocks, and Mesozoic igneous and sedimentary rocks are also locally exposed in upper plate positions. Upper plate rocks dip, on the average, moderately to the southwest and are cut by northwest-striking listric-normal faults. Relative tectonic transport of upper plate rocks is mostly to the northeast and is as young as 15 m.y. (Davis and others, 1980; Rehrig and Reynolds, 1980).

Geological Evolution

In the Precambrian, west-central Arizona was the site of tectonic unrest, crustal construction and stabilization via a series of depositional, metamorphic, and plutonic episodes. Deposition of clastic and volcanic rocks was closely followed by metamorphism, deformation, and plutonism around 1.6 to 1.7 b.y. Besides possible emplacement of diabasic intrusions in late Precambrian time, the next youngest rocks in west-central Arizona are Paleozoic. Equivalents of younger Precambrian Apache Group rocks are eivdently absent from the area. Paleozoic rocks are a relatively thin sequence of carbonate and clastic rocks that represent a cratonic platform environment.

After the Paleozoic interval of relative tectonic quiescence, the area experienced major mid-Mesozoic volcanism, plutonism, and tectonism. The mid-Mesozoic plutons and volcanic rocks are parts of a subduction-related (?), northwest-trending magmatic arc. After the mid-Mesozoic arc swept or jumped westward, thick sequences of clastic rocks were deposited unconformably on the volcanic rocks. Clastic sedimentation was followed by plutonism and metamorphism in the Late Cretaceous and Early Tertiary as magmatism swept eastward across Arizona. Metamorphism was, in part, synchronous with plutonism, and formed high-grade gneissic and migmatitic terranes that are exposed in the metamorphic core complexes. This was successively followed by northward-vergent Laramide thrusting and intrusion of early Tertiary muscovite-bearing granites. Mylonitization in the core complexes postdates these events and is early or middle Tertiary in age.

A period of widespread early Tertiary erosion was followed by deposition of middle Tertiary conglomerates, sandstone, siltstone, lacustrine units and volcanic rocks. Plutonism and extensive thermal disturbances accompanied the volcanism. Middle Tertiary rocks were tilted and rotated during dislocation and listric-normal faulting. Final cooling in the core complexes occurred at this time. Block-faulting formed the present-day basins and ranges between 14 and 5 m.y. Variably sized clastics were shed into the downdropped basins; evaporites were deposited in some closed basin. The region was moderately tectonically stable when the Pliocene Bouse Formation was deposited in a partly marine embayment accompanying development of the Gulf of California. Basins that had earlier been characterized by internal drainage became interconnected as part of the integrated Colorado-Gila River system.

ROAD LOG EAGLE EYE PEAK TO WHITE MARBLE

Mile Post

Leave Eagle Eye Peak Stop. Return to Aguila and turn west (left) onto U. S. 60.

82 Smith Peak at 2:45 is the highest point (el. = 5242') in the Harcuvar Mountains. At Smith Peak amphibolite grade (Precambrian?) gneisses have been intruded by shallowly inclined sheets of biotite granite which resembles the Tank Pass pluton at the west end of the Harcuvars. The biotite granite contains a penetrative mylonitic lineation that trends N60E - S60W.

80 Bullard Peak at low 3:00 backed by main mass of eastern Harcuvar Mountains. Dark rocks at Bullard Peak are 15 m.y. southwest to south-southwest dipping volcanics. The volcanics are intercalated with coarse conglomerates and megabreccias. One of the common clast in these megabreccias are pebble through boulder-sized class of volcanic-derived arkoses and graywackes that strongly resembles the Livingston Hills assemblage of Mid-Mesozoic age in the Plomosa Mountains. The closest exposure of these rocks to Bullard Peak is in the western Granite Wash Mountains 25 miles west-southwest of Bullard Peak. Also no mylonitic clasts have been recognized in the Miocene conglomerates. The entire Bullard Peak sequence has been tilted southwest and rests as an allochton on a low-angle normal fault that strongly resembles the Buckskin dislocation surface summarized by Rehrig and Reynolds (1980) and Shakelford (1980). The map trace of the low-angle fault in the eastern Harcuvar Mountains suggest it has been deformed by the ENE trending fold that runs along the crest of the Harcuvar Mountains.

79 Pioneer Mountain at 9:00. Pioneer Mountain is entirely underlain by a biotite granite which strongly resembles the Tank Pass granite in the western Harcuvar Mountains. The granite carries mylonitic foliation that strikes NW, dips NE, and contains a lineation that trends N60E.

77.8 Dirt road on left provides access to Dushey Canyon area at 9:00.

76.2 Berg of Gladden.

75.2 Medusa-like multiple-armed saguaro on left.

74.5 Yuma County Line.

72 Main physiographic features of the Harquahala Mountains are now in good view to the left. Harquahala Mountain caps the high cliffs at 9:00 and is the highest point in the Harquahala Mountains (el. = 5681' Sunset Canyon, and Pass are at 8:00 and provides the best example of a very common physiographic form within the Harquahala Mountains. As at Dushey Canyon Sunset Canyon trends northwest (the Canyon displays a very sharp northwest trending linear on aerial imagery of various kinds and scales). Also, as at Dushey Canyon, Sunset Pass is connected to a shallowly inclined east-sloping ridgeline to the west and steeply inclined west-sloping ridgeline to the east. This physiography is a clue to a major, northwest-striking, northeast-dipping fault zone that strikes through Sunset Pass and closely follows the stream bed in Sunset Canyon. This structure is simply one of the better examples of a group of northwest-striking, northeast-dipping group of faults spaced at 1 to 3 km intervals

ROAD LOG EAGLE EYE PEAK TO WHITE MARBLE
(Continued)

Mile Post

throughout the length of the Harquahala Mountains. Our mapping in the western Harquahala Mountains has disclosed that these faults offset the low-angle thrust hypothesis emphasized on this trip. Indeed, the thrust stratigraphy provides a datum to evaluate offset on these faults. Our mapping in the western Harquahala Mountains reveals that these faults have consistent, moderate, northeast dips and reverse and right lateral separation. The faults contain common, shallowly-inclined slickensides and less common dip-slip slickensides. A reverse slip and right slip movement history that post-dates thrusting seems to be required for these faults. It is interesting that the Sunset Canyon structure is virtually on strike with the Lincoln Ranch fault, a major northwest-trending fault with post-mid Miocene reverse movement, in the Rawhide and Buckskin Mountains. The Lincoln Ranch fault offsets the Rawhide-Buckskin dislocation surface which itself has experienced a major 18 to 15 m.y. low-angle normal movement. If the northwest-striking structures in the Harquahala Mountains are correlative with the Lincoln Ranch fault and its kindred then the entire Rawhide to Harquahala region has experienced post-mid Miocene reverse faulting.

71 Harquahala Mountain massif now dominates the view to the left. The trace of the Harquahala thrust occurs near the top of the prominent cliffs. The country above the cliffs is one of low topographic relief and is underlain by amphibolitic grade metavolcanics and metasediments of probable Precambrian age within the Harquahala plate. The Harquahala thrust, the principal thrust within the main mass of the Harquahala Mountains, is structurally the highest fault of the regional thrust fault network (refer to the White Marble mine field guide for a summary of the regional thrust network). The bold cliffs below Harquahala Mountain are mostly underlain by mylonitically deformed porphyritic Precambrian granite. In the lower slopes this granite is intruded by numerous dikes and masses of garnet-bearing muscovite granite and pegmatites (the light-colored outcroppings in the lower slopes of the mountain). Some of the muscovite pegmatites extend upwards and intrude through the Harquahala thrust into the overlying Harquahala plate. Thus, the muscovite-bearing pegmatites and granite post-date thrusting. A Rb-Sr mineral-whole rock isochron for samples of the muscovite granite collected just west of Sunset Canyon has yielded an Eocene age and provides a minimum age for the thrusting.

70.7 Rest area on left. Canyon to the west of Harquahala Mountain at 9:30 exposes about 2,500 feet of mylonitic granite below the Harquahala thrust. We believe this mylonitization was imposed on the granite during the thrusting (see White Marble mine Field Guide).

69.9 Rest area on right.

69 Socorro Peak at 10:00.

FIELD GUIDE TO THE WHITE MARBLE MINE AND VICINITY

by

Stanley B. Keith, Stephen J. Reynolds, and
Stephen M. Richards

INTRODUCTION

As one drives southward on the dirt road leading to the White Marble Mine in the Harquahala Mountains, inspection of the slopes to the left and below the conspicuous conical peak on the skyline at 12:30 to 1:00 position, termed "the hat", reveals an inclined ledge (Figure 1). This ledge marks the trace of the Golden Eagle thrust (See below for definition and geographic distribution.).

Twenty kilometers southwest of the White Marble mine one may observe the same thrust 1.5 km northeast of the Golden Eagle mine. Here, vertically standing Paleozoic formations are spectacularly truncated by a flat fault that places the Paleozoic section on highly broken, but recognizable, porphyritic Precambrian granite.

The Golden Eagle thrust is one member of a major, regionally distributed series of low-angle thrust fault slices in the Harquahala and Little Harquahala Mountains (Figures 1, 2, & 3). Evidence of a former widespread Mesozoic event that completely inverted much of the Paleozoic section was severely overprinted and masked by the great thrust faults. The thrust faults were bowed, warped, and broken by subsequent late Cenozoic folding and faulting. In effect, the region consists of a vast thrust fault sandwich that was emplaced on a Mesozoic sedimentary and volcanic "basement" in the western Harquahala and Little Harquahala Mountains (Reynolds and others, 1980). As presently conceived, the thrust fault sandwich is composed of three major, regionally continuous plates (Refer to Figure 3 for nomenclature and location of the three plates.).

The lowermost plate is separated from the Mesozoic "basement" by the Hercules thrust, named for exposures near the Hercules mine in the western Harquahala Mountains. The overlying plate is designated the Hercules plate which corresponds to the lowermost Precambrian sheet of Reynolds and others (1980). The Hercules plate, in the Little and western Harquahala Mountains, consists entirely of crystalline rocks of probable Precambrian age. The middle plate is separated from the underlying Hercules plate by the Golden Eagle fault, named for excellent exposures of the fault at the Golden Eagle mine and vicinity in the Little Harquahala Mountains. The overlying plate is named the Golden Eagle plate which corresponds to the Paleozoic sheet of Reynolds and others (1980).

The Golden Eagle plate in the Harquahala and Little Harquahala Mountains consists almost entirely of Paleozoic rocks with local areas of Precambrian granite, beneath the lowermost Paleozoic unit, and local imbrications that contain granite of probable Precambrian age. The uppermost plate is separated from the underlying Golden Eagle plate by a fault designated as the Harquahala thrust because of its widespread distribution throughout the Harquahala Mountains.

In general, the Harquahala thrust has placed Precambrian(?) age amphibolite-grade metasedimentary, metavolcanic, and leucocratic plutonic rocks over Paleozoic rocks in the Golden Eagle plate. This uppermost plate is named the Harquahala plate and corresponds to the uppermost Precambrian crystalline sheet of Reynolds and others (1980).

Locally, the Harquahala plate rests directly on Precambrian crystalline rocks of the Hercules plate or it is separated from the Paleozoic rocks of the Golden Eagle plate by a thin thrust sheet of porphyritic granite in exposures within the Harquahala Mountains (the porphyritic granite sheet of Reynolds and others, 1980). This thrust is named the White Marble thrust for its conspicuous presence at the White Marble mine and vicinity. For reasons discussed at Location E, the White Marble thrust is considered part of the Golden Eagle plate. (Fig. 2)

The White Marble mine complex is situated virtually in the middle of the thrust fault pile. At the White Marble mine, an upside-down Paleozoic section comprises a thin thrust sheet of carbonate rocks which are tectonically sandwiched between the White Marble and Golden Eye thrust sheets.
A detailed look will be given to this thrust "stratigraphy".

WHITE MARBLE MINE ROAD LOG

Mileage From U.S. 60	
0.0	Turn south from U.S. 60 at mile post 66.7. Marble chip stockpile area and trailer mark the location of the exit. Road into marble stockpile area is gated. Once into marble stockpile area, bear slightly right through marble stockpiles following worn set of tracks. Once through the marble stockpiles, proceed down an excellent graded dirt road. (Cadillac grade when mine is being operated).
0.4	As you traverse south-southeast down the road, the following features will be in view. Harquahala Mountain is on skyline at 10:30 while the Marble mine (white scar not in full view yet) is at 12:05 low. Nipple-like feature on skyline ridge at 12:30 is referred to here as 'the hat'. 'The hat' is in the vicinity of much of the more choice thrust fault action in the region. Socorro Peak is the prominent peak at 1:00 with Tenahatchapi Pass at low spot on the skyline in the 2:00 position.
2.1	Windmill and water tank on right. The Harquahala thrust forms a subhorizontal ledge below the skyline ridge at 11-12:00. The ledge separates ledgy layers of amphibolitic grade Precambrian rocks in the Harquahala plate (in upper third of skyline ridge) from more knobby outcrops of mylonitic granite in lower two thirds of ridge. Prominent cliffs at 12:00 are Bolsa Quartzite within the Golden Eagle plate below the Harquahala plate.
2.6	Twin saguaros on left. 'The hat' is now at 1:00. Below 'the hat' is a prominent inclined ledge that from this view, slopes to the right and passes beneath prominent cliffs (up and to right) composed of Bolsa Quartzite. The inclined ledge marks the trace of the Golden Eagle thrust. In this area the Golden Eagle thrust truncates Bolsa Quartzite through Supai formation of the Paleozoic section.

3.0 Inselberg hill on right is composed of mylonitically foliated Precambrian porphyritic granite in the Hercules plate. Foothills at 10:00 are mainly composed of the above granite plus other more equigranular, mylonitic, leucocratic, alaskitic granitoids of presumed Precambrian age. Mylonitic foliation in these rocks strikes northeast and dips northwest. Lineation in the foliation planes plunges northwest. The mylonitic Precambrian rocks are intruded by a prominent microdiorite dike swarm of east-west to west-northwest strike, nearly vertical, that postdate the mylonitic deformation. Similar dikes elsewhere in the Harquahala Mountains have yielded K-Ar ages of 22.1 m.y. and 28.6 m.y. on biotite and hornblende respectively. (Shafiqullah and others, 1980).

4.0 Road to right. This road leads around the ridge to the west and to the canyon northeast of 'the hat' (a two-mile drive). Four-wheel drive is required. The road does provide good access to the thrust fault geology north of the hat. The White Marble mine is at 11:45 low and is partially screened from view by a narrow canyon that is comprised of steep cliffs of Bolsa Quartzite on either side.

4.3 Stream crossing. Hill and adjacent outcrops on right contain good exposures of the mylonitically foliated Precambrian granite. Foliation strikes northeast, dips northwest, and contains a northwest-plunging mineral lineation. Structurally, one is in the upper part of the Hercules plate at this juncture.

In the foliation planes of mylonitic varieties of porphyritic granite, within the Hercules plate north of the White Marble mine, a streaky mineral lineation is apparent and is composed of parallel alignments and trains of biotite and quartz. The mineral lineation trends WNW to NW (see Figure 4). Linear structural elements within more mylonitic porphyritic granite, in the upper part of the Hercules plate, have a different orientation. At, or near, the Golden Eagle thrust the lineation trends are more northerly to north-northeasterly and have a slickensided aspect (Fig. 5). This style and orientation of lineation is also present in mylonitic granite immediately below the Harquahala thrust in the White Marble plate. It is our impression that these two lineations represent a difference in structural style of lineation rather than a change in orientation of the same lineation. We will inspect the north-trending linear structural elements in mylonitic granite of the White Marble Thrust sheet between Locations B and C (Fig. 5).

4.5 Parking area on right. The road ahead is commonly blocked by a locked cable. The Field Trip Stop will begin here. The full traverse will take about 2 hours so take the usual precautions. From here navigation will be according to the geologic map provided. Participants will continue 100 m up the dirt road to Location A which is a roadcut exposure of the Bolsa/granite contact.

WHITE MARBLE MINE TRAVERSE

LOCATION A. BOLSA QUARTZITE/PORPHYRITIC GRANITE CONTACT

The contact between the Bolsa Quartzite and porphyritic granite dips 25 degrees to the south at Location A. The granite beneath this contact is weakly sheared but not to the degree expected at a major thrust surface. The Bolsa Quartzite here consists of coarse grained arkose with the feldspar detritus identical to that in the underlying granite. The basal arkose rapidly grades upward into a well-sorted, medium-to fine-grained, feldspathic quartzite. From these facts, we interpret that this is a deformed depositional contact which is similar to other exposures in the Harquahala and Little Harquahala Mountains.

We have now passed into the Golden Eagle plate. The Golden Eagle thrust is concealed by surficial gravel veneer but occurs between Location A and the parking area.

LOCATION A to LOCATION B

From the Bolsa Quartzite-porphyritic granite contact, continue southeast, up the road, towards the White Marble mine. While walking, note that the Bolsa Quartzite steepens in dip to a nearly vertical position. Also, notice that a flat-dipping, locally penetrative, fracture cleavage is present in the quartzite. We interpret that this fracture cleavage formed during thrusting because of its parallel alignment with the major thrusts; here, the Golden Eagle thrust occurs about 50 meters beneath the road. Prior to leaving the quartzite and entering the White Marble mine area, note that the Bolsa Quartzite is overturned in the wash that is west of the road.

The bulldozer cuts, seen upon entering the White Marble mine area, are in metamorphosed, fine-grained dolomites of the Martin Formation. Walk 100 yards into the mine area and look west. Climb the hill with the prominent subhorizontal ledge of Bolsa Quartzite; Location B is at the top of this ledge.

During your climb, look for purplish, slaty fragments and outcrops of phyllitic shale between the light-colored dolomitic marble; these rocks are metamorphosed Abrigo lithologies. By the time you have reached the quartzite ledge, it should be apparent that you have traversed an overturned, lower Paleozoic section.

LOCATION B. RECUMBANT FOLD AND HARQUAHALA THRUST OVERVIEW.

From the top of the ledge, look northeast and observe the reason for the overturned Paleozoic section you just saw. Although a fold is not immediately obvious, the following evidence can deduce its presence. First, focus on the overturned Bolsa Quartzite that you observed west of the road upon entry into the White Marble mine. You will notice a slope-forming unit between the quartzite exposure and the bulldozer scars cut in dolomitic marble of the Martin Formation . There, the Abrigo Quartzite dips about 60° NNW in lower parts of the hill and flattens near the top of the low ridge. The quartzite-Abrigo contact can be traced northeast up the low ridge. Near the top of the ridge, the contact flattens, as marked by a southeastward deflection in the Bolsa Quartzite/Abrigo contact on the geologic map.

Dozer cuts occur in metamorphosed Martin at the north end of the White Marble mine. There, the Martin is overlain by overturned, flat-lying Bolsa Quartzite and metamorphosed Abrigo that form the low ridge above the cuts. This relationship is identical to the inverted Bolsa Quartzite that you are standing on.

We have mapped a fold hinge where the flat-lying, inverted Bolsa/Abrigo section gives way to the steeply overturned Abrigo/Bolsa section. The trace of the fold hinge crosses the top of the low ridge west of the White Marble mine and follows the small, southwest drainage located between the cuts in the marble and the northeast-trending Bolsa Quartzite ridge. The fold hinge then continues southwestward up the ridge we are now on and crosses the ridge about 100 m north of Location B. The axial plane of the fold dips about 30° south-southeast. As mapped, this fold represents a recumbant synclinal fold. Because the fold opens southeastward, it can be interpreted that the fold represents the lower half of a giant, nappe-sized, recumbant fold that is overturned towards the southeast. As such, the structure indicates tectonic transport from northwest to southeast or southeastward vergence. This fold exposure represents the best locality we have found thus far for the southeast vergent folding formed during the pre-Laramide, Mesozoic deformation. The top half of the fold was completely decapitated by the Harquahala thrust in the White Marble mine area.

The Harquahala thrust is also present on the ridge west of the White Marble mine. The position of this thrust occurs just above the road near the top of the ridge and above the light-colored outcrops of Paleozoic carbonate rocks. The road is cut in slope-forming, mylonitic, porphyritic granitoid rocks of the White Marble sheet.

At the White Marble mine below, the White Marble thrust occurs at the contact between the brownish slope-former and more irregular, light-colored, cliffy knobs of the metamorphased Martin and Escabrosa Formations. A similar relationship occurs west of the White Marble mine, (southwest of Location A) and will now be the object of your scrutiny.

Just before you leave Location B and walk southwestwards (Fig. 7), the following observations will provide perspective for what you are about to walk through. Location B is on a flat, table-like bench at the top of an inverted Bolsa Quartzite section. The grass-covered slopes, immediately southwest of this bench, are underlain by mylonitic granitoid rocks of the White Marble sheet. Hence, the break in slope between the quartzite bench and the granite represents the White Marble thrust. It is now clear that Location A is located virtually at the White Marble thrust surface. A careful search of the quartzite will reveal numerous north-south-trending slickensides (Fig. 5) that reveal the transport direction of the White Marble thrust.

Above Location B, a conspicuous 5 to 10 m thick, dark-green ledge, seen above the grass-covered slopes, is ultramylonitic granite which directly underlies the Harquahala thrust. Here, the White Marble thrust sheet is about 50 to 75 m thick. The alternating slopes and ledges above the ultramylonitic ledge are transposed amphibolite-grade rocks of the Harquahala plate.

With this framework in mind, you can make sense of some of the ledges in the distant main ridge of the Harquahala Mountains located about a km northeast of the White Marble mine. The dark brownish-green ledges occur at several intervals on the middle slopes of the north-facing side of the main ridge. All of the conspicuous ledges are exposures of ultramylonitic, porphyritic granite that are immediately beneath the Harquahala thrust.

Subsequent offset of the Harquahala thrust by northwest-trending faults has caused the ledges to be at different elevations (Fig. 7). The first of the more subdued ledges, above the prominent ultramylonite ledge, contain locally abundant 'S' and 'Z' fold structures. We will see a good exposure of these folds in the Harquahala plate, above the ultramylonite ledge, on the east side of the ridge we are now on. Those interested in folds will find superb exposures of these structures in the upper part of the ultramylonite ledge within the Harquahala thrust zone.

LOCATION B to LOCATION C

As you leave Location B and climb the grass-covered slopes, you will encounter poor exposures of the mylonitic granite. A careful search will reveal the presence of relict feldspar augen. If luck prevails, a few "box car" feldspars can be found, especially near the middle of the White Marble sheet.

As you climb towards the ultramylonite ledge, note how the grain size and distance between foliation planes lessens until, at the mylonite ledge, all that remains of the original feldspars are a few strung-out, faint, light-colored wisps. Lineations trend northerly, within the shallow, inclined, mylonitic foliation planes, and are parallel to slickensides developed in the Bolsa Quartzite, near Location B, that were formed on the White Marble thrust. The mylonite ledge marks the position of the Harquahala thrust zone located near, or at the top of, the ledge.

Once on top of the ultramylonite ledge, you are now at the base of the Harquahala plate. This plate is widespread throughout the higher elevations of the main mass of the Harquahalas for a few kilometers east and northeast of the White Marble mine.

From the top of the ultramylonite ledge, one can climb up a slope-covered interval to examine the subhorizontal ledges in the lower part of the Harquahala plate. The original Precambrian fabric was thoroughly obliterated and transposed by foliation that is sub-parallel with, and probably related to, the Harquahala thrust. Locally, this foliation is folded. The rock here is an amphibolite-grade, aphanitic felsite (possibly a silicic metavolcanic) interfoliated with darker quartz-feldspar-mica schistose rocks (possibly a metasediment). Quartz veins and segregations are common and, indeed, characterize many exposures in the lower part of the Harquahala plate.

Once the amphibolite grade rocks have been perused, contour around the ridge to the east staying in the Harquahala plate about 10 m above the Harquahala thrust. A study of the more cliffy ledges, at Location C, will quickly reveal numerous folds that deformed the subhorizontal foliation and are thought to be related to thrusting.

LOCATION C. FOLDS RELATED TO THE HARQUAHALA THRUST.

The folds exposed in the cliffy ledge are typical of many of the folds found at, or just above, the Harquahala thrust. Twenty-one fold axes, measured from various localities at this structural level, show a preference for an east-west direction. These axes are nearly orthogonal to slickensides in quartzite at the base of the White Marble thrust and to lineation directions in mylonitic granite within the White Marble plate (Fig. 5).

Asymmetry of 'S' and 'Z' folds is overwhelmingly northeast with middle limbs dipping southerly. However, as you can see at this outcrop, a few folds exhibit southerly asymmetry. The middle limbs of those folds are commonly detached from upper and lower hinges by small reverse faults and, locally, 'S' and 'Z' fold pairs are present which exhibit opposing asymmetries (double vergence) and display conjugate 'box' fold geometries. The box folds suggest north-south shortening associated with the thrusting, whereas the preferred northward asymmetry, or vergence, suggests northward transport for the thrusting.

After viewing those folds, move down the slope and upstream towards the main road in the White Marble mine.

LOCATION C to LOCATION D

Once at the main road, proceed southwards, up the road, to the furthest upstream quarry accessible by the main road. Marble mined here is generally used for decorative purposes (rooftops, etc.) in the Phoenix area. As you walk up the road, you will pass through overturned Martin Formation, the lower, massive, brownish, metamorphosed Escabrosa limestone and the upper, thin-to-medium-bedded, cherty marble member of the Escabrosa Limestone. These beds generally dip gently to the northwest.

Commonly, this pattern is complicated by local folding and by offsets of numerous east-west-striking faults that postdate the thrusting. Mesocratic, microdiorite dikes of middle Tertiary age are commonly present along the faults. One of these dikes intrudes carbonates of the Escabrosa Limestone along the road about .5 km SSE of Location C (Fig. 7). The White Marble thrust is exposed near the top of both ridges that flank the White Marble mine complex where the fault dips gently to the north, parallel to layers in the underlying Paleozoic carbonate rocks.

At the hairpin turn, located 0.5 km SSE of Location E, leave the road and walk towards the slope on the west side of the stream which is south of a prominent knob of Escabrosa carbonate rocks. This slope consists of the overturned, metamorphosed Supai Formation. Various clastic-dominated lithologies can be seen on the way up the hill towards an abandoned road. The metamorphosed Supai is separated from the Escabrosa marble knob, to the north, by one of the more prominent east-northeast-striking faults in the White Marble mine area.

While metamorphosed Supai slope contains siltstones, quartzites and abundant phyllites, much carbonate material is present; much more than is typical of the Supai stratigraphy present along the southern edge of the Colorado Plateau. Carbonate-rich areas in many of the siltstone units have been dissolved by surface erosion and contain a distinctive texture that resembles termite holes in rotten wood. This 'termite effect' is diagnostic of Supai and metamorphosed equivalents throughout the Harquahala and Little Harquahala Mountains.

The knob of Escabrosa Limestone, located above the bulldozed road, contains a rather picturesque 'Z' fold in the carbonate rocks. This fold is a good example of inconspicuous, but significant, folding that locally pervades the carbonate section. Twenty-three fold axes, measured from folds with definite asymmetry within Paleozoic rocks of the Golden Eagle plate, cluster in two populations around an east-west axis (Fig. 6).

Linear fabrics from foliation surfaces in Paleozoic strata strongly show a preference for north-south bearings. The phyllitic lithologies of the metamorphosed Supai Formation commonly display these lineations. We interpret that the lineation represents the line of tectonic transport.

Asymmetry of the folds shows an overwhelming preference for northward overturning (look again at the knob). It is instructive to note that an impressive geometric similarity exists between structures in the Paleozoic rocks of the Golden Eagle plate and structures at, or just above, the Harquahala thrust in the Harquahala plate (compare Figs. 5 and 6).

LOCATION D. OVERTURNED CONTACT BETWEEN THE ESCABROSA LIMESTONE AND SUPAI FORMATION.

The abandoned road you reached was cut along the contact between the Escabrosa Limestone and Supai Formation. Because the older Escabrosa Limestone rests on top of the Supai, you have just climbed through an overturned Paleozoic section. This reaffirms our interpretation that the Paleozoic section at the White Marble mine is inverted.

In these road cut exposures, the contact between the Escabrosa and Supai is placed where cherty, thin-bedded carbonate rocks of the upper Escabrosa Limestone overlie phyllitic schists of the lowest Supai Formation. Small pods and lenses of chert-pebble conglomerate and breccia occur at the base of the Supai Formation in an area 100 m south of Location D (Wes Peirce, 1980 oral communication). These rocks strongly resemble similar lithologies present in basal Supai units from less metamorphosed exposures in the Little Harquahala Mountains. Although the basal contact of the Supai Formation is tectonized at Location D, we are confident that only minor tectonic transport occurred (Fig. 7).

At the White Marble mine, at least 1 km of overturned section was confirmed along a line that is perpendicular to the fold hinge described at Location B. This inversion involves units of Bolsa Quartzite through the Supai Formation. Thus, a feeling for the dimension of this large, nappe-sized fold can be obtained.

An even more impressive section of overturned Paleozoic strata was mapped 2 km south of the White Marble mine in the vicinity of the Silver Queen mine. Map relationships here and near the Silver Queen mine suggest that the length of the middle limb of the southeast overturned nappe is between 1 and 2 km.

LOCATION D to LOCATION E

When you reach the bulldozer road you will be at Location D. Proceed southward to the end of this road and contour along the slopes to an animal trail that descends to the stream bed about 0.3 km SSE of Location D. Move upstream to Location E (Fig. 7). The geology between Locations D and E consists of overturned and metamorphosed units of the Escabrosa Limestone and the Supai Formation.

Numerous east-west-trending, post-nappe, normal faults formed small horst and graben structures in the Paleozoic units. The Supai Formation, west of the stream is juxtaposed against strata of the upper Escabrosa Limestone by a north-striking fault mapped in the drainage (Fig. 7). As you enter the stream bed, the initial lithologies consist entirely of overturned, metamorphosed Supai strata. Soon, another brownish-gray, slope-forming unit will be seen beneath the prominent ledges of Supai. This rock, and its relationship to the overlying, upside-down Supai Formation will be the object of our scrutiny at Location E.

LOCATION E. GOLDEN EAGLE THRUST.

By the time you reach Location E you probably guessed that the punky, brownish-gray rock you are walking on is mylonitic granite. Comparatively undeformed 'box car' feldspar relicts are common in exposures on the west side of the stream at Location E. The mylonitic Precambrian granite rests in the Hercules plate which here is tectonically overlain by overturned Supai Formation which rests in the Golden Eagle plate.

The Golden Eagle thrust separates the cliff-forming, reddish-brown Supai Formation from the lower, slope-forming mylonitic granite. Here, this thrust dips gently to the north. Paleozoic units that comprise the Golden Eagle plate, west of Location D, total 100 m thick. Upstream from Location D, at the White Marble mine, the plate measures 200 m thick between the Golden Eagle and White Marble thrust faults. The Paleozoic thrust sheet becomes progressively attenuated until it thins to a few meters thick near the ridge crest that is west of Location D. A good view of this tectonic thinning is available from the ridge west of Location E.

The Paleozoic thrust sheet is absent 1 km northwest of Location D. There, mylonitic Precambrian granite, of the White Marble plate, is separated from mylonitic Precambrian granite, of the Golden Eagle plate, by a 30 m thick zone of ultramylonite. It is interesting that the ultramylonite zones, associated with the Golden Eagle thrust, are thin or absent when that thrust involves Paleozoic rocks, as at Location E, while these zones are 10 to 30 m thick when the thrust occurs entirely within granite, as seen 1 km northwest of 'the hat'.

The ridge top west of Location D is composed of mylonitic Precambrian granite of the White Marble plate. Although this plate is present throughout the White Marble mine area, we consider that the White Marble plate is an imbrication within the Golden Eagle plate because of relationships seen at the Silver Queen mine and at 'the hat' which are located 1 ½ to 2 km south and southwest of the White Marble mine.

Recent mapping between the Silver Queen and Hidden Treasure mines (Fig. 7) disclosed that the Harquahala plate rests directly on the Golden Eagle plate with no intervening porphyritic granite sheet. Hence, the White Marble thrust cannot be traced regionally. Also, the geographic feature termed 'the hat' is capped by a small outcrop of Paleozoic carbonate (possibly metamorphosed Martin Formation) which rests, tectonically, on a thin, 50-75 m thick thrust sheet of mylonitic granite that is similar in structural position, thickness, and lithology to the foliated granite found in the porphyritic granite sheet by Reynolds and others (1980) in an area 0.5 km east of 'the hat'. The presence of a Paleozoic carbonate section above the foliated granite suggests that small pods of Paleozoic rock might be present locally between the granite sheet and the Harquahala plate.

Location E is the last stop of our field guide. Participants can most easily return to the White Marble mine by hiking a short distance downstream from Location E and climbing the ridge east of the stream. Once on top of this ridge, a dirt road that provides easy access back to the main quarries can be seen on the next ridge to the east.

White Marble to 'S' Mountain

Mile Post	
	Return to U. S. 60 and turn west (left).
61.5	Intersection on right with Alamo Dam road. This road provides the main access to portions of the central Harcuvar Mountains at Cunningham Pass.
57.6	International Inn in the metropolitan Salome area (our main staging area for field work in the area).
56.7	Salome town limit. Cross a short bridge and make a left turn onto Buckeye Road one block beyond bridge.
0.0	Left onto Buckeye road. Begin cumulative mileage here.
0.3	Y intersection with Harquahala Mine road on right. We will return to this intersection after the 'S' Mountain Window Stop.
2.0	Cross Centennial Wash. Centennial Wash, from here for next several miles downstream, crosses a bedrock sill (largely in Precambrian granite) between the Harquahala and Little Harquahala Mountains. This sill is largely a pediment surface that separates the ground water basin in McMullen Valley from that under the Harquahala Plain south and southwest of the Harquahala and Big Horn Mountains.
2.1	Intersection on left. Well graded dirt road leads to Centennial Park which provides camping facilities and to Wenden and U. S. 60.
3.9	House with trees on right. Look for dirt road on left.
4.0	Turn left onto dirt road for S Mountain stop. Prominent ledge former on top of, and south of, S Mountain is a quartzite marker ledge in a structural window of clastic-dominated Mesozoic-aged sedimentary rocks.

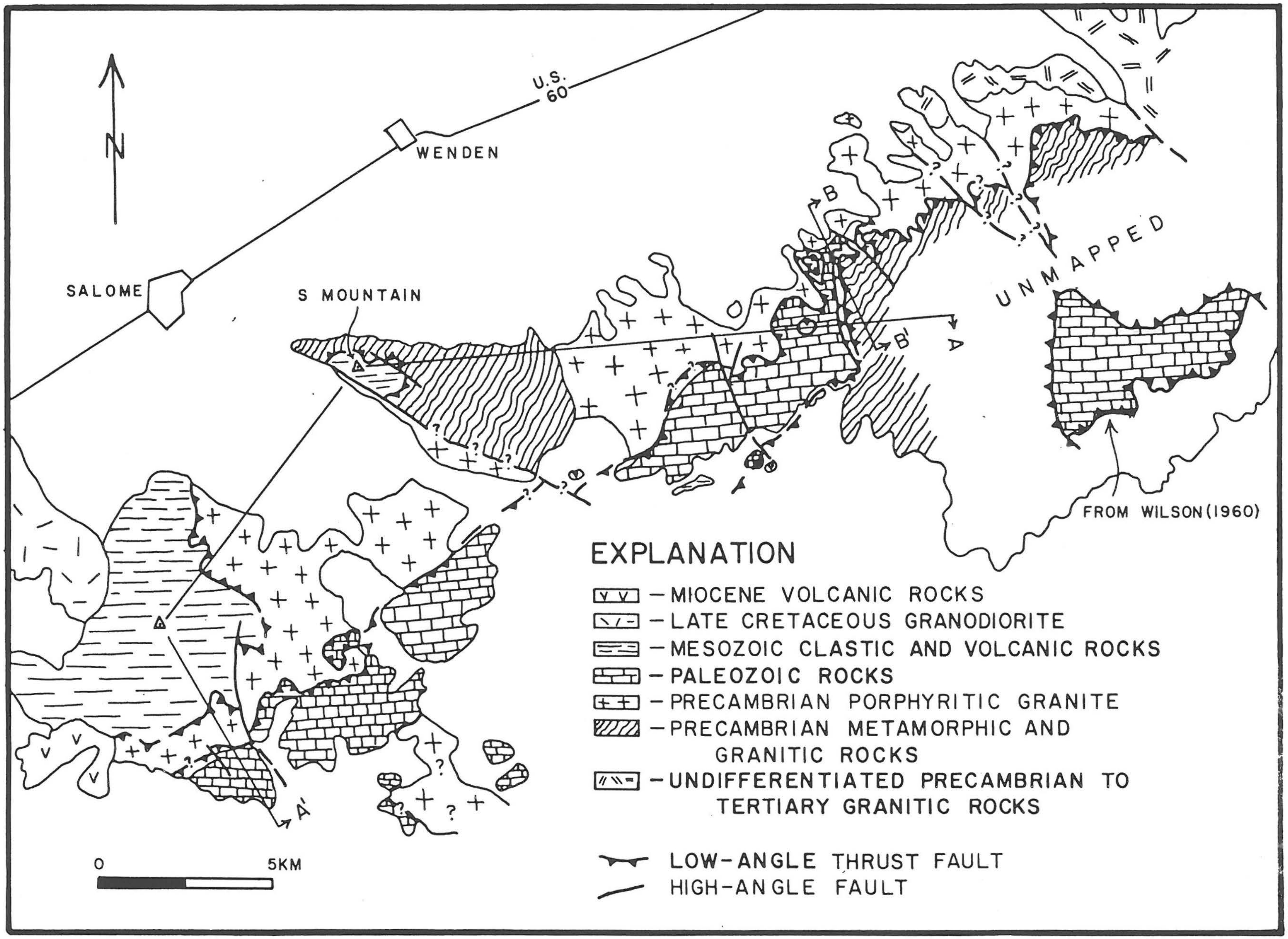


Fig. 1. Generalized geologic map of the western Harquahala Mountains and Little Harquahala Mountains. Includes data from Wilson (1960), Varga (1976, 1977), Rehrig and Reynolds (1980), and new geologic mapping by S. B. Keith and S. J. Reynolds.

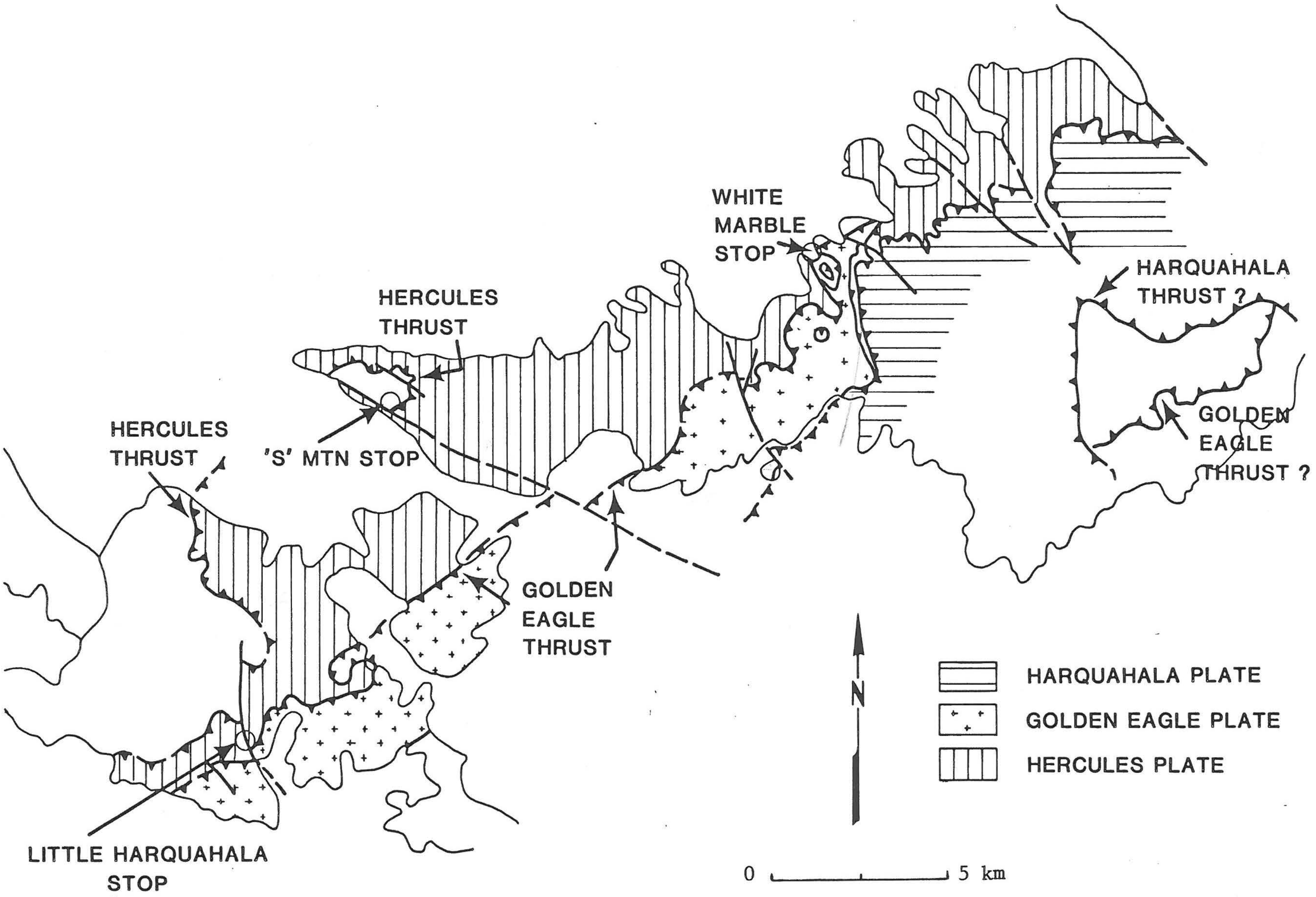


Figure 2. Proposed terminology for Laramide thrust plates in the Harquahala and Little Harquahala Mountains, west-central Arizona.

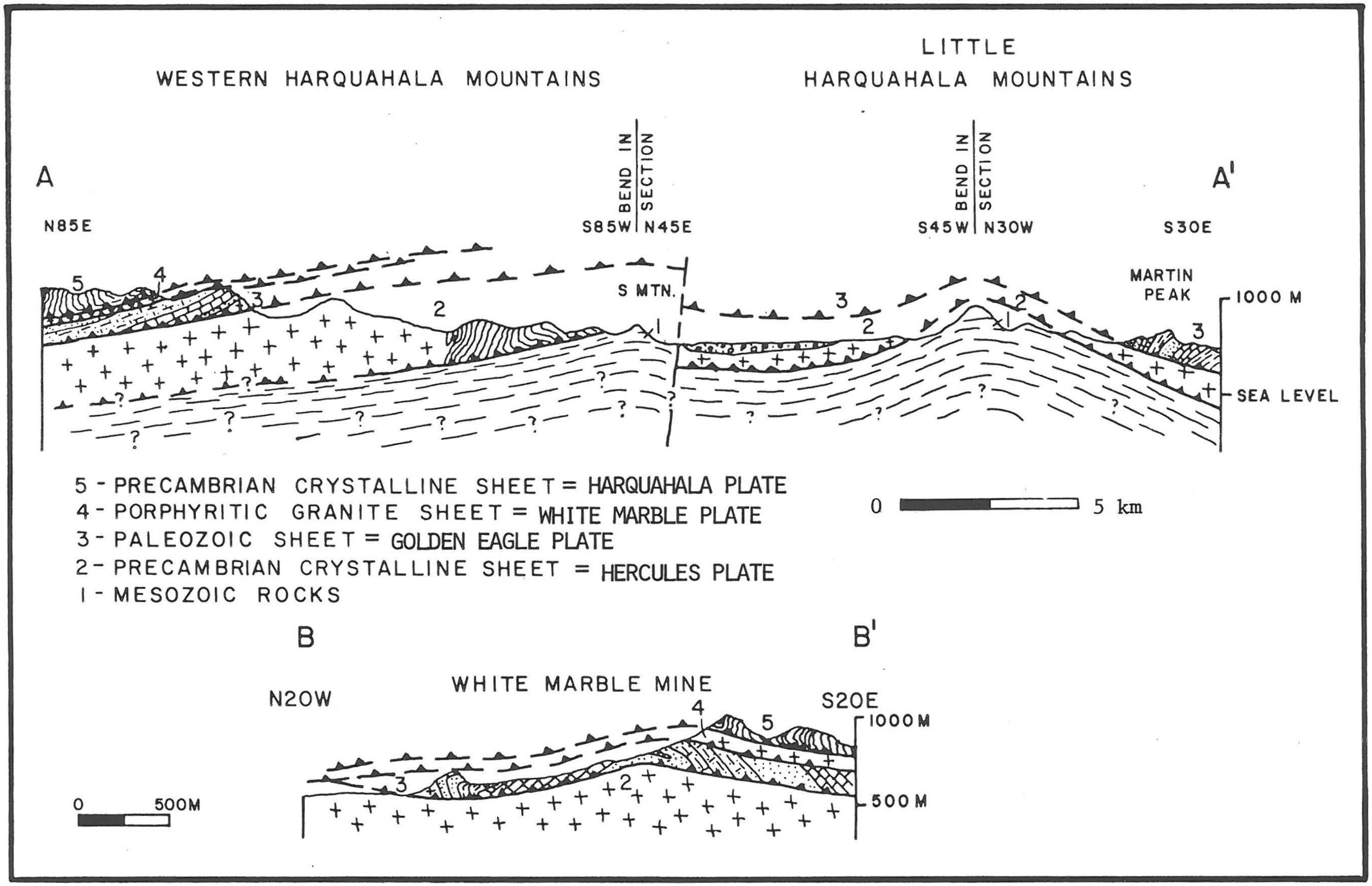
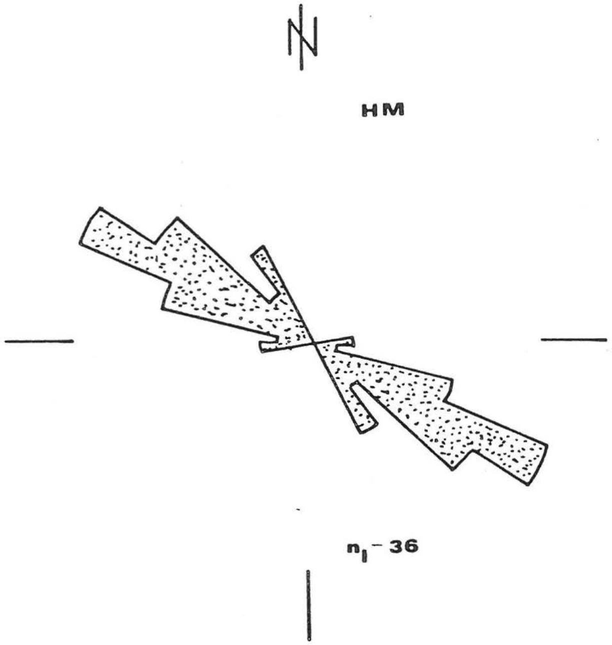
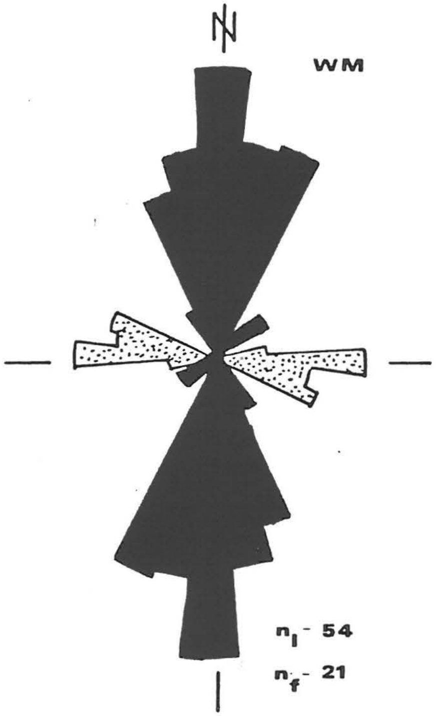


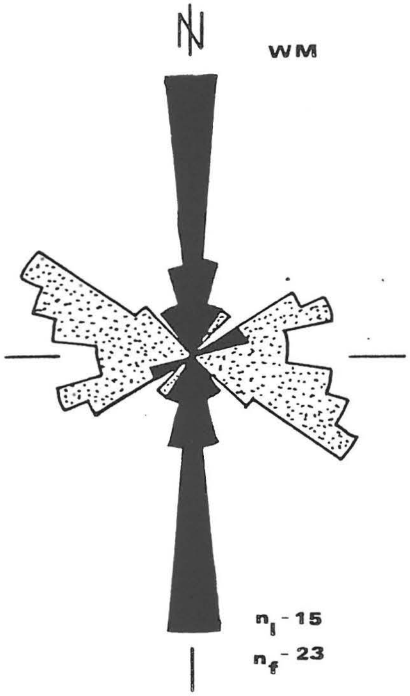
Fig. 3. Schematic cross sections A-A' and B-B'. See Figure 2 for location of cross sections. Note that A-A' is viewed to the south and east.



4



5



6

Figure 4. Trend rosette diagram for lineations in porphyritic granite within Hercules plate north of White Marble mine.

Figure 5. Trend rosette diagram for lineations in mylonitic granite within White Marble plate and uppermost Hercules plate and for folds near or at Harquahala thrust. Fold axes are represented by a stipple pattern.

Figure 6. Trend rosette diagram for linear elements and fold axes from Paleozoic rocks within Golden Eagle plate. Fold axes are represented by a stipple pattern.

'S' Mountain Stop.

The Hercules thrust is well exposed in the area around 'S' Mountain. This thrust is a low-angle fault that places Precambrian crystalline rocks over somewhat metamorphosed Mesozoic sedimentary rocks. The Mesozoic section includes a lower unit of feldspathic sandstone and arkose, overlain by calcareous strata, ledgey quartzite, and a streched-quartz-pebble conglomerate. The upper-plate of the fault has crystalline rocks of Precambrian age. These include foliated quartz diorite, dioritic gneiss, amphibolite, quartzo-feldspathic gneiss, and a foliated leucocratic granitic rock that locally immediately overlies the low-angle fault. Lineation in the upper and lower plate rocks is parallel and generally north- to north-northeast-trending. Minor structures indicate that the direction of transport is parallel to the lineation. This transport direction is consistant with that documented for faults of the White Marble Mine area. We interpret the Hercules thrust to be offset by a north-northwest-trending fault that nearly follows the present-day course of Centennial Wash. According to this interpretation, the east side of the fault has been uplifted relative to the west side.

The Hercules thrust is easily observed by climbing up to the conspicuous ledge that is visible on a number of small hills. This ledge is composed of the resistant quartzite and quartz-pebble conglomerate that immediately underlies the Hercules thrust. After examining the thrust, return to the cars and drive back to the intersection of the Buckeye-Salome Road and the road to the Harquahala Mine. At this intersection, bear hard to the left onto the Harquahala Mine Road and begin new cumulative milage.

SUPLEMENTAL ROAD LOG - LITTLE HARQUAHALA MOUNTAINS

Cumulative
Milage

0.0 - Intersection of the Buckeye-Salome Road and the Harquahala Mine road. Facing south-southwest parallel to the road, Harquar Peak is the prominant peak at 12:00. It is undelain by an assortment of Mesozoic sedimentary and volcanic rocks. The Granite Wash Mountains are located at 3:00. They are composed of a similar Mesozoic sequence and two late Cretaceous plutons (the older Tank Pass Granite and the younger Granite Wash Granodiorite). These rock units are intruded by a dramatic north-northwest-trending swarm of middle Tertiary dikes.

3.0 - Entering the Little Harquahala Mountains. Small hills to the right at 3:00 are Precambrian crystalline rocks that occur in the upper plate of the Hercules thrust. In these hills, locally deformed biotite-rich granite is the predominant rock unit.

3.5 - Road to right. Continue straight. Hills to left and right are in Hercules thrust plate.

4.4 - Low ridge on the right contains the Hercules thrust on its west side. Rocks visible from the road consist of Precambrian granite that overlies the thrust.

4.6 - Cross wash. Road in wash leads to exposures of the Hercules thrust. Road to left leads to the Rio Del Monte Mine area. The Rio Del Monte Mine consists of workings within quartz veins that cut the upper-plate rocks.

Cumulative
Milage

5.2 - Trailers on right side of road. Rocks in this area consist of altered Precambrian granite that occupies the upper plate of the Hercules thrust. The Hercules thrust is exposed along the break in slope along the east side of Harquar Peak. The peak itself is underlain by coarse- to fine-grained clastic rocks of Mesozoic age along with fewer exposures of Mesozoic volcanic rocks. Both series of Mesozoic rocks occur in the lower plate of the Hercules thrust.

5.5 - The Hercules thrust crosses the road but is very poorly exposed and difficult to trace due to alteration of both upper and lower plate rocks. Mesozoic rocks occur along the road for the next mile and consist of dark, intermediate volcanics which are locally highly altered.

6.5 - Road crosses the trace of a north-trending, east-dipping, high-angle fault which has undergone normal and possible strike-slip movement. This fault offsets the Hercules thrust and juxtaposes upper and lower plate rocks (lower-plate Mesozoic rocks lie to the west of the fault).

7.0 - Prospect on the right of the road is located along the high-angle fault.

7.4 - Park cars for traverse to Hercules thrust and upper and lower plate rocks. Stop 1.

Stop 1 - Little Harquahala Mountains Traverse.

In this stop, we will examine the Hercules thrust and lithologies of the upper and lower plates. Lower-plate rocks consist of Mesozoic clastic rocks that range from conglomerate to siltstone. Volcanic-derived detritus is locally very abundant. Volcanic rocks are also present below the Hercules thrust, but few volcanic rocks will be observed along this traverse. In this area the Hercules thrust dips very gently to the SSE and projects over the top of Harquar Peak. Above the fault are Precambrian granitic rocks which are commonly altered. In a few exposures, Precambrian metamorphic rocks accompany the granitic rocks in the upper plate of the thrust. Slivers of Paleozoic rocks occur in some exposures of the thrust. Minor structures along the thrust indicate that transport was to the north-northeast.

This is the last stop of the field trip unless time permits examination of the Paleozoic section and of significant gold mineralization at Martin Peak. The easiest way to Tucson follows the Harquahala Mine - Hovatter Road south to Interstate 10.

Figure 7. Geological map of White Marble mine and vicinity. Symbols are as follows: p€g = mylonitic porphyritic granite (protolith equals probable 1400 m.y. biotite granite) and minor amounts of probable Precambrian alaskitic granitoids; €b = Cambrian Bolsa Quartzite; €a = Cambrian Abrigo Formation; Dm = Devonian Martin Formation; Me = Mississippian Escabrosa Limestone; PIPs = Permian-Pennsylvanian Supai Formation; Pc = Permian Coconino Sandstone; Pk = Permian Kaibab Formation; M = ultramylonite at Harquahala thrust. Diamond-shaped arrows are slickensides; arrows are lineation on foliation surfaces. P€m = Precambrian age amphibolite grade metavolcanic and metasedimentary rocks locally intruded by probably Precambrian age alaskitic rocks.

VERY SELECTED REFERENCES

Avedisian, G. E., 1966, Geology of the Phoenix South Mountain Park, Arizona: M. S. Thesis, Arizona State University, 54 p.

Banks, N. G., 1980, Geology of a zone of metamorphic core complexes in southeastern Arizona: Geological Society of America Memoir 153, in press.

Briscoe, J. A., 1967, The general geology of the Picacho Peak area: Masters Thesis, University of Arizona, Tucson, 52 p.

Davis, G. H., 1980, Structural characteristics of metamorphic core complexes, southern Arizona: Geological Society of America Memoir 153, in press.

Keith, Stanley B., Reynolds, S. J., Damon, P. E., Shafiqullah, M., Livingston, D. E., and Pushkar, P. D., 1980, Evidence for multiple intrusion and deformation within the Santa Catalina-Rincon-Tortolita metamorphic core complex: Geological Society of America Memoir 153, in press.

---, 1979, The treat wouthwestern Arizona oil and gas play: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 9, no. 1, p. 10-15.

---, 1980, The great southwestern Arizona oil and gas play: Drilling commences: Arizona Bureau of Geology and Mineral Technology Fieldnotes, v. 10, no. 1, p. 1-3, 6-8.

Keith, Stanton, B., 1978, Index of mining properties in Yuma County, Arizona: Arizona Bureau of Geology and Mineral Technology Bulletin 192, 185 p.

Rehrig, W. A., Shafiqullah, M., and Damon, P. E., 1980, Geochronology, geology, and listric normal faulting of the Vulture Mountains, Maricopa County, Arizona: Arizona Geological Society Digest 12, p. 89-110.

--- and Reynolds, S. J., 1980 Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic complexes in southern and western Arizona: Geological Society of America Memoir 153, in press.

Reynolds, S. J., 1980, Geologic framework of west-central Arizona: Arizona Geological Society Digest, v. 12, p. 1-16.

--- and Rehrig, W. A., 1980, Mid-Tertiary plutonism and mylonitization, South Mountains, central Arizona: Geological Society of America Memoir 153, in press.

---, Keith, S. B. and Coney, P. J., 1980, Stacked overthrusts of Precambrian crystalline basement and inverted Paleozoic sections emplaced over Mesozoic strata, west-central Arizona: Arizona Geological Society Digest, v. 12, p. 45-51.

Varga, R. J., 1976, Stratigraphy and superposed deformation of a Paleozoic and Mesozoic sedimentary sequence in the Harquahala Mountains, Arizona: M. S. Thesis, University of Arizona, Tucson, 61 p.

Wilson, E. D., 1960, Geologic map of Yuma County, Arizona: Tucson, Arizona Bureau of Mines; scale 1:375,000.

---, Moore, T. R. and Peirce, H. W., 1957, Geologic map of Maricopa County, Arizona: Arizona Bureau of Geology and Mineral Technology County Map Series.

---, Moore, R. T. and Cooper, J. R., 1969, Geologic Map of Arizona: Washington, DC, Arizona Bureau of Mines and U. S. Geological Survey Map, scale 1:500,000.

Yeend, W., 1976, Reconnaissance geologic map of the Picacho Mountains, Arizona: U. S. Geological Survey map MF-778, scale 1:62,500.