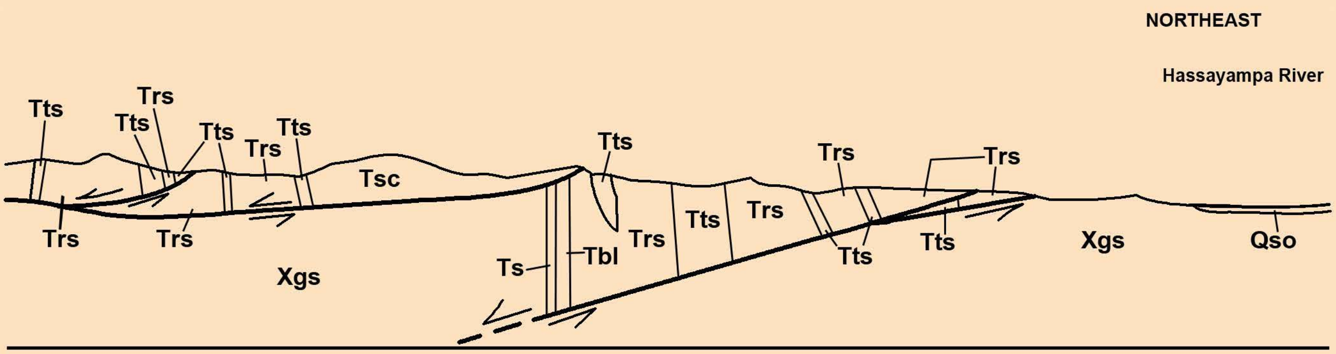
Field Guide to the New Waddell Dam Site, Vulture-Hieroglyphic Mountains area, and Mystic, Clemontine, Newsboy, and Yarnell gold deposits, Central Arizona

Edited by

Stephen J. Reynolds

Arizona Geological Survey



Arizona Geological Society Field Trip

December 8 and 9, 1990

Arizona Geological Society

P.O. Box 40952

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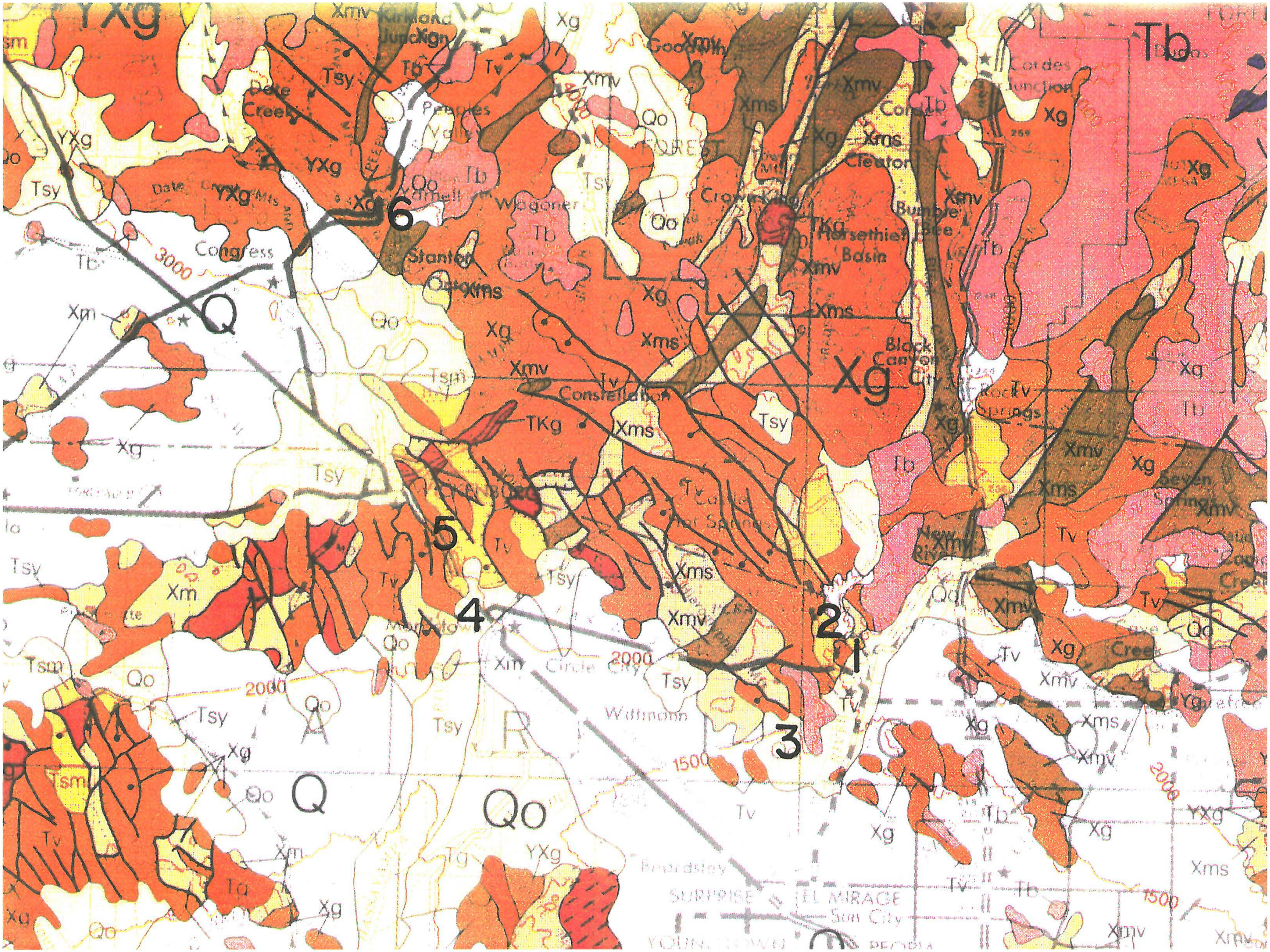
Cover illustration from Grubensky, M.J.,, 1990, Geologic map of the Vulture Mountains, west-central Arizona: Arizona Geological Survey Map 27, 1:24,000, 3 sheets.



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Geologic Highlights and Route of the December 1990

Arizona Geological Society Field Trip

Stephen J. Reynolds

INTRODUCTION

This short article summarizes the geologic highlights of the December 1990 AGS Field-Trip route from Phoenix to Yarnell via Wickenburg and the Lake Pleasant region. Previously released road logs for the Carefree-Wickenburg Highway (AZ 74) and for connecting roads (I-17 and US 60) are included elsewhere in this field-trip guide.

START OF TRIP AND STOP 1:

SCENIC OVERLOOK AND NEW WADDELL DAM SITE

(Leaders: Mike Pryor, U.S. Bureau of Reclamation
and Steve Reynolds, Arizona Geological Survey)

Route: The field trip begins at the Scenic Overlook near Lake Pleasant, between Wickenburg and I-17 north of Phoenix. To reach Stop 1, take I-17 north from Phoenix and exit onto AZ 74, the Carefree Highway (exit 223). Proceed west on AZ 74 to the stop sign about 6 miles west of I-17 and turn right, following AZ 74 to the north. After another 2.3 miles, the road gradually turns to the west and heads toward the Agua Fria River. Drive 0.1 miles west of the Agua Fria River, turn right (north) onto the paved road, and proceed to the Scenic Overlook at the end of the road. The road to the overlook crosses flat-lying Tertiary conglomerate that overlies Miocene basalt, rhyolite, and tuff.

Geologic Highlights: The southern and eastern Hieroglyphic Mountains were mapped during 1985 to 1988 as part of the Arizona Geological Survey (AZGS) - U.S. Geological Survey Cooperative Geologic Mapping Program (COGEOMAP). Two 1:24,000-scale AZGS geologic maps cover most of the region adjacent to Stop 1 (see maps and text by Capps and others and Wahl and others included in this field guide) and more detailed maps of the New Waddell Dam site have been made by Bureau of Reclamation geologists. Mapping revealed that the area consists of Proterozoic metavolcanic, metasedimentary, and granitic rocks overlain by lower to middle Miocene mafic flows, felsic flows with associated proximal tuffs, and syntectonic clastic rocks. The Tertiary volcanic units dip eastward, generally at 30 to 60 degrees, and are cut by numerous southwest-dipping normal faults. The volcanic rocks are overlain by clastic rocks that were deposited during faulting and tilting and that show fanning dips (moderate dips at the base of the section to subhorizontal dips at the top). This domain of east- to northeast-tilted Tertiary fault blocks extends from the edge of the Bradshaw Mountains southwestward through the Wickenburg, Vulture, and eastern Big Horn Mountains.

The New Waddell Dam is being constructed on a foundation of Tertiary mafic flows, tuff, and clastic rocks. Additional geologic features of interest include various types of breccia, old, filled channels of the Agua Fria River, and several faults.

OPTIONAL STOP 2: MIOCENE VOLCANIC AND TECTONIC FEATURES

(Leader: Steve Reynolds, Arizona Geological Survey)

Route: Return to AZ 74, turn right, and continue west for 1.9 miles to the Castle Hot Springs Road and turn north (right). Continue north for 4.8 miles (past the turn off for Lake Pleasant Park) to the long roadcut 0.4 miles north of the Maricopa-Yavapai county line.

Geologic Highlights: This road cut illustrates some aspects of the volcanic stratigraphy of the region and contains excellent exposures of several southwest-dipping normal faults that repeat the volcanic section and one layer-parallel fault zone that probably formed in response to oversteepening of the volcanic section during faulting. The units here include, from top to bottom, (1) an upper brownish basalt, (2) a tan tuff that grades downward into a white tuff, (3) bedded pyroclastic rocks, (4) a middle basalt with an irregular, tuff-filled flow top, and (5) a lower basalt with a weathered-baked zone at its top. The layer-parallel fault cuts out units at the base of the white tuff and cuts across a preexisting southwest-side down normal fault that downdrops a wedge of the bedded pyroclastic unit on the east side of the road. An unusual large fold is present in pyroclastic rocks beneath the layer-parallel fault on the west side of the road.

Retrace the route back to AZ 74.

STOP 3: MYSTIC-CLEMONTINE GOLD PROPERTIES

(David Wahl and Dale Armstrong, Consultants)

Route: Proceed east on AZ 74 through the gradual bend to the south, but keep going straight (toward Sun City) at the intersection 2.3 miles south of the bend rather than turning east toward I-17. Proceed south to Jomax Road (about 5 miles south of the intersection) and turn right (west). Drive west 1.5 miles where the road crosses the Agua Fria River. Continue across the river for another 0.5 miles and follow the left-hand fork of the Y in the road. The road crosses under a water pipeline and turns north for 3.5 miles across the CAP and to the Mystic property. The Clemontine property is 2.2 miles to the west via the road on the north side of CAP.

Geologic Highlights: The Mystic-Clemontine prospects are located in Proterozoic rocks in the southern Hieroglyphic Mountains. Most mineralization is hosted by shear zones.

FROM STOP 3 TO WICKENBURG

Route: Wickenburg can be reached from Stop 3 by (1) retracing route to AZ 74, proceeding west on AZ 74, and going north on U.S. 60, (2) retracing route to the Sun City - Lake Pleasant Road, then going south to Sun City, west on Bell Road, and then north on U.S. 60, or (3) proceeding north from the Mystic Property along a dirt road to AZ 74 and then west to Wickenburg.

Geologic Highlights: These roads traverse through poorly consolidated Late Tertiary and Quaternary deposits and underlying tilted Tertiary volcanic and sedimentary rocks, Cretaceous granitoid rocks, and Proterozoic crystalline rocks.

START OF DAY 2 AND STOP 4: NEWSBOY MINE

(Leaders: Fred Bickford and Patti Tuve, Newsboy Gold Mining Company)

Route: Day 2 begins at the rest area 5.5 miles south of Wickenburg on the west side of U.S. 60/U.S. 89. From here, proceed south on U.S. 60 to Morrison, turn west, and cross the Hassayampa River to the Newsboy mine.

Geologic Highlights: Gold mineralization at the Newsboy deposit is localized along a low-angle normal fault that places Miocene San Domingo Rhyolite over Proterozoic metamorphic rocks. Associated alteration includes alunite, kaolinite, silica, and iron oxides.

STOP 5 AND LUNCH: HASSAYAMPA RIVER PRESERVE

(Leader: Holly Richter, Nature Conservancy)

Route: Retrace the route back to Morrison, turn left (north) toward Wickenburg on U.S. 60, proceed for 6.1 miles north of the junction of AZ 74 and turn left into the Hassayampa River Preserve (coming from Wickenburg, the turn off is 3.3 miles south of the Hassayampa River bridge in Wickenburg).

Highlights: The Preserve includes riparian habitat along the Hassayampa River and is managed by the Nature Conservancy. The geology includes several generations of Quaternary alluvium along the Hassayampa River and Proterozoic rocks west of Palm Lake. Further to the west, steeply dipping Tertiary volcanic and sedimentary rocks overlie the Proterozoic rocks along a west-dipping low-angle normal fault.

STOP 6: YARNELL GOLD DEPOSIT

(Leaders: Mark Miller and James Sell, ASARCO)

Route: Proceed north into Wickenburg, turn right at the stop light onto U.S. 89, north to Congress, and then up the Yarnell grade (see road log by Mark Miller).

Geologic Highlights: The Yarnell deposit consists of a north-dipping fault or shear zone within the Proterozoic Yarnell Granite. Gold mineralization is associated with iron oxides and quartz veins and stockwork. The escarpment along the Yarnell grade represents the southwestern edge of the Transition Zone, which was uplifted in Oligocene and Miocene time based on fission-track apatite ages.

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New Waddell Dam

<u>9</u> A.M. Meet at the Overlook Parking Lot. This area can be reached by traveling west on State Highway 74 from Phoenix. After crossing the Agua Fria River Bridge, turn right into the construction area, follow the paved road bearing left at a Y. Drive up the hill and make a right turn at the overlook road; the road ends at the Visitor's center.

At the visitor's center we will discuss the project history (see attached fact sheet) and site geology.

The dam foundation consists of middle Tertiary andesites and tuff overlain by conglomerate and is crossed by three alluvium-filled buried channels.

After the discussion we will observe various construction activities and how they relate to the site geology. Hard hats are required. Some will be available but please bring your own if you have one.

Depending upon the contractor's schedule we should be able to see the following activities:

1. Secant Pile Wall Construction. This is constructed by drilling 100 ft. deep, overlapping 20 inch diameter holes that are backfilled with concrete.

The purpose of the wall is to prevent seepage through fractured andesite.

2. Foundation Grouting. This technique is used to minimize seepage and prevent embankment material from eroding and moving into the foundation. This activity is monitored by computer and consists of drilling holes from 30 to 300 feet deep and pumping cement into the rock.

3. Foundation Treatment. This is to shape and seal the foundation with concrete.

4. Embankment Placement. Various zones of specific gradation and compaction techniques are used for various functions within the dam.

5. Dewatering System. This consists of two slurry wall cofferdams and dewatering wells and was used to drain and keep dry the foundation below Lower Lake.

6. Instrumentation. The instrumentation program at present includes vibrating wire piezometers, observation wells, shear strips, and inclinometers.

If time permits we will look at core samples from the foundation exploration program and visit the borrow area located about four miles to the east.

Mike Pryor

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
LOWER COLORADO REGION
ARIZONA PROJECTS OFFICE

CAP
CENTRAL ARIZONA PROJECT

New Waddell Dam Fact Sheet

The Bureau of Reclamation is constructing New Waddell Dam on the Agua Fria River about 35 miles northwest of Phoenix, Ariz., as part of the Central Arizona Project (CAP). New Waddell Dam's primary purpose is to store Colorado River water for CAP use. The dam also will store Agua Fria River runoff, and provide incidental flood protection by controlling flood flows of the river.

New Waddell Dam is located about one-half mile downstream of the existing Waddell Dam, which was built by the Maricopa Water District. The dam's reservoir, Lake Pleasant, stores Agua Fria River water for irrigation use by the district. The existing dam will be breached when the new dam is completed, but the district will continue to receive water from Lake Pleasant.

A KEY FEATURE

New Waddell Dam is a key feature of the CAP, providing many benefits to Arizona.

* **More Colorado River water.** With New Waddell Dam, the CAP can deliver more Colorado River water into Arizona when the water is available, and store that water for later use. Without the dam, the project could only bring in Colorado River water when there was a demand for it; this would result in less use of the water resource.

* **Increase reliability of water deliveries.** The CAP canal between the Colorado River and New Waddell Dam may occasionally be out of service for maintenance or because of damage. During these periods, Colorado River water could still be delivered out of Lake Pleasant to customers from Phoenix to Tucson, which is the highest demand area for the water.

* **Project repayment revenues.** Colorado River water must be pumped uphill from Lake Havasu to CAP customers. The electricity for the CAP pumping plants comes from the federal government's 24.3 percent share of the Navajo Generating Station, located near Page, Ariz. All of this power will normally be used during the winter, when the project will pump as much water as possible from the Colorado River to fill the enlarged lake and meet customer demand. During the summer, water will be released from New Waddell Dam to help meet project demands. This will reduce the pumping required from the river, resulting in a power surplus. This power will be sold, and the revenue used to help repay the CAP's construction costs.

* **Increased water-based recreation.** New Waddell Dam will add 7,000 surface acres to Lake Pleasant, greatly increasing the recreational value of Lake Pleasant Regional Park.

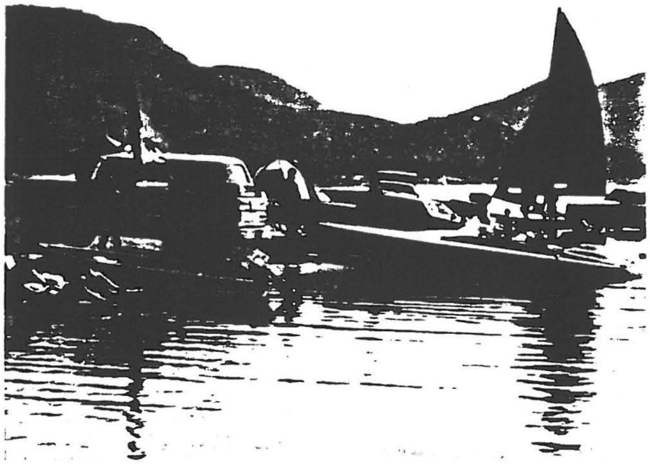
To help meet an anticipated visitor increase to the park, Reclamation will provide about $18.5 million to replace existing recreation facilities, and to jointly develop new facilities with the park manager. Reclamation will purchase all lands needed for the expanded lake and for recreation development, plus a minimum 300-foot buffer above the high water elevation.

Recreational facilities will be concentrated on the reservoir's western shore. An outdoor education center will be located on its eastern shore, but the remaining eastern shore, and part of the northern shore, will be closed to development.

Planned facilities include 3 multi-lane boat launch ramps, 450 picnic sites, 225 campsites, 14 group use areas, 4 overlooks, a full-service marina, and 7 miles of trail. Approximately six miles of new park road will be constructed, and support facilities such as restrooms, fish cleaning stations, a ranger station, concession facilities, and recreational vehicle sanitary dump facilities are also planned.

Because the reservoir water level may fluctuate as much as 125 feet during a typical year's operation, the recreational facilities have been sited so access to them, and to the water, will be available during both high and low water periods.

Artist's rendering, New Waddell Dam and enlarged Lake Pleasant. Colorado River water will be pumped into storage from the Central Arizona Project canal. The dam will increase the project's ability to use surplus Colorado River water, and planned recreation development at the enlarged lake will greatly increae its recreational value.



New and replacement recreation facilities at the enlarged Lake Pleasant will be built to handle an expected visitor increase.

HOW IT WILL WORK

The Waddell Canal will deliver Colorado River water from the CAP aqueduct to New Waddell Dam. This canal connects with the main CAP aqueduct about five miles south of the dam site.

The water will be pumped from the Waddell Canal into Lake Pleasant by a pumping-generating plant. When the water is released from New Waddell Dam to CAP customers, it will flow back through the pumping-generating plant and the Waddell Canal to the main CAP aqueduct. The water will generate small amounts of non-polluting hydroelectric power as it is released.

Colorado River water will be pumped into storage from October through March during a normal operating year. From April to September, water will be released from the reservoir to meet CAP and Maricopa Water District needs.

If necessary, floodwaters will be released from the dam through the river outlet works tunnel into the river immediately below the dam. If the reservoir's flood storage capacity is ever exceeded, floodwaters also will be released pass over a spillway located about 7,500 feet west of the dam. This water would flow down Morgan City Wash and back to the Agua Fria River at a point about one mile below New Waddell Dam.

EXTENSIVE CONSTRUCTION EFFORT

Many different types of work must be performed in construction of New Waddell Dam. That work began in 1985, and will continue through 1993.

Initial work included damsite clearing, construction of a new access road to the regional park, and construction of a concrete cutoff wall in the Agua Fria River bed to prevent seepage under the new dam.

Following that, the dam's foundation was excavated, Colorado River water delivery tunnels and the river outlet works and diversion tunnel were constructed, a pipline was built to carry water releases from the existing dam around the new dam site during its construction, and the Waddell Canal was completed.

Construction of the dam's pumping-generating plant began in 1988, and that work is now about 80 percent complete. Installation of pumps, motors, and generating units in the plant is underway. In addition, construction of a new entry station to Lake Pleasant Regional Park is now underway, as is construction of an observation structure that will be used as a visitor facility during construction of New Waddell Dam. The observation structure is scheduled to be open during the summer of 1990.

Construction of the dam embankment also is underwayn, following the award of a $135 million contract in December 1989. The embankment is scheduled to be complete in late 1992. But the dam is not scheduled to be fully operational until the end of 1993, after the pumping-generating plant is completed and fully tested.

As the dam and pumping-generating plant are being completed, other activities also will be occurring. These will include construction of new recreational facilities and additional park roads, construction of a new outdoor education center for Maricopa County, and relocation of Maricopa County and Maricopa Water District facilities. All work associated with New Waddell Dam is scheduled for completion by the end of 1993.

The Waddell Pumping-Generating Plant structure is eighty percent complete. The plant will pump Colorado River water through the two tunnels behind it for storage in Lake Pleasant. A small amount of hydroelectric energy will be generated when the water is released back to the CAP.

ENVIRONMENTAL PROTECTION A HIGH PRIORITY

Protecting the natural environment around Lake Pleasant from potential negative effects of New Waddell Dam's construction and operation, or mitigating specific impacts, is a high Reclamation priority.

Accordingly, we have:

* constructed several wildlife water catchments on the west and north sides of the lake to help reduce animal/vehicle collisions and improve wildlife distribution; and,

* funded a study to assess what effect, if any, the introduction of fish species from the Colorado River into the reservoir would have on the existing fishery and to determine what effect the reservoir's operation will have on the existing fishery and bald eagles that use the lake. The results of this study are now being compiled. Reclamation will also conduct a post-construction study, after the reservoir has been in operation, to further determine its impact.

In addition, we have committed to:

* fencing lands acquired for the enlarged reservoir to restrict grazing and off-road vehicle access;
* leave as much vegetation in the reservoir as possible for fish habitat;
* maintain a minimum water pool to provide carry-over habitat for fish in times when the reservoir would normally be dry;
* evaluate the feasibility of developing the Agua Fria River floodplain between New Waddell Dam and Highway 74 as a riparian habitat;
* close the area around a bald eagle nest on the reservoir to boaters, vehicles, and hikers during those breeding seasons that the eagles occupy the nest; and,
* erect a barrier on a tributary in the upper lake to protect a population of endangered native Gila topminnow from non-native fish that might move upstream from the reservoir during high water periods.

ESTIMATED COST

The estimated cost of constructing New Waddell Dam and accomplishing the associated work is more than $500 million. The Central Arizona Water Conservation District, which will operate and maintain the CAP and repay the project's construction costs to the federal government, will provide $175 million of this cost, and the federal government will pay the rest.

PHYSICAL DATA

NEW WADDELL DAM

Type: rockfill embankment
Height: 440 feet (300 feet above streambed)
Crest elevation: 1,730 feet
Crest length: 4,700 feet

SPILLWAY

Type: Ungated, free-overflow
Crest Length: 1,000 feet
Crest elevation: 1706.5 feet

RESERVOIR

Maximum storage capacity (including flood space):
902,100 acre-feet
Elevation at maximum storage capacity: 1,706.5 feet
Surface acres at maximum storage capacity: 10,340
Conservation storage capacity: 816,000 acre-feet
CAP water: 658,400 acre-feet
MWD replacement: 157,600 acre-feet
Minimum Pool: 40,500 acre-feet
Elevation at maximum conservation storage: 1,702 feet
Surface acres at maximum conservation storage: 9,970

PUMPING-GENERATING PLANT

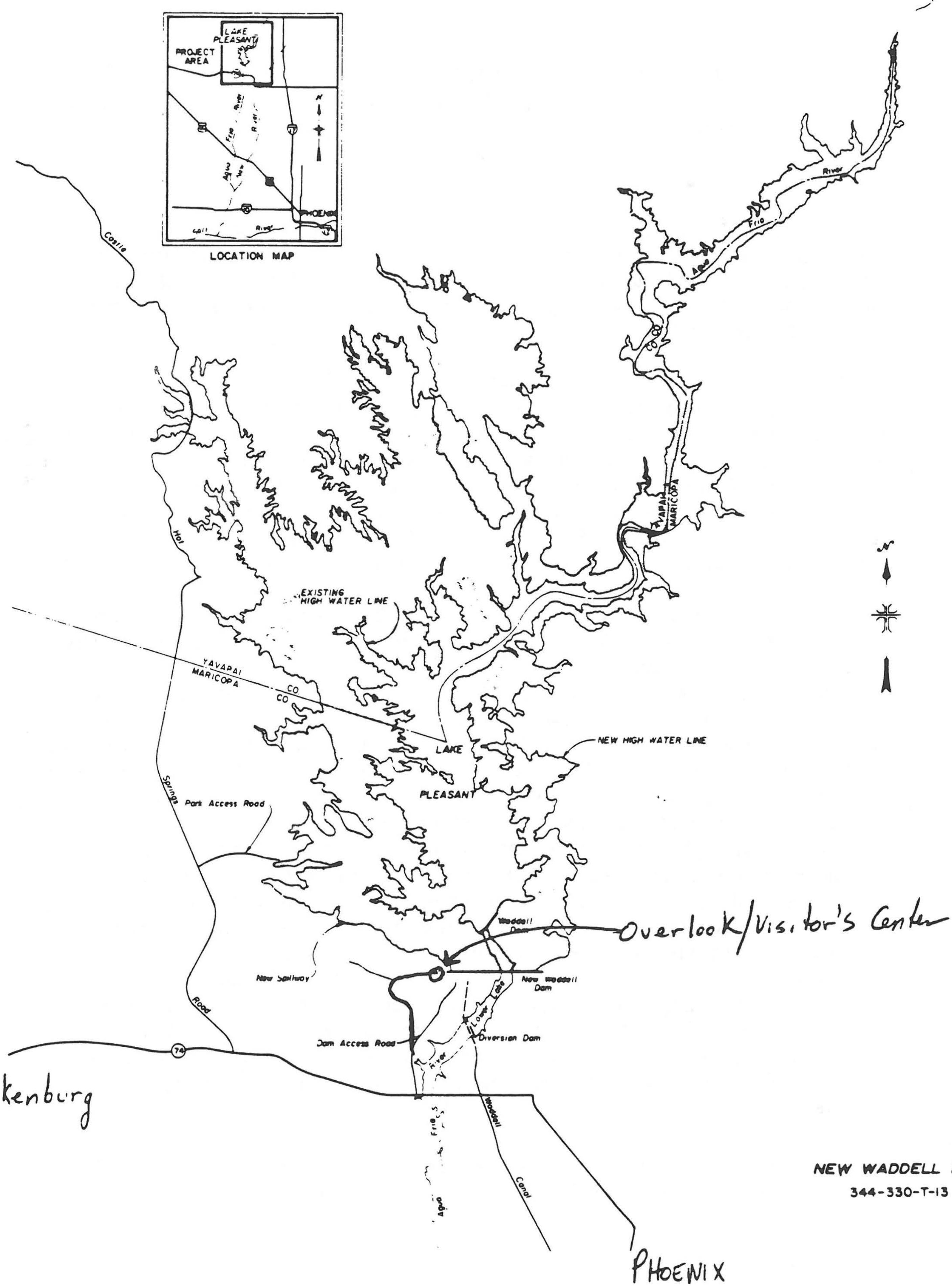
No. of units: 8
Pump capacity: 3,000 cubic feet per second
Power generation (maximum): 45 megawatts
Maximum lift: 192 feet

WADDELL CANAL

Length: 4.9 miles
Typical cross section: 24 foot bottom width, 82.5 to 88.5 feetwide at top of lining, lining height of 19.5 to 21.5 feet
Lining thickness: 4 inches
Capacity: 3,000 cfs

EXISTING WADDELL DAM

Type: concrete multiple arch
Height: 176 feet
Crest Length: 2,160 feet
Maximum storage capacity: 157,600 acre-feet
Surface acres at maximum storage capacity: 3,760



NEW WADDELL DAM

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Geologic Map of the Northeastern Hieroglyphic Mountains, central Arizona[1]

Richard C. Capps, Stephen J. Reynolds, Curtis P. Kortemeier, and Elizabeth A. Scott
Arizona Bureau of Geology and Mineral Technology Open-File Report 86-10
August 1986

INTRODUCTION

This report presents a preliminary 1:24,000-scale geologic map of the northeastern Hieroglyphic Mountains in central Arizona. The mapping, completed between January and June, 1986, was jointly funded by the U. S. Geological Survey and the Arizona Bureau of Geology and Mineral Technology as part of the cost-sharing, Cooperative Geologic Mapping Program (COGEOMAP).

GEOLOGIC OVERVIEW

The Hieroglyphic Mountains are composed of a metamorphic-plutonic basement that is overlain by middle Tertiary volcanic and sedimentary rocks.The oldest rocks in the range are Proterozoic schist, gneiss, metasedimentary and metavolcanic rocks, and several generations of plutonic rocks. These rocks are intruded by a small granite pluton that is similar in mineralogy to the Late Cretaceous Wickenburg batholith of the Vulture and Big Horn Mountains (Rehrig and others, 1980; Capps and others, 1985). The entire basement assemblage is cut by numerous felsic to mafic dikes, most of which are inferred to be middle Tertiary in age.

The crystalline rocks are commonly overlain by a thin sequence of pre-20 Ma Tertiary sandstone and conglomerate. These clastic rocks are generally too thin to map separately from the overlying volcanic units.

The Miocene (20 to 16 Ma) volcanic rocks consist of a complex sequence of basalt and andesite flows, latite and rhyolite flows and lithic tuffs, and lesser amounts of volcaniclastic rocks. Basalts are interlayered with areally restricted rhyolite flows and associated lithic tuffs. Stratigraphic relationships and differences in phenocryst assemblages in the rhyolites and latites have been used to designate informal units, each of which probably represents multiple extrusions from one or more vents within discrete eruptive centers.

Low- to high-angle normal faulting and rotation of the volcanic rocks and subjacent crystalline basement occurred soon after the extrusion of the youngest volcanics at 16 Ma. Most normal faults trend north-northwest and are associated with north- and northeast-trending faults that locally accommodated differential rotation or strike-slip displacement. Most northwest-striking faults dip southwest and most beds dip northeast.

The volcanic rocks are overlain by conformable to unconformable coarse fanglomerate and landslide-related megabreccia deposited in the larger half-grabens. Tilting continued during deposition of these deposits because they typically grade upward into conformable to locally unconformable, more gently dipping sandstone and siltstone. Essentially flat-lying basalts probably equivalent to the 14- to 15-m.y.-old Hickey Formation occur adjacent to the map area along the eastern shore of Lake Pleasant.

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[1]The complete version of this report and the accompanying map are contained in Arizona Bureau of Geology and Mineral Technology Open-File Report 86-10.

Argillic and silicic alteration locally occurs in both Tertiary and pre-Tertiary rocks and is most intense in the Cedar Basin area. Precious- and base-metal mineralization also occurs in the crystalline basement and in overlying Tertiary volcanic rocks.

POST-VOLCANIC MIDDLE TERTIARY UNITS[2]

FANGLOMERATE (MIDDLE MIOCENE)

Consolidated to semiconsolidated fanglomerate, and conglomerate, sandstone, and siltstone with a discontinuous thin cover of QTs. Moderately tilted, coarse, consolidated fanglomerate and laharic breccia in the lower parts of the section are generally conformable to slightly unconformable on Tertiary volcanic rocks and commonly grade upward into less consolidated finer-grained conglomerate, sandstone, and siltstone. Stratigraphically higher units in the southern part of the map area are unconformable over the volcanic rocks. This unit was commonly deposited across rugged topography and locally overstepped fault scarps. Paleocurrent direction, as inferred from pebble imbrication, is indicated directly on map.

SILTSTONE AND SANDSTONE FACIES

Moderately tilted, consolidated to semiconsolidated siltstone and sandstone associated with fanglomerate. This facies occurs in stratigraphically higher levels within the fanglomerate near Lake Pleasant, but locally occupies the basal part of the fanglomerate section northwest of the lake.

MEGABRECCIA AND SEDIMENTARY BRECCIA; PROTOLITH OF BRECCIA IN PARENTHESES WHERE KNOWN (MIDDLE MIOCENE)

Shattered landslide blocks (megabreccia) derived from various older rock units. Megabreccia is locally associated with monolithologic and polylithologic sedimentary breccia.

MIOCENE VOLCANIC AND SEDIMENTARY ROCKS[3]

The volcanic rocks overlie basal Tertiary clastic rocks and the crystalline basement, underlie the fanglomerate and megabreccia, and are 20 to 16 m.y. old (Kortemeier and others, 1986; Scarborough and Wilt, 1979).The lower part of the volcanic section is composed of two multiple-flow rhyolite units intercalated with phenocryst-rich basalt, phenocryst-poor basalt, andesite flows, tuff, and volcaniclastic sedimentary rocks. Overlying these rocks is a sequence of highly porphyritic latite flows, flow breccia, debris flows, volcanic breccia, and tuff. The volcanics have been subdivided into the following informal units (from youngest to oldest):

(1) Hells Gate latite
(2) Castle Creek volcanics
(3) Spring Valley rhyolite
(4) Morgan City rhyolite
(5) Basalts and andesites, interbedded with (3) and (4)

The two lower rhyolites (numbers 3 - 4) may be partly time equivalent and are both interbedded with basalt and andesite.

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[2]Abbreviated.

[3]Abbreviated.

The rhyolite flows are underlain and overlain by lithic tuffs that are moderately to poorly welded and contain abundant accessory and accidental lithics. These tuffs are much more extensive than the associated rhyolite flows and represent phreatic and phreatomagmatic base-surge deposits and minor air fall. Some tuffs exhibit low-angle cross-bedding structures and others contain accessory lithics as large as 6 m.

The rhyolite and latite flows and tuffs are ridge-and-cliff formers, whereas the more easily eroded basalts and poorly welded tuffs form valleys and hummocky terrain. Abundant section-repeating normal faults and post-volcanic erosion make estimation of the total thickness of the volcanic section difficult. There are about 520 m of Tertiary volcanic rocks in the fault-bounded, but most complete, section near Garfias Wash.

Abundant hypabyssal rhyolite dikes intrude the prevolcanic basement and Tertiary volcanics and commonly have phenocryst assemblages similar to those in the adjacent and overlying volcanics. Some of the dikes probably represent conduits for the volcanics.

HELLS GATE LATITE

Medium-gray, light-purplish-gray, medium- to dark-brown and light-grayish-pink porphyritic latite flows, flow breccia, debris flows, lahars, volcanic breccia, and lithic tuff.

The unit unconformably overlies Proterozoic basement and conformably overlies Tertiary basalt and andesite, Castle Creek volcanics, and Spring Valley and Morgan City rhyolite flows and tuffs. Hells Gate latite is the top volcanic unit in the map area and is overlain with small to moderate angular unconformity by Tertiary fanglomerates with a general lack of obvious paleosols along the contact. Hells Gate latite flows are at least 480 m thick on the unnamed mountain along the northern flank of Burro Flats. A K-Ar biotite age for this unit near Castle Creek is 16.1 $\pm$ 0.5 Ma. (Kortemeier and others, 1986). A biotite age of 17.98 $\pm$ 0.43 was obtained from a probable Hells Gate flow in the Buckhorn Mountains, north of the map area (Shafiqullah and others, 1980).

UNDIFFERENTIATED DEBRIS FLOWS, LAHARS, AND VOLCANIC BRECCIA

Medium- reddish brown, medium-grayish-brown, dark-brown, and light-grayish-pink, debris flows, lahars, and volcanic breccia. Clasts are from Hells Gate flows and tuffs, Tertiary basalt and andesite, Spring Valley and Morgan City rhyolites, and Proterozoic metamorphic and intrusive rocks. Southwest of Squaw Mesa, the stratigraphically lowest debris flows typically contain abundant basalt clasts. Proterozoic clasts dominate this unit north of Big Hells Gate, where brecciated rafted blocks of Tertiary basalt larger than 30 m diameter are also present. The thickness of this unit is greater than 150 m near Big Hells Gate. Clasts in associated volcanic breccias are mainly cognate lithics of Hells Gate flows.

VOLCANIC BRECCIA

Light-purplish-gray, medium-gray, and light-grayish- pink, poorly sorted, and crudely bedded volcanic breccia. The clasts are angular to subrounded and composed of Hells Gate latite flows. They average about 15 cm diameter, but clasts as large as 4 m diameter are present near Cow Creek. Volcanic breccia in Crater Canyon and south of Cedar Basin is crudely bedded and contains some tuff. These rocks are probably massive crumble breccia marginal to very thick flows or domes.

FLOW BRECCIA

Angular autobreccia associated with Hells Gate latite flows. The maximum diameter of the clasts is about 3 meters.

YOUNGER HIGHLY PORPHYRITIC LATITE FLOWS

Medium- to dark-gray, medium- reddish brown, and light-grayish-pink, highly porphyritic latite flows.

LITHIC TUFF

Medium-gray, pinkish-white, light-grayish-pink, and light- to medium-brown, poorly sorted lithic tuff. The dominant clasts are angular cognate lithics of Hells Gate latite although lithics of Spring Valley rhyolite, Tertiary basalt and andesite, and Proterozoic intrusive and metamorphic rocks are also locally present.

OLDER PORPHYRITIC LATITE FLOWS

Medium-gray, light-grayish-purple, medium-brown, and light-grayish-pink, porphyritic latite flows.

CASTLE CREEK VOLCANICS

Dark-greenish-gray, and mottled dark- and medium- gray, dense, porphyritic andesite flows and minor flow breccia. This unit conformably overlies Tertiary basalt, andesite, undifferentiated tuff, and basal sandstone and conglomerate. Near French Creek, the Castle Creek volcanics rest unconformably on Proterozoic rocks. In the Governors Peak area, the unit is conformably overlain by a thin basalt flow and by Hells Gate latite. Castle Creek volcanics are as much as 200 m thick near Castle Creek, but they are more typically less than 90 m thick.

SPRING VALLEY RHYOLITE

Mottled, light-pink, light-pinkish-gray, and light- gray, weakly to moderately porphyritic, flow-foliated rhyolite flows and minor flow breccia. The unit unconformably overlies Proterozoic basement and Cretaceous granitic rocks, and conformably overlies cogenetic Spring Valley tuff and Tertiary basalt and andesite. Spring Valley rhyolite is conformably overlain by Tertiary basalt and andesite, Spring Valley rhyolite tuff, and Hells Gate latite. Flows are overlain with some angular unconformity by Tertiary fanglomerate. The remnant of a rhyolite dome at Spring Valley is at least 360 m thick. A K-Ar whole-rock date from a vitrophyre near Garfias Wash is 18.7 ± 0.6 Ma (Kortemeier and others, 1986).

LITHIC TUFF AND TUFFACEOUS SEDIMENTARY ROCK

Light-yellowish-brown, pinkish-white, light-pinkish-gray, and light-pinkish-brown, poorly to moderately welded, lithic rhyolite tuff that contains accidental and accessory lithics, and locally abundant pumice. The tuffs are nonpersistant and occur both stratigraphically above and below the rhyolite flows. The Spring Valley rhyolite tuff is as much as 180 m thick on the eastern side of Garfias Wash.

UNDIFFERENTIATED LITHIC RHYOLITE TUFFS AND TUFFACEOUS SEDIMENTARY ROCKS

Light-pinkish-gray, light-tan, and light-pinkish-brown poorly to moderately welded, phenocryst-poor, lithic rhyolite tuff and poorly indurated tuffaceous sedimentary rocks. The lithics range in size from less than 3 cm to about 6 m and are principally fragments of Tertiary volcanic rocks and Precambrian metamorphic and intrusive rocks. The largest lithics occur near Cow Creek. The tuffs are at least 200 m thick in the Burro Flats area. These tuffs are associated with and probably genetically related to Spring Valley rhyolite and Morgan City rhyolites.

The tuffs unconformably overlie Proterozoic schist and are conformably overlain by Tertiary basalt, Castle Creek volcanics, and Hells Gate latite.Tertiary fanglomerate overlie the tuffs with some angular unconformity.

MORGAN CITY RHYOLITE

Light- to medium-gray, medium-pinkish-gray, and medium-grayish-brown, dense, moderately flow-foliated, porphyritic rhyolite flows and flow breccia. The unit conformably overlies Tertiary basalt and andesite, undifferentiated tuff, and volcaniclastic sedimentary rocks. Conformably overlying the Morgan City rhyolite are Tertiary basalt and andesite, undifferentiated lithic tuff, Spring Valley rhyolite tuff, and Hells Gate latite. The Morgan City rhyolite is 240 m thick at Pikes Peak.

UNDIFFERENTIATED BASALT AND ANDESITE

Very-dark- to medium-gray, pinkish- to reddish-brown, and pinkish-gray, vesicular, amygdaloidal, locally scoriaceous, locally porphyritic, trachytic to pilotaxitic basalt, basalt-derived sedimentary rocks, and andesite flows. Scoriaceous beds 0.4 to 6 m thick and associated abundant bombs occur near former cinder cones. The bombs are mostly spindle shaped (bipolar fusiform) and are as large as 1.5 m long and 0.3 m wide. Scoria fragments seldom exceed 2.5 cm in diameter. Basal flows are typically highly fractured and incipiently to moderately altered.

The basalts are intercalated with quartz-bearing and quartz-free andesitic rocks, Spring Valley rhyolite, Morgan City rhyolite, and associated lithic tuff, and Castle Creek volcanics. The unit unconformably overlies Proterozoic metamorphic and intrusive rocks and Cretaceous granitic rocks, and conformably overlies the basal Tertiary sandstone and conglomerate. Basalt and andesite are conformably overlain by Hells Gate latite and an angular unconformity locally exists between this unit and Tertiary fanglomerate. The sequence of basalt and andesite is at least 280 m thick at Baldy Mountain and about 120 m thick along the east side of Garfias Wash. A K-Ar whole rock age date of 16.63 ± 0.35 Ma was obtained from a sample taken along the west side of Lake Pleasant (Scarborough and Wilt, 1979).

QUARTZ-BEARING ANDESITIC ROCKS

Mottled, medium-pinkish-gray, poorly porphyritic, fine-to medium-grained, dense rocks with abundant liesegang banding. Flows contain phenocrysts of biotite, amphibole, pyroxene, and quartz. The mafics are generally altered. A sample taken from Burro Flats is K-metasomatised. These rocks are complexly intercalated within the lower basalts and andesites.

BASAL SANDSTONE AND CONGLOMERATE (OLIGOCENE - EARLY MIOCENE?)

Reddish- brown to greenish-gray coarse sandstone, conglomerate, and minor laharic breccia. Clasts are of Precambrian metamorphic and intrusive rocks and rare basalt. These clastic rocks are typically about 1 m thick, but are locally 12 m thick near the microwave tower beside the Castle Hot Springs Road. This unit nonconformably overlies Precambrian metamorphic and intrusive rocks and is overlain conformably by Tertiary basalt, Castle Creek volcanics, and Hells Gate latite. Large outcrop areas occur in the adjacent Buckhorn Mountains.

MIOCENE (?) INTRUSIVE ROCKS[4]

PRE-TERTIARY ROCK UNITS

GRANITE (LATE CRETACEOUS?)

Light- to moderate-gray, coarse- to medium- grained granite averaging 30 to 40 percent orthoclase, 10 to 15 percent plagioclase, 10 to 15 percent quartz, 3 to 5 percent biotite and muscovite, 1 to 2 percent magnetite, 1 to 3 percent anhedral opaques, and a trace to 5 percent sphene, zircon and other accessory minerals. A sample taken from Spring Valley yielded a 129 m.y. K-Ar paragonite (0.6 percent K) age of uncertain significance (Shafiqullah and others, 1980).

QUARTZ VEINS (PROTEROZOIC)

White and very-light-pinkish-gray, massive quartz occurring in Proterozoic metamorphic and intrusive rocks and generally conforming to principal schistosity. The quartz is as much as 6 m wide and extends along strike for greater than 500 m.

GRANITE (EARLY PROTEROZOIC)

Medium- to coarse-grained equigranular granite with several percent amphibole and biotite. Granite occurs in the west- central Morgan City Wash area.

GABBRO (EARLY PROTEROZOIC)

Dark-greenish-gray gabbro with abundant pyroxene phenocrysts and lesser amounts of opaques and feldspar. These thin layers within the Proterozoic schists and gneisses generally conform to the principal schistosity.

ALASKITE, TOURMALINE-BEARING GRANITE, AND PEGMATITE (EARLY PROTEROZOIC?)

Very coarsely crystalline, leucocratic, weakly-foliated intrusive rocks.Quartz, microcline feldspar, muscovite and locally abundant euhedral schorl tourmaline are the principal components. Minor magnetite and anhedral opaques are present in some outcrops. Muscovite locally comprises 15 percent of the alaskite. The alaskite occurs both as large pods within the enclosing schists as well as narrow, unmapped bodies that conform to the principal schistosity.

BANDED IRON FORMATION (EARLY PROTEROZOIC)

Banded dark-brown and very light- to dark-gray hematitic quartz and chert. Principal outcrops strike northeast and are southwest of Morgan City Wash, near the Pikes Peak iron deposit. Recrystallized carbonate and other metasedimentary rocks are associated with this unit in the southern part of the map area.

SCHIST, PHYLLITE, GNEISS, AND METAMORPHIC ROCKS (EARLY PROTEROZOIC)

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[4]Descriptions of these rocks, which include apyric rhyolite, feldspar-rich latite, and mafic-intemediate compositions, are contained in OFR 86-10.

Light- to medium-silvery-gray, greenish-gray, brown, and dark-gray, foliated, micaceous and chloritic schist, phyllite, quartz and feldspar schist and gneiss, and other metasedimentary and metavolcanic rocks. Garnet and hornblende are locally abundant in the schist. These rocks are part of the Proterozoic Yavapai Supergroup with an age of approximately 1.8 Ga.

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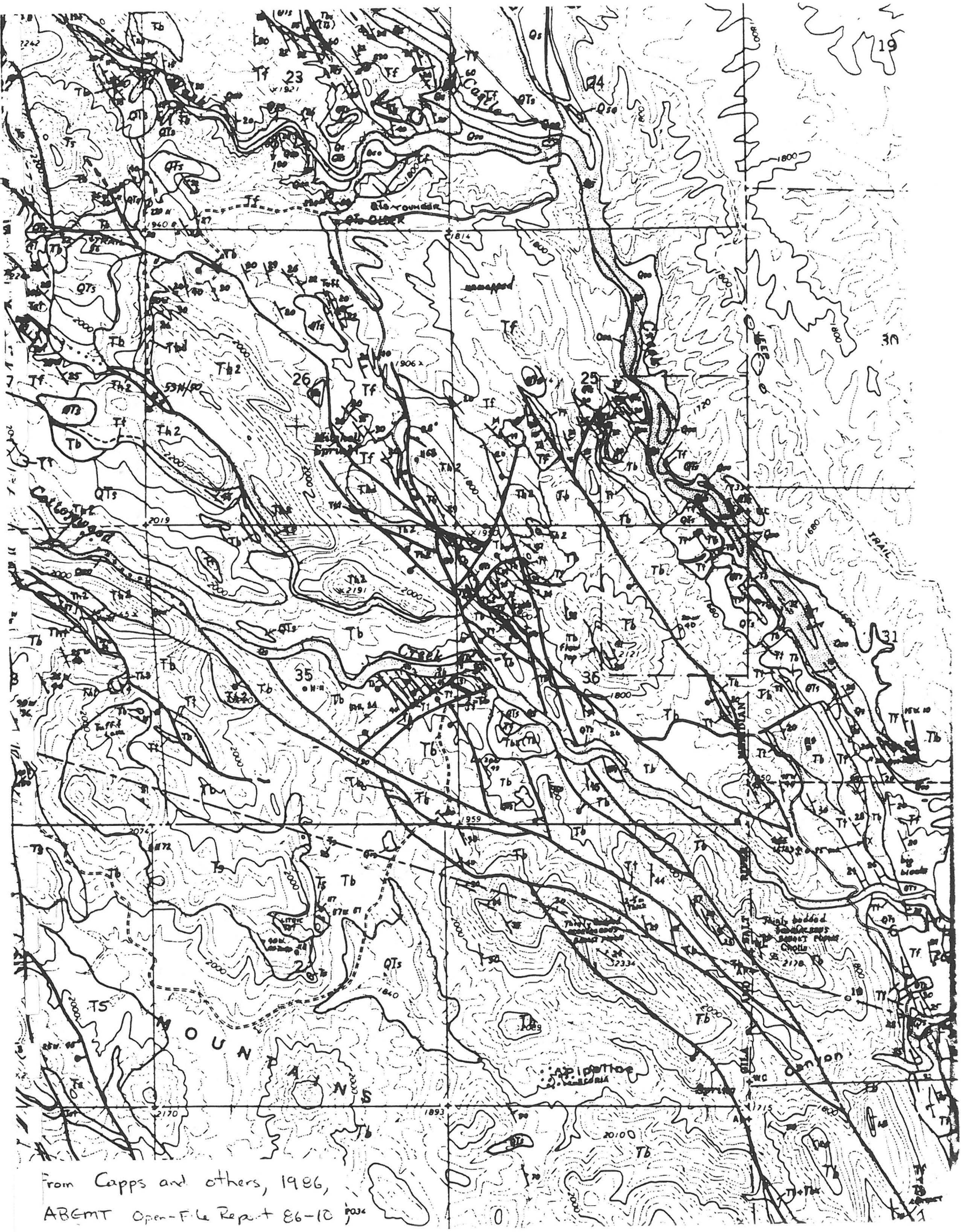


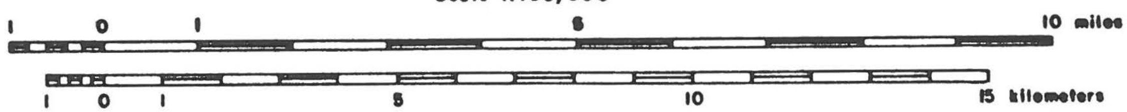
From Capps and others, 1986, ABGMT Open-File Report 86-10

GEOLOGIC MAP OF QUATERNARY AND UPPER TERTIARY ALLUVIUM IN THE PHOENIX NORTH 30' X 60' QUADRANGLE, ARIZONA

by Karen A. Demsey

1988

Scale 1:100,000



Introduction

The Phoenix North 30' x 60' quadrangle covers an area in south-central Arizona that straddles the boundary between the Sonoran Desert and Mexican Highland sections of the Basin and Range Province. The semiarid climate and the subdued or quiescent tectonic regime that have prevailed during Quaternary time within the area have resulted in the predominance of broad basins and piedmonts in much of the map area. Basinward transport and deposition of material derived from adjacent mountains and higher piedmont deposits have been the predominant geologic processes active in this area during the Quaternary.

Alluvial deposits differentiated for this map are assigned to Quaternary and Upper Tertiary geologic units primarily on the basis of the estimated ages of abandonment of major deposition on the corresponding surfaces, as evidenced by the relative topographic positions of the geomorphic surfaces, degree of surface preservation, and soil development. The deposits and their associated surfaces and soils have been divided into the following map units according to relative age: a mainly pre-Quaternary basin-fill unit (Tbf); a late Tertiary to early Quaternary river gravels unit (QTrg); an oldest Quaternary unit (O); a "middle to old" Quternary unit (MO); three categories of middle Quaternary alluvium (M1 -- older, M2 -- younger, and Mu -- undifferentiated); and two youngest Quaternary units (Y -- alluvial fans and large terraces, and Yc -- active alluvial in major channels). The estimated numerical ages of the surfaces are inferred largely from radiometric dates and geologic studies in southern Arizona (especially Bull, in press, and Morrison and Menges, 1982). This map indicates the distribution of alluvial deposits of different ages, and thereby provides a basis for evaluating the Quaternary geologic history of the area.

The mapping is based primarily on interpretation of U2 high-altitude aerial photographs (scale 1:125,000), supplemented locally by natural-color (1:24,000) and historic black-and-white (1:30,000) aerial photographs. Unit designations and surface characteristics were checked at several sites in the field. In the highly urbanized Phoenix metropolitan area, and in extensive agricultural tracts in the Phoenix basin, Soil Conservation Service soil surveys (Soil Conservation Service, 1974; 1977; 1986) were used to evaluate surface ages and to delineate boundaries between Quaternary geologic units.

This project was supported by the Arizona Geological Survey and the U.S.G.S. Cooperative Geologic Mapping (COGEOMAP) Program. Aerial photographs were provided by Raymond A. Brady of the U.S. Bureau of Land Management.

Explanation of map units

The distinguishing features of the map units described below represent the criteria on which the mapping is based. The estimated ages assigned to the map units are also given. The ages ascribed to map units on the Phoenix North quadrangle are based on morphologic and pedologic similarities between these units and Quaternary alluvial units defined and locally dated by investigators working in adja[...] most extensively drawn from [...] surfaces along the lower Color[...] have been obtained directly [...] quadrangle, and therefore [...] approximations. However, the [...] represents a reasonable int[...] regarding timing of major de[...] formation in the southwestern [...]

Unit	Estimated age (year[...]
Yc	≤ 1000

Confined to active and recen[...] drainages. Primarily sand a[...] development has occurred in a[...]

Y	0 - 10,000

Represents deposits of infe[...] perhaps locally latest Pleist[...] of major drainages. Surface[...] sorted sand and silt, with [...] Surfaces are very slightly -- [...] by active gullies and washes. [...] in appearance; remnant bar-and[...] Incipient to light varnish on [...] occurs. Minimal soil develop[...] strongly developed profiles c[...] over stage I to II calcic [...] description of morphologic st[...] Soil great groups are typica[...] Camborthids.

M2	10,000 - 250,000

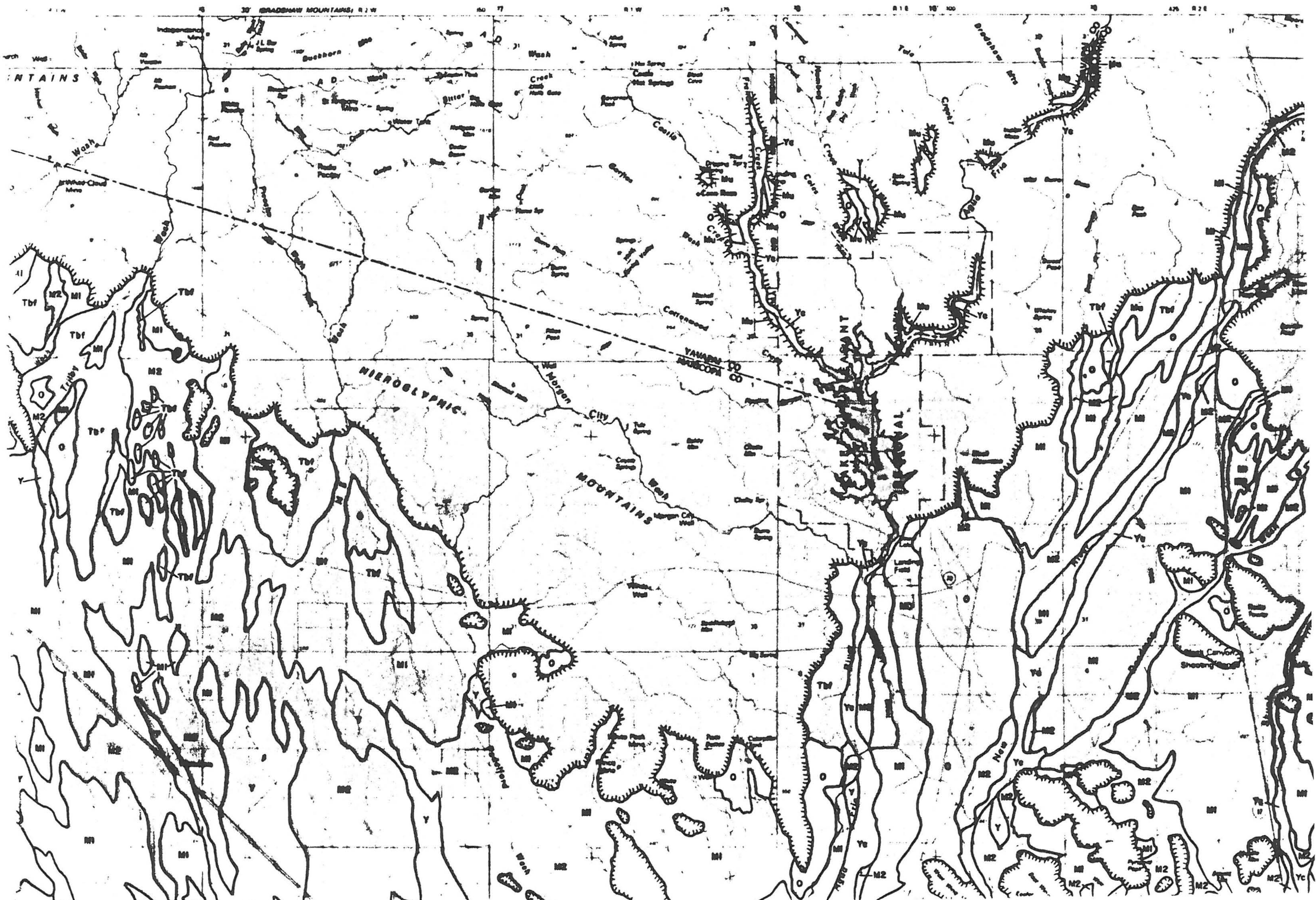
Represents alluvium of inferr[...] Surfaces are underlain by d[...] gravels; generally well-sor[...] moderately dissected -- ~1 to [...] typically have smooth and fi[...] lag. Mafic clasts on the [...] varnished; felsic clasts appe[...] remnants exhibit slightly- t[...] horizons (cambic or argillic [...] above a stage II to III calc[...] Camborthids to Haplargids.

M1	250,000 - 790,000

Alluvium of inferred middle [...] Deposits include sand and f[...] general, moderately sorted. T[...] -- ~3 to 6 m above active chan[...] ~60 m -- in the north-central [...] the Agua Fria River). Surfac[...]

Prepared in cooperation with U. S. Geological Survey Cooperative Geologic Mapping (COGEOMAP) Program [illegible]4-0[illegible]01-[illegible]78

AZGS Open-File Report 88-17



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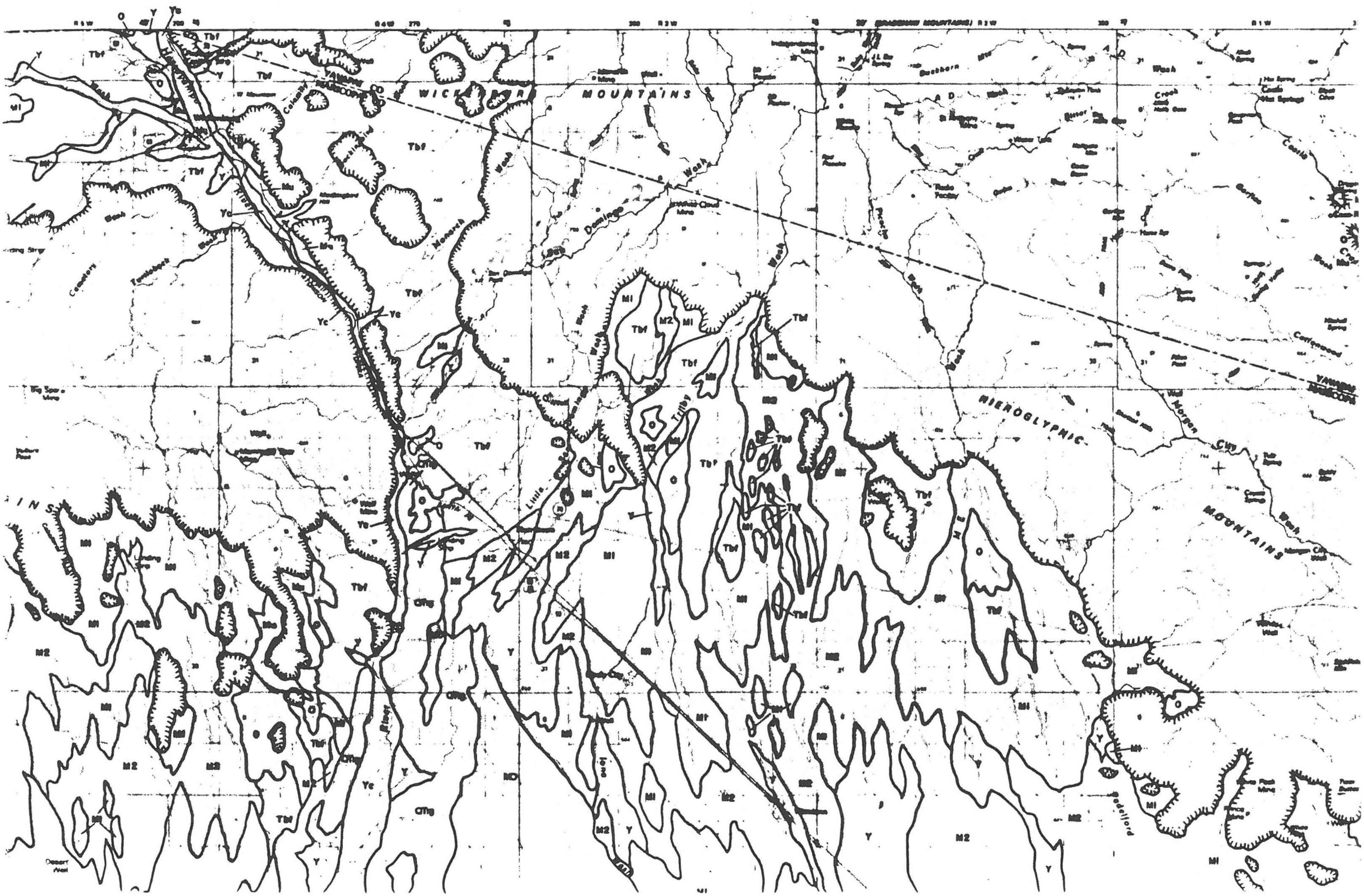

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GEOLOGIC MAP OF THE SOUTHERN HIEROGLYPHIC MOUNTAINS, CENTRAL ARIZONA

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Geological Survey Branch
Arizona Bureau of Geology and Mineral Technology

February 1988

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Open-File Report 88-1

Jointly funded by the Arizona Bureau of Geology and Mineral Technology and the U.S. Geological Survey Cooperative Geologic Mapping Program (COGEOMAP) Contract No. 14-08-0001-A0378
Principal Investigators:
Stephen J. Reynolds
Larry D. Fellows

INTRODUCTION

This reconnaissance geologic map covers both the Baldy Mountain and the Hieroglyphic Mountains SW 7.5 minute quadrangles of central Arizona. The geologic mapping was done between January and June, 1986 and November and December, 1987. This mapping was jointly funded by the U. S. Geological Survey and the Arizona Bureau of Geology and Mineral Technology as part of the cost-sharing, Cooperative Geologic Mapping Program (COGEOMAP). The aim of COGEOMAP is to produce high-quality geologic maps for areas that have been inadequately mapped and that have high mineral resource or natural potential.

This mapping was done on 1:24,000-scale topographic maps and on 1:24,000-scale color aerial pholographs provided by Raymond A. Brady, U. S. Bureau of Land Management, Phoenix. The reader is referred to a previous report on the northeastern Hieroglyphic Mountains (Capps, R.C., and others, 1986) for a more detailed discussion of the geology of the region. Additional descriptions of the area are contained in Ward (1977). Rock-unit names in this report are from Stimac and others (1987) and Capps and others (1986) as modified from Ward (1977).

MAP-UNIT DESCRIPTIONS

Qy — UNCONSOLIDATED SEDIMENTARY DEPOSITS-(HOLOCENE)--Poorly sorted to well-sorted sand, silt, and gravel in active drainages. These deposits are especially conspicuous by sparse or no vegetation cover.

Qy_1 — UNCONSOLIDATED SEDIMENTARY DEPOSITS-(HOLOCENE)--Poorly sorted sand, silt, and gravel that underlie flood-plain terraces 1 to 3 m above active drainages.

Qt — TALUS-(QUATERNARY)--Unconsolidated pebbles, boulders, and cobbles along the base of hills and ridges formed by resistant map units, especially some of the younger basalt flows (map unit Tbu) in the southeastern portion of the map.

Qal — PARTLY CONSOLIDATED SEDIMENTARY DEPOSITS-(QUATERNARY)--Poorly sorted sand- to cobble-sized material on pediment surfaces and other areas of low relief and along drainages where recent incision is not severe. This unit also includes relatively thick soils developed on gently dipping erosional surfaces on upper basalt flows (map unit Tbu).

QTs — SANDSTONE, SILTSTONE, AND CONGLOMERATE, UNDIVIDED-(LATE MIOCENE TO QUATERNARY)--Consolidated to partly consolidated sedimentary rocks that flank bedrock exposures; includes pediment developed on Proterozoic schist (map unit Xs) fans and plains of alluvium considered to be basin fill. Thin soil horizons developed on alluvium are probably Quaternary in age, and substantially younger than gently dipping, underlying material.

Tf — FANGLOMERATE AND SANDSTONE-(MIOCENE)--Consolidated to partly consolidated sedimentary rocks dominated by clast- and matrix-supported conglomerate that unconformably overlies the upper basalt flows (Tbu). Stratigraphically lowest beds in this unit dip steeply to the east, whereas higher beds are progressively less tilted. The youngest beds, which are exposed along the western bank of the Agua Fria River, are flat-lying. About 10 to 20m of section of tilted rocks in the northern part of the map area (section 25, T7N, R1W) consist of a well-bedded sequence of arkosic sandstone and matrix supported conglomerate. Beds are typically 20cm thick, but range from 5 to 40 cm. These deposits are inferred to be mostly sheetflood deposits predominated by debris flows and hyperconcentrated flood-flows. Clasts are typically subangular, up to 4cm in diameter, and locally imbricated.

Tbu BASALT FLOWS-(MIDDLE MIOCENE)--Vesicular, dark-gray-weathering, resistant, plagioclase-clinopyroxene-olivine-phyric basalt with an aphyric groundmass. Phenocrysts include approximately 15% olivine and clinopyroxene and 5% plagioclase. Olivine is conspicuous as it alters to iddingsite, and clinopyroxene occurs as euhedral, light-green prisms that locally cleave with an iridescent coating. Plagioclase occurs as colorless, euhedral, singular grains up to 3mm long. Olivine is locally associated with clinopyroxene in glomeroporphyritic aggregates less than 3mm across.

Tdf DEBRIS FLOWS-(MIDDLE MIOCENE)--Several tens of meters of yellowish-colored, non-resistant, poorly bedded, matrix-supported conglomerate overlain by sandstone and conglomerate, which are locally clast-supported. Clasts are mostly angular and dominantly vesicular, basaltic rocks. Sandstones are bedded on the scale of 20-30cm. The upper contact with the overlying basalt is sharp, whereas the the lower contact with the underlying tuffaceous rocks (map unit Tt) is a 10 to 15^{o} angular unconformity.

Th HELLS GATE VOLCANICS-(MIOCENE)--Strongly rhyodacitic or dacitic flow rock with phenocrysts of biotite, hornblende, and plagioclase. This unit contrasts with rhyolites of either Spring Valley (map unit Ts) or Morgan City (map unit Tcm) in that this unit lacks sanadine phenocrysts and its abundant hornblende phenocrysts. Phenocryst assemblage includes approximately 3% plagioclase feldspar and 1% hornblende, as well as 1/2% biotite. Groundmass is aphyric. Plagioclase content locally increases upsection to at least 10% and some grains are as much as 1cm across, although most commonly grains are 3-4mm across.

Tmc MORGAN CITY RHYOLITE-(MIOCENE)--Crystal-poor rhyolite intrusions with sparse phenocrysts of sanadine and biotite; unit is quite similiar texurally and mineralogically Spring Valley rhyolite (map unit Ts).

Ts SPRING VALLEY RHYOLITE-(MIOCENE)--Light-tannish-green-weathering, purple- or gray-colored, conspicuously flow-foliated rhyolite flows and intrusions with less than 5% phenocrysts of biotite and sanadine. Sanadine occurs as discrete, subhedral, 1 to 2mm-long phenocrysts. Biotite, in various stages of oxidation, occurs as 1-to-2mm-thick books or plates. Quartz-coated fractures are abundant in many exposures, as are thin seems of vapor-phase alteration and lithophysae.

Tt TUFFACEOUS ROCKS-(MIOCENE)--Very light-gray, fine-grained, consolidated and unconsolidated, locally welded tuffaceous rocks including poorly sorted, lithic-rich lapilli tuff, well-sorted ash, and lithic-poor lapilli tuffs. Thinly bedded to laminated tuff locally includes abundant lithic fragments of sand-sized material, which is probably reworked from pyroclastic rocks like those common in the northern part of the map area. Some horizons consist of only ash and probably represent air-fall tuffs. Ignimbrites exposed immediately south of Morgan City Wash have phenocrysts of biotite, plagioclase, and quartz, and the pebble-sized accidental fragments.

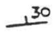
Tbl BASALT FLOWS-(MIOCENE)--Dark reddish-brown-weathering, nonresistant, olivine-phyric basalt with 10 to 15% fine- to medium-grained phenocrysts. This map unit is substantially less resistant than the upper basalt flows (Tbu) and does not exhibit the flow fronts. Talus is poorly developed around the low hills. The older basalt flows are also more steeply tilted than the those of the upper basalt. Some basalt flows of this unit contain quartz as 1-2mm rounded grains without any apparent reaction rim. Tiny calcite stringers and amygdules are also present locally. Unit is locally interbedded with tuffaceous rocks of unit Tt, and locally includes some 10- to 20-m-thick sections of well-preserved mafic pyroclastic rocks beneath Saddleback Mountain, in section 35, T6N, R1W.

Xg PORPHYRYTIC GRANITOID-(PROTEROZOIC)--Biotite-bearing granitoid with conspicuous megacrysts of potassium feldspar locally more than 1cm across.

Xs SCHIST-(PROTEROZOIC)--Includes several fine- to medium-grained metamorphic mineral assemblages including, chlorite-quartz-plagioclase, amphibole-quartz-plagioclase, quartz-plagioclase-K-feldspar, quartz-muscovite, quartz magnetite, and muscovite-biotite-quartz. Generally non-resistant but quartz- or chert-rich lithology are very often underlie precipitous ridges.

Xbi BANDED IRON FORMATION-(PROTEROZOIC)--Lenticular bodies of interbedded chert, iron oxide, phyllite, carbonate, and metavolcanic rocks, ranging in width from 15 to 100 m and rarely more than 350 m in length (Slatt and others, (1978).

SYMBOLS

 STRIKE AND DIP OF BEDDING

 STRIKE OF VERTICAL BEDDING

HORIZONTAL BEDDING

 STRIKE AND DIP OF FOLIATION

 STRIKE OF VERTICAL FOLIATION

 STRIKE AND DIP OF FOLIATION OR CLEAVAGE

 STRIKE AND DIP OF SPACED CLEAVAGE

 STRIKE OF VERTICAL CLEAVAGE

 LOW-ANGLE NORMAL FAULT -- Dashed where approximately located, dotted where concealed; hachures on upper plate.

 HIGH- TO MODERATE-ANGLE FAULT -- Dashed where approximately located, dotted where concealed; bar and ball on down-thrown block.

 HIGH-ANGLE FAULT -- Dashed where approximately located, dotted where concealed.

 FAULT DIP

 RELATIVE SLIP DIRECTION OF FAULT

 DIRECTION OF PEBBLE IMBRICATION IN FANGLOMERATE

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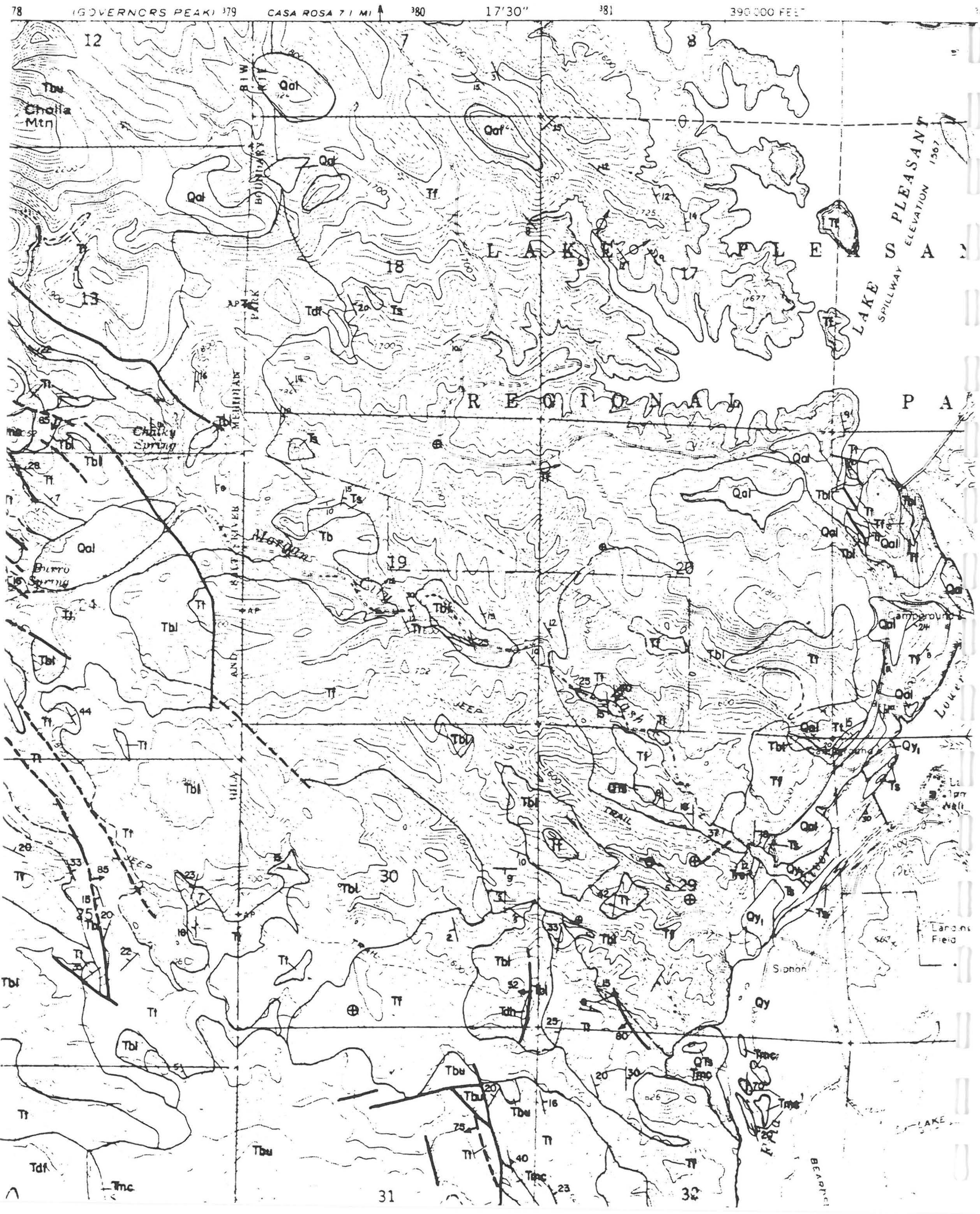

(GOVERNORS PEAK)
CASA ROSA 7.1 MI
17'30"
390 000 FEET
Cholla Mtn
L A K E P L E A S A N
LAKE PLEASANT
SPILLWAY ELEVATION 1567
R E G I O N A L P A
BOUNDARY
PARK
MERIDIAN
GILA AND SALT RIVER
Chalky Spring
Burro Spring
Morgan City
JEEP
TRAIL
Campground
Siphon
Landing Field
Qal
Tbl
Tf
Ts
Tdf
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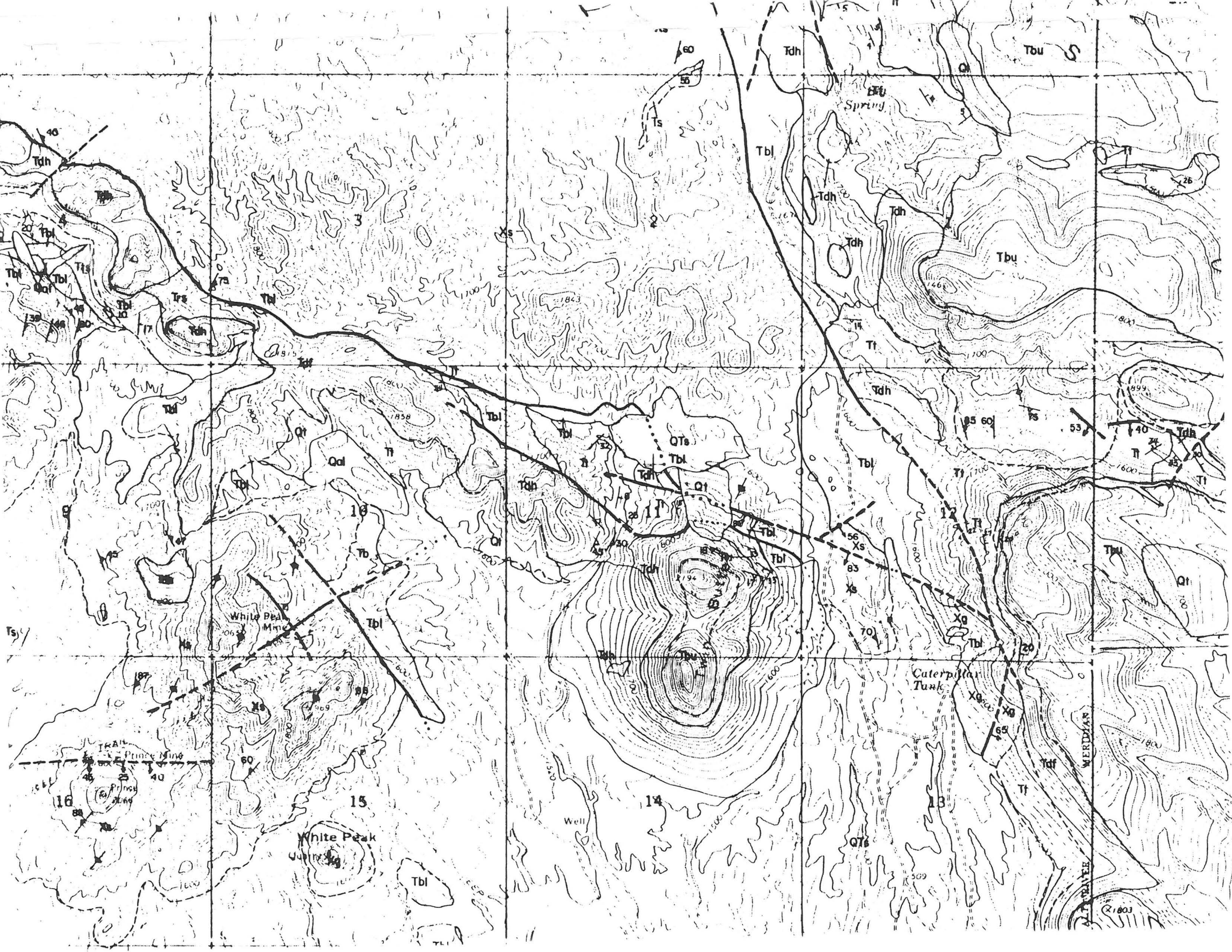

Spring
White Peak Mine
White Peak
Caterpillar Tank
Well
Tbu
Tdh
Tbl
Tdf
QTs
Qal
Xs
Xg

GOLD MINERALIZATION AT THE MYSTIC MINE MARICOPA COUNTY, ARIZONA

Dale G. Armstrong
Consulting Geologist
Tucson, Arizona

Introduction

The Mystic Mine is located approximately 12 miles north of Sun City, Maricopa County, Arizona; Township 6 north Range 1 west, within the southern end of the Hieroglyphic Mountains, Figure 1. It is situated in a boundary region between Tertiary aged felsic to intermediate volcanics and Proterozoic meta-volcanics and metasediments. Gold mineralization occurs within wide northwest trending shear zones. The property is currently managed by Fisher-Watt Gold Co. Inc.

Historically, gold exploration was concentrated in the vicinity of the "Mystic Shaft," resulting in the discovery of approximately 26,000 tons of 0.7 opt Au known as the Harding Pod. Subsequent drilling done by Ranchers Exploration in the late 1970s and early 1980s extended the limits of the gold-bearing host environment several hundred feet to the west. Reserves for the Harding Pod were not improved.

An exploration program during 1987 and 1988 undertaken by a joint venture between Terra Technologies, Sovereign Explorations Inc., and Fisher-Watt Gold Co. Inc. consisted of 2460 feet of backhoe trenching and sampling, 6440 feet of reverse circulation drilling, 2160 feet of airtrack drilling, a 28.5 line mile ground magnetometer survey, and surface and trench geologic mapping.

This new drill data coupled with the data from the past drilling, indicates a geological gold reserve surrounding and including the Harding Pod of 37,600 tons grading 0.423 opt.

Geology

The geologic setting of the Mystic property is within the Transition Zone separating the Colorado Plateau from the Basin and Range Province. Proterozoic metavolcanics are the predominant country rocks within the property, Figures 2-4. They consist of mafic to intermediate volcanics, as perhaps flows and crystal lithic pyroclastics metamorphosed to lower amphibolite facies. A retrograde greenschist overprint of chlorite and epidote is pervasive.

Deformation accompanying the metamorphism resulted in the development of no fewer than two foliations. S_1 predominates over S_2 to such a degree that S_2 is rarely observed. S_1 generally trends N 45°-65° E with dips of -50° to -80° SE and generally defines compositional layering.

These Precambrian rocks are found to be both in fault contact and unconformably overlain by the Tertiary volcanics. These volcanics are seen as ash to lapilli tuffs of generally felsic composition. They are capped by a younger basalt flow. The felsic volcanics may be correlative to the Hells Gate latite found in the northern Hieroglyphic Mountains.

These pyroclastics are involved in the structural setting at the Mystic as well as some of the mineralization. Feeder dikes of the volcanics are present throughout the property.

All of these lithologies are to a large degree covered by late Tertiary-aged fanglomerates. The thickness of these fanglomerates ranges from a few feet to in excess of 30 feet. An estimated 70% of the project area is covered by these recent sediments.

Structural Setting.

The area is host to at least two regional-sized fault zones. These zones are defined by broad but linear environments of intense shearing and brecciation. Width of these zones is customarily 30 to 50 feet but may exceed 100 feet.

Two predominant fault trends seen at the surface are N 60° W and N 10°-25° W. The offset on both fault systems is complex. Apparent reverse movement is indicated by the position of the displaced volcanics.

These fault systems are probably synkinematic. Conjugate shear fabrics both synthetic and antithetic were observed in some of the trenches.

Magnetics.

The main structural features can be recognized from the contoured magnetic data, Figure 5. Magnetic gradients are observed over the Mystic at N 60° W as well as along the N 20° W fault zone to the east. They may also reflect some of the more subordinate faults and structurally disturbed areas covered by Tertiary fanglomerates.

As a result of these geophysical and structural observations the host environments for the gold mineralization becomes apparent. They are large areas of structural disturbance acting as environments within which hydrothermal cells could exist. Due to the localized hydrothermal alteration of the host lithologies, weak to moderate magnetic contrasts were developed. These hydrothermally derived contrasts are a major contributor to the linear features identified by the magnetics survey.

Gold Mineralization

The structural setting as outlined above was the predominant control for the gold mineralization at the Mystic. Drilling indicates that the predominant trend for the highest grade gold is sub-parallel to the N 60° W trend of the Mystic shear. Mineralization is present over intervals of from 5' to 60' in width. There are complicating factors within the Mystic shear which have affected the location of the highest grade gold zone(s). These factors are probably synthetic faulting and fracturing and the near-surface supergene enrichment of hypogene gold mineralization.

The gold system developed at the Mystic is associated with an alteration assemblage of hematite, clays, sericite, calcite, dolomite, manganocalcite, quartz, adularia, ilmenite, chlorite and perhaps epidote. A crude zoning of these minerals is observed as a clay, sericite, quartz, chlorite core surrounded by epidote and chlorite.

The hematite development is thought to be predominantly hypogene. There is a complete lack of limonite pseudomorphs and a near total lack of other sulfide derived limonite, namely jarosite and goethite. Hematite is the most pervasive of the alteration assemblage.

Clay and sericite are easily the next most wide spread but are still confined to the main shear zone. The degree of clay development at the surface may exceed 75%. In drill cuttings it was observed to be slightly less.

Sericite alteration within the clay zone was difficult to discern during visual inspection of the cuttings. In thin section it was observed to make up as much as 50% of the "clay" alteration.

Carbonate alteration was observed to be represented by three species. Calcite the most common, followed by dolomite and then by a manganese-rich calcite. All of the carbonate was seen as veins and micro veinlets in the drill cuttings. Calcite flooding is very pervasive and thought to reflect a regional overprint.

Dolomite is associated with other carbonate veins and is considered to be part of a quartz-calcite-dolomite vein system independent from the regional calcite overprint.

The remaining carbonate in the vein system is seen as psilomelane-rich calcite. The psilomelane is present as inclusions within the calcite.

Silicification is found in several different modes. The most pervasive is microveinlets of milky white quartz distributed generally within the central portion of the Mystic shear complex.

Additionally there are quartz selvages within the mixed carbonate veins. The timing of the quartz alteration phase is complex. Some of the veinlets cross-cut the shear foliation while a high percentage of the quartz within the veins exhibit a fault-induced fabric, seen as a cleavage.

Adularia is observed only within quartz carbonate veins as cross-cutting microscopic veinlets. It appears to be late in the overall alteration paragenesis. The abundance of adularia is fairly minor when compared with clay, sericite, and quartz.

Chlorite and epidote veinlets and flooding were found in the trenches and the drill cuttings. The degree to which these minerals are a relict of greenschist metamorphism is not clear. Certainly the chlorite within the most intense portion of the clay-sericite alteration is probably hydrothermal. The epidote and chlorite peripheral to the Mystic shear is of questionable origin.

Visible gold in the drill cuttings is present only within the Mystic shear zone. It can be located virtually anywhere within the shear however. It is present as very coarse-to fine-grained particles generally only partially coated by clays and iron oxides. Samples of panned concentrates from the drill cuttings indicate that about 15% of the gold contains quartz "matrix". The rest is free of "matrix" minerals.

Alteration mineral association with gold is not absolutely confirmed. Factor analysis of the drill log data and assays indicates that gold has only one direct association, which is silver. A subset of the data from the deeper portions of the drill holes, below most of the apparent effects of supergene enrichment, begin to indicate that there is a quartz-gold association.

During an SEM investigation of panned concentrates from drill samples, quartz, ilmenite, and hematite were found to be attached to some of the gold.

The coarse-grained nature of the gold is partially responsible for the large nugget effect reflected in the assay results. The degree to which the reserve calculations reflect this problem is unknown. The true degree of the nugget effect on the sampling can not be determined until bulk samples are collected and analyzed.

Summary

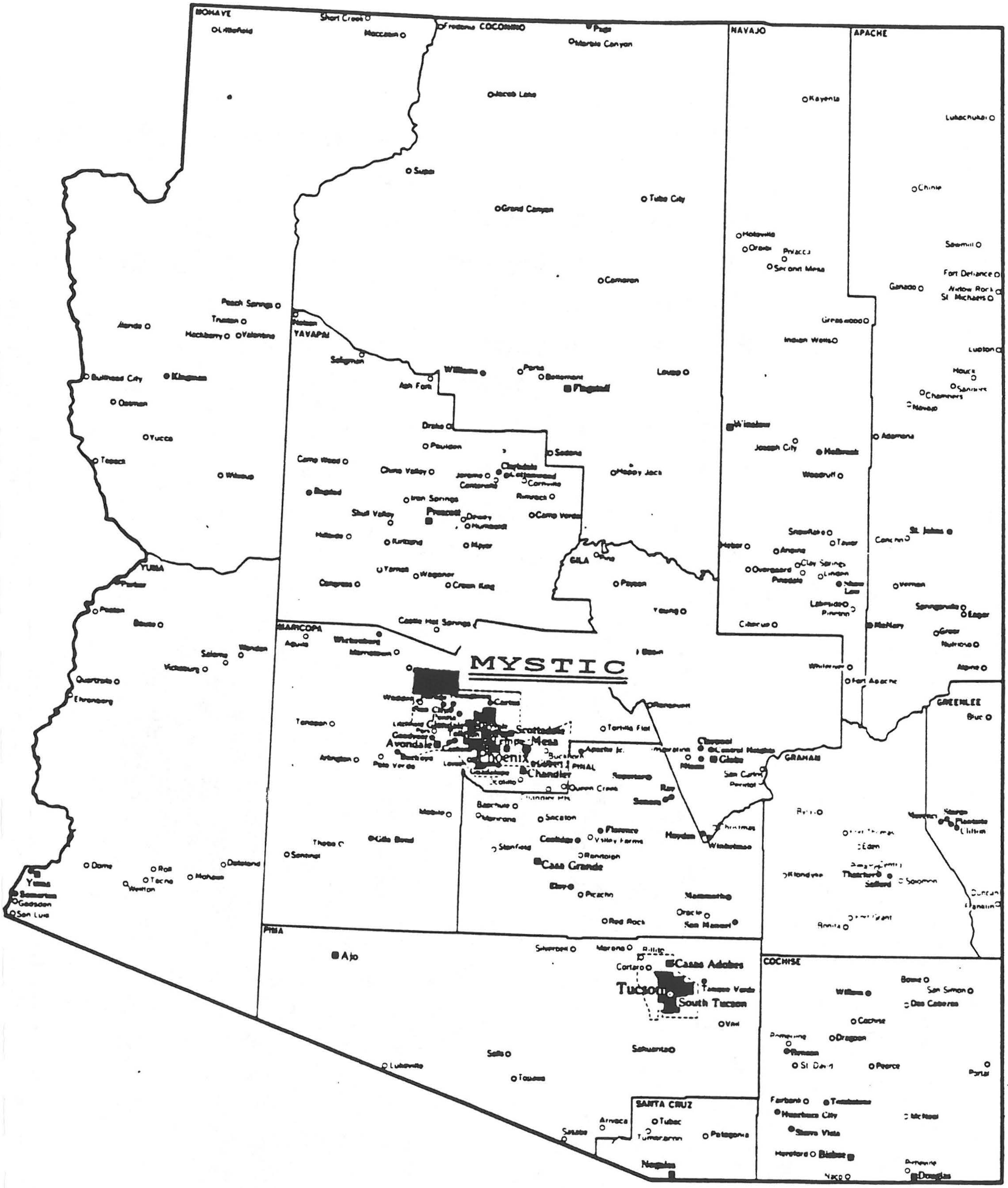
The mystic project has encompassed several phases of exploration. As a result a "probable" reserve of gold ore exists at the Mystic of 37,600 tons of 0.423 opt Au, using a conservative calculation based on cross section and long section data. Potential for increasing these reserves exists along strike to the west as well as at depth directly adjacent to the Harding pod.

This geologic environment depicts a Tertiary-aged epithermal gold system localized along and within a wide and northwest trending fault system that overprints and juxtaposes Precambrian metamorphics and Tertiary volcanics. The associated alteration of quartz, sericite, clays, and hematite is fairly typical of some epithermal gold deposits of the Southwest.

Potential for additional reserves exist both to the west and in a down dip direction.

Acknowledgements.

The author wishes to thank Fisher-Watt Gold Co. Inc. for permission to publish these data. Additionally my deepest gratitude to Mark C. Olm and J. Vance Longley. Without their keen insight and drive this project would have never been undertaken or completed.


MOHAVE
COCONINO
NAVAJO
APACHE
YAVAPAI
YUMA
MARICOPA
GILA
GREENLEE
GRAHAM
PINAL
PIMA
COCHISE
SANTA CRUZ
MYSTIC
Phoenix
Scottsdale
Mesa
Chandler
Avondale
Casa Grande
Tucson
South Tucson
Casas Adobes
Ajo
Yuma
Kingman
Flagstaff
Grand Canyon
Tuba City
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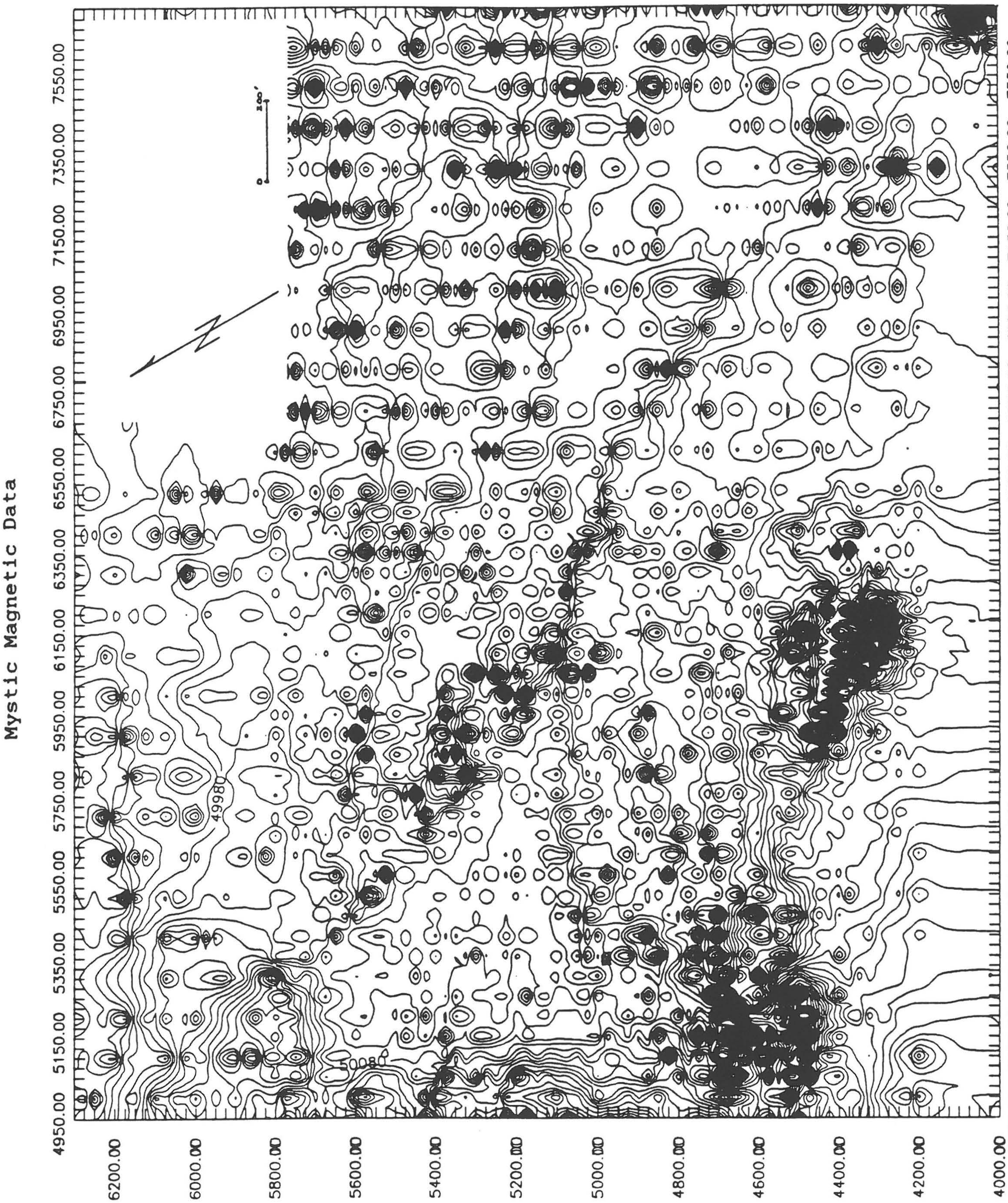
Prescott
Sedona
Payson
Globe
Florence
Safford
Nogales
Bisbee
Douglas

Figure 1



Mystic Magnetic Data
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5150.00
5350.00
5550.00
5750.00
5950.00
6150.00
6350.00
6550.00
6750.00
6950.00
7150.00
7350.00
7550.00
6200.00
6000.00
5800.00
5600.00
5400.00
5200.00
5000.00
4800.00
4600.00
4400.00
4200.00
4000.00
4998
5008

Figure 5

EXPLANATION

UNIT #	DESCRIPTION
1	Precambrian metavolcanics, intermediate chemistry. Hornblende plagioclase quartz epidote chlorite schist.
2	Brecciated zones. Diverse lithologies within the "Mystic Shear" showing various degrees of rotation and comminution.
3	Basaltic-andesite dikes. Post or very late kinematic. Generally highly clay-altered. Plagioclase and pyroxene phenocrysts set in an aphanitic matrix completely altered to clay.
4	Black quartz-carbonate veins. Carbonate is mostly black calcite. Quartz regions of the veins generally contain small amounts of adularia.
5	Precambrian mafic metavolcanics. Hornblende plagioclase epidote chlorite schist to semi-schist.
6	Red aphanitic welded volcanic ash or hypabyssal dike; moderate to strong clay alteration. Probably intermediate to felsic chemistry.
7	Carbonate-poor quartz veins. Pre-or syn-kinematic as evidenced by weakly developed shear cleavages. Veins consist of quartz, adularia, clay, minor carbonate as calcite and dolomite, and various iron oxides.
8	Mafic dikes. Post brecciation, aphanitic, chloritic and calcareous. Basaltic chemistry.
KTv	Tertiary volcanic cover. Felsic ashes and tuffs, usually well laminated. Subscript "r" and "g" designate red or grey subunite.
14	Feldspar porphyry dike. Large phenocrysts of plagioclase and potassium feldspar set in a grey aphanitic matrix of mixed quartz and clay-altered feldspars. Quartz latite porphyry to quartz dacite porphyry.
15	Coarse lithic breccia. Rock fragments range from 0.1" to 6.0" and consist of Precambrian schists and "bull quartz" set in a matrix of rock flour altered to chlorite and muscovite. Comminution is minimal but fragment rotation is complete. entire exposure shows iron staining.
Qfg	Quaternary fanglomerates.

SYMBOLS

- Shear foliation
- Metamorphic foliation.
- Jointing.
- Fault.
- Brecciation.
- Lithologic contact, dashed = approximate dotted = inferred location.
- Alluvial contact.
- Drill hole, reverse circulation.
- Drill hole, air track.
- Geochemical sample location.
- Old mine workings.

GEOLOGIC MAP OF

THE MYSTIC MINE AREA

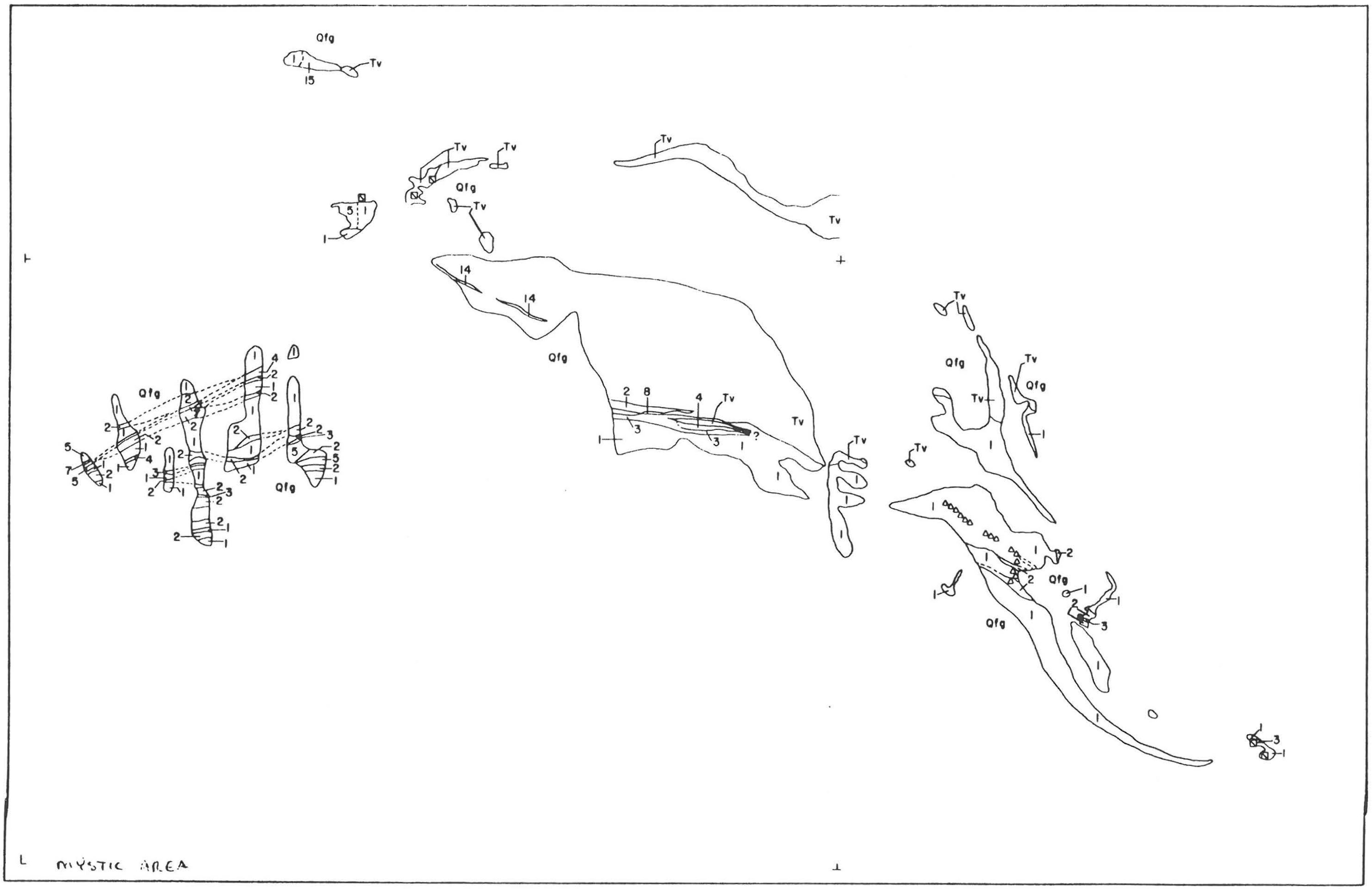
CENTRAL ARIZONA
SECTIONS 11 & 12, T.5N., R.1W.
SHEET 1 OF 3

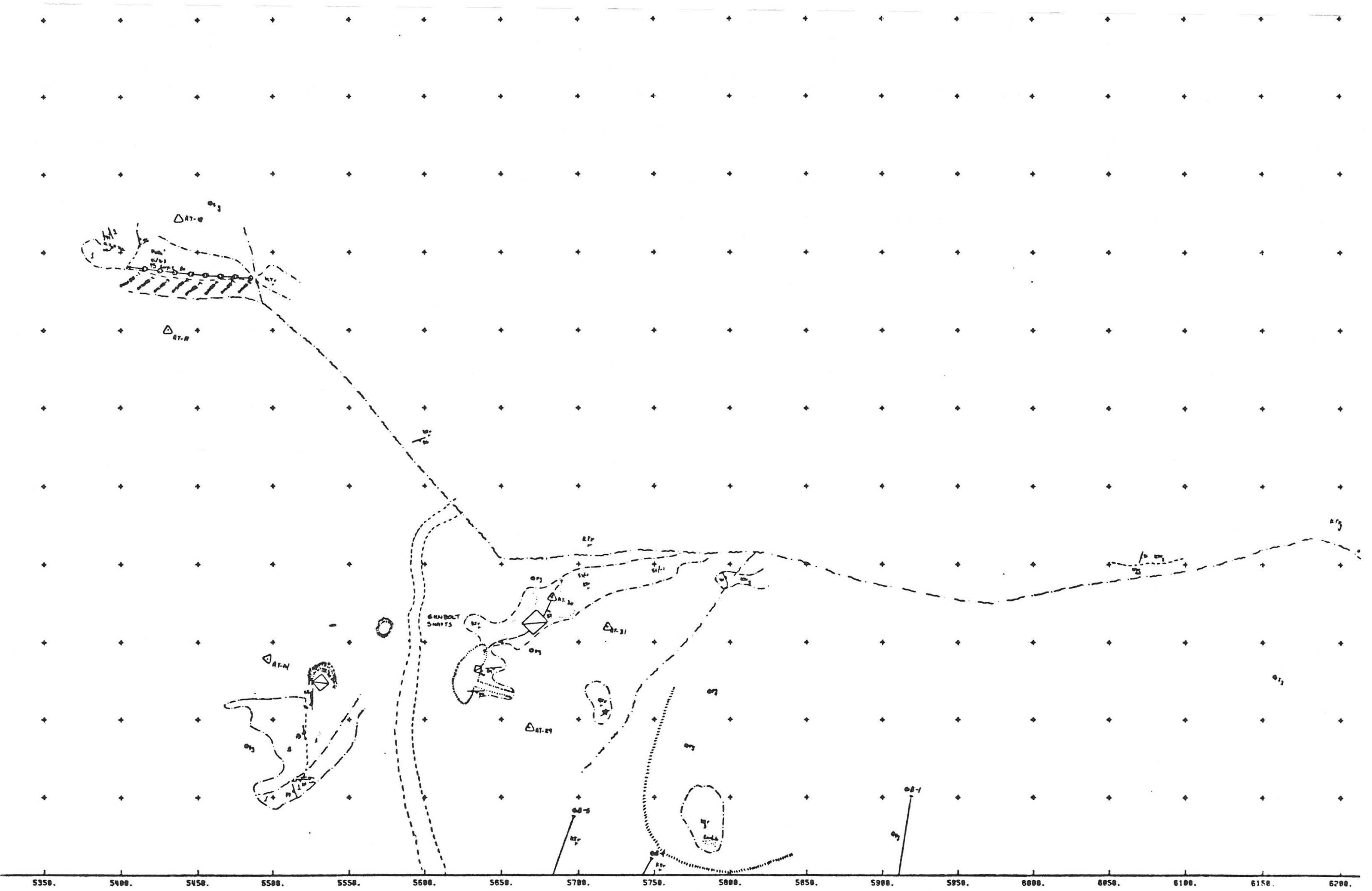
DALE G. ARMSTRONG
CONSULTING GEOLOGIST
TUCSON, ARIZONA

SCALE: 1:480 — 4/88

4700. 4650. 4600. 4550. 4500. 4450. 4400. 4350. 4300. 4250. 4200.

5700. 5750. 5800. 5850. 5900. 5950. 6000. 6050. 6100. 6150. 6200. 6250. 6300. 6350. 6400. 6450. 6500.


Qfg
Tv
15
14
MYSTIC AREA



GUNBOLT
SHAFTS
5350.
5400.
5450.
5500.
5550.
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5650.
5700.
5750.
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5850.
5900.
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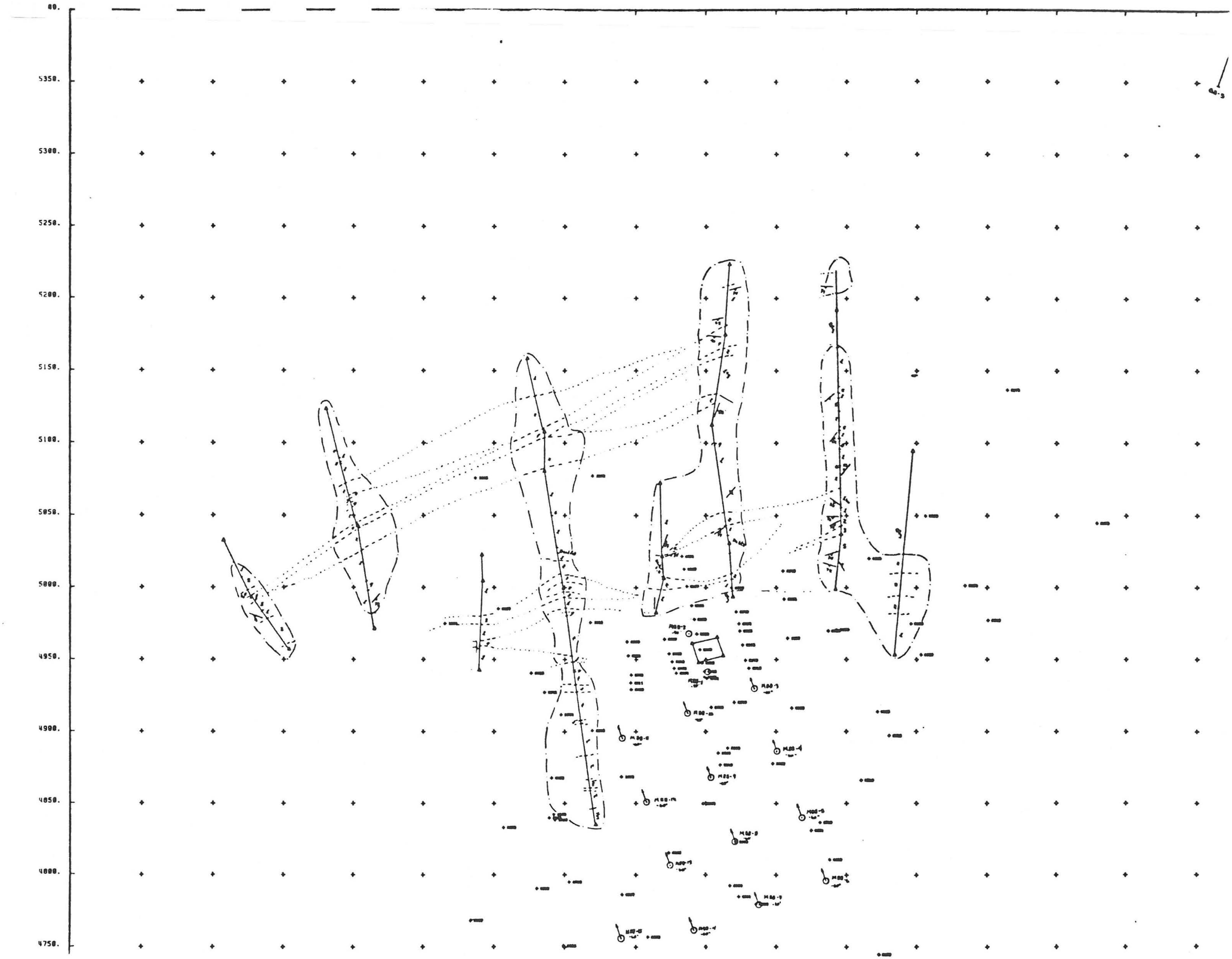

80.
5350.
5300.
5250.
5200.
5150.
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5000.
4950.
4900.
4850.
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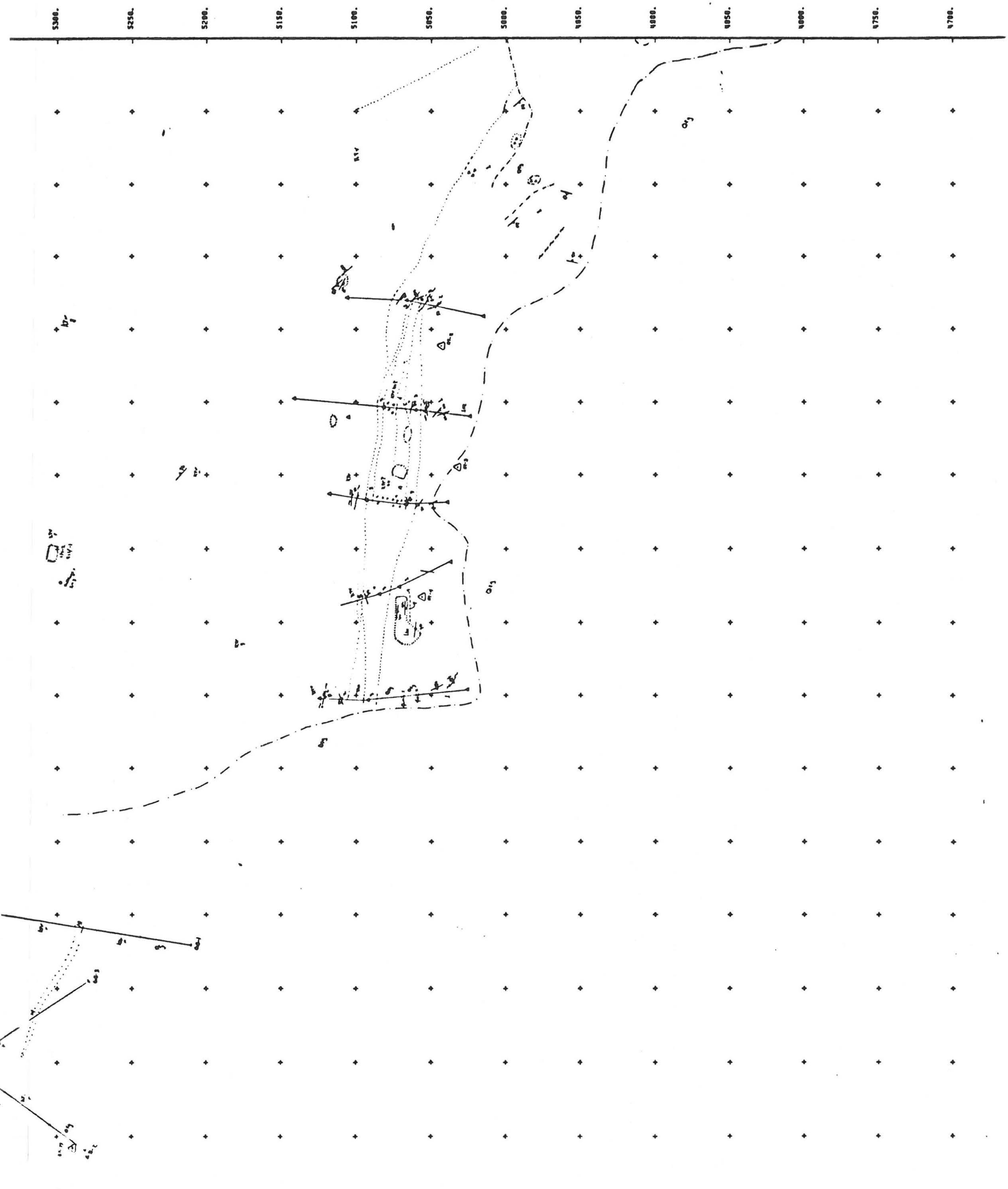
4750.


5300.
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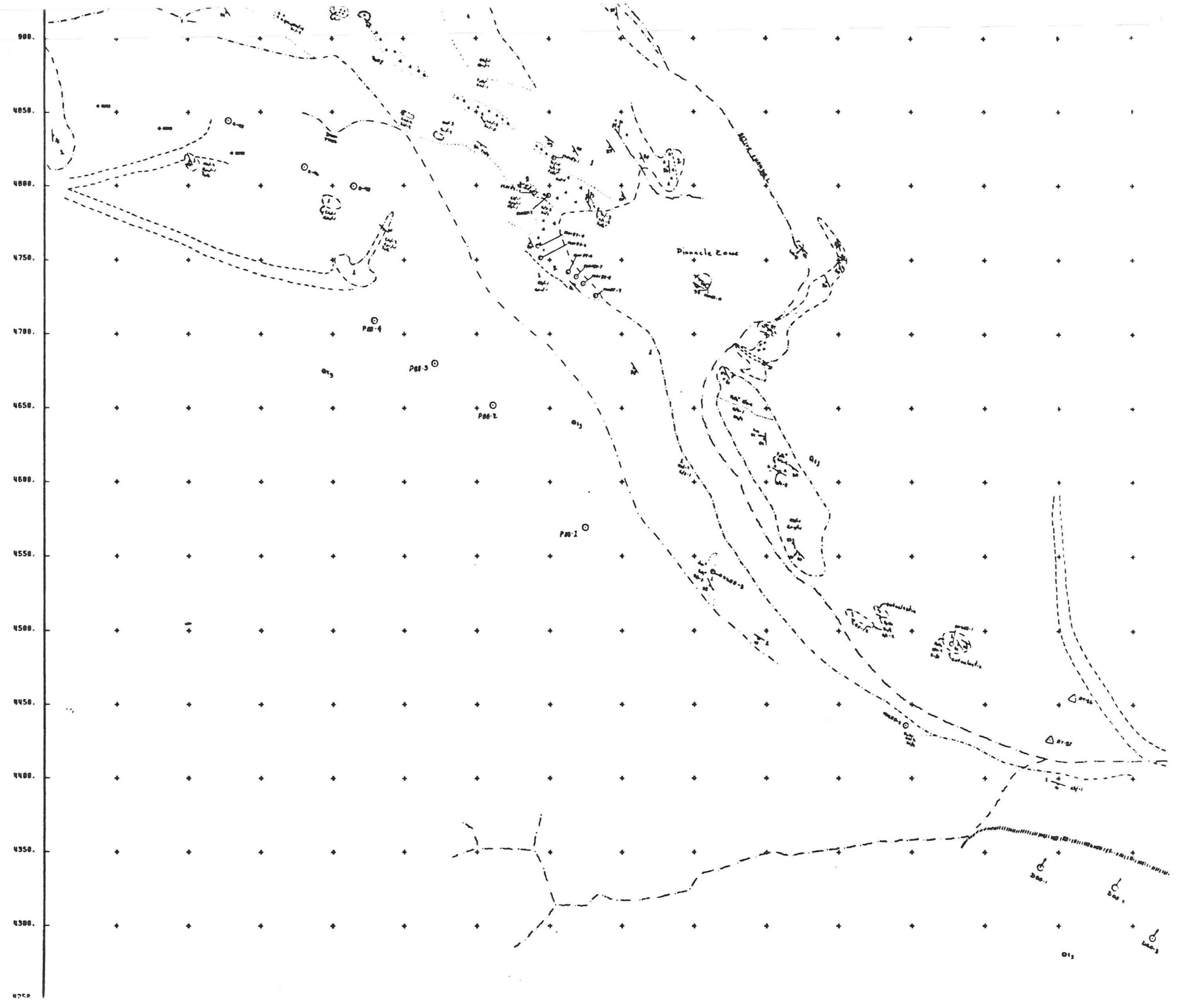


900.
4850.
4800.
4750.
4700.
4650.
4600.
4550.
4500.
4450.
4400.
4350.
4300.
Pinnacle Zone
PBB-1
PBB-2
PBB-3
PBB-4

CLEMENTINE MINE AREA, MARICOPA COUNTY, ARIZONA

David E. Wahl, Jr., Consulting Geologist
P.O. Box 10758 Scottsdale, AZ 85271

Introduction: The Clementine mine is located within SW/4 Section 10, T. 5N, R. 1W, G&SRPM, in the southern Hieroglyphic Mountains approximately ten miles north of Sun City, Arizona. The Clementine mine is a small inactive open pit that was operated briefly in the early 1980's by Copper Lake Mining Company. Copper Lake reports reserves of slightly more than 900,000 tons grading ca. 0.05 oz/ton Au in the inactive pit area. Approximately 70,000(?) tons of mine-run, uncrushed material were cyanide heap-leached, and precious metal recovery was low. In late 1981, this worker spent about fifteen field days mapping Clementine project area geology and collecting seventy-nine samples for gold analysis.

Geologic Synopsis: Oldest exposed rocks in the Clementine area are subvertical, variably foliated northeast-trending members of Early Proterozoic Yavapai schist whose protolith may represent a strand line to marine volcanic basin facies tract. Strand line facies rocks are characterized by quartz-rich metasiltstones and metasandstones. The deeper-water facies is composed of carbonate-rich metasediments (marls, shales, volcaniclastics) that contain cherty iron formations and recrystallized silica/carbonate exhalites. A Late Proterozoic(?) granodioritic plug intrudes schist approximately one mile south of the Clementine open pit.

Mid- to late-Tertiary volcanic rocks unconformably overlie and intrude the Proterozoic units. Basal andesites are locally altered and contain mineralized dark carbonate veins. Younger silicic flows and tuffs originated from at least two vents in the Clementine mine study area. The largest vent is located approximately one mile northeast of the Clementine pit. Although most exposed silicic rocks are not altered, small pods of altered intrusive(?) rhyolite have been observed. Youngest rocks in the project area are late Tertiary/Quaternary basalt caps, and colluvial-alluvial cover that occurs most extensively as valley fill.

Structure: Proterozoic rocks are isoclinally folded, and three distinct fault systems exist within the Clementine area. Generally steep, NW- to N60W-trending faults are regionally extensive, and high angle NE-oriented faults are locally well-developed. A low- to moderate-angle EW-trending fault with possible right lateral offset is exposed at the Prince mine.

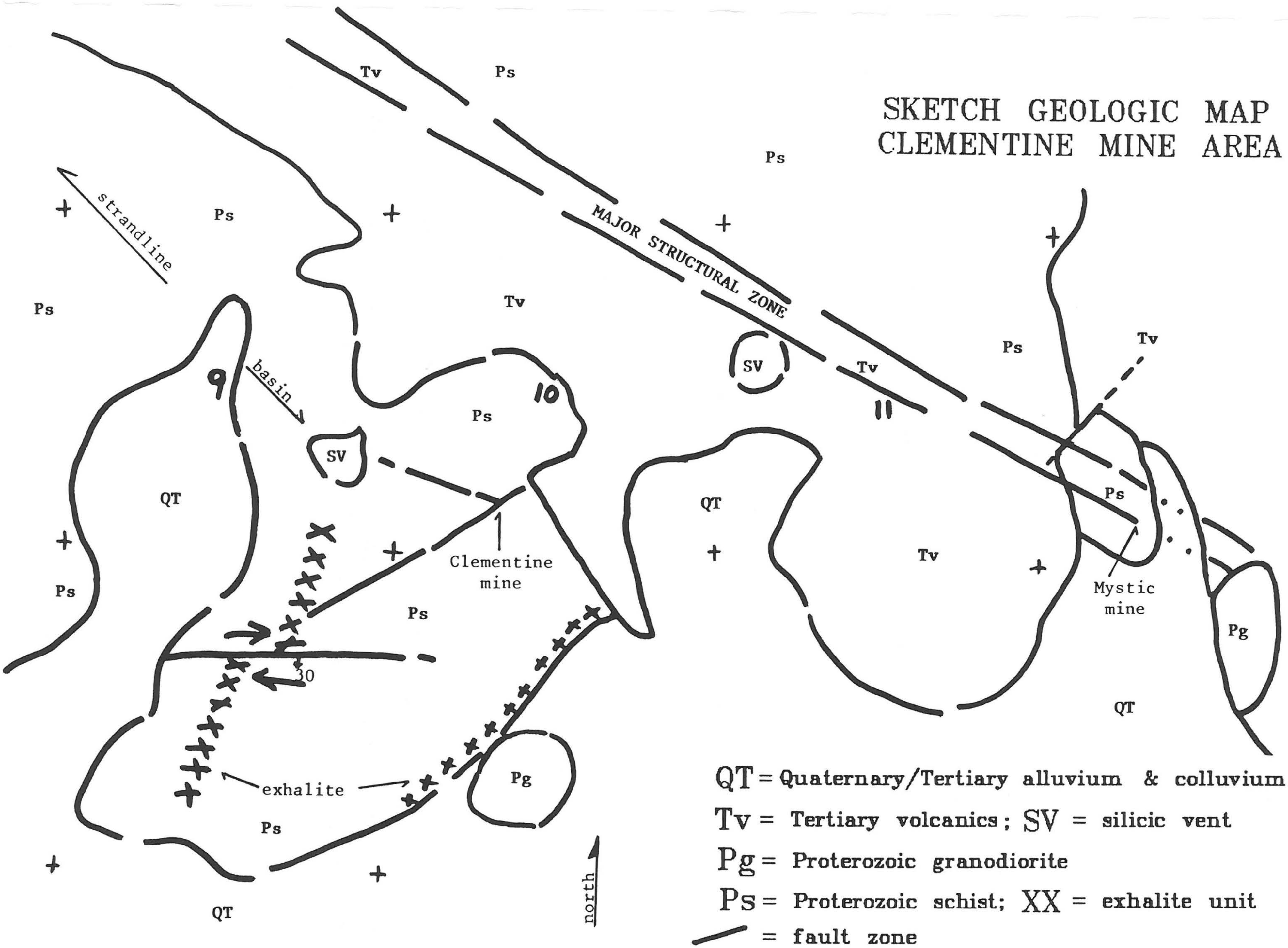
Mineralization: Clementine open pit mineralization appears to be concentrated in quartz/calcite veinlets within a shattered zone at the projected intersection of N60W and NE fault zones. Copper Lake Mining Company drill information suggests that a metamarl may be a favorable host rock in the pit area. Major pit mineralization dips SSE at 35 to 40 degrees.

My limited property-wide sampling (all analytical work done in house by Copper Lakes Mining Company) suggests that certain Proterozoic stratigraphic units are gold-enriched, and could have been at least a partial source for gold mineralization found in later vein systems. The carbonate-rich, gold-anomalous low angle vein at the Prince mine is best developed where it cuts a Proterozoic carbonate-rich exhalite layer.

Source of hydrothermal fluids which produced mineralized quartz/carbonate veining is uncertain. Although fluids migrated along fault zones associated with regional tectonism, it is possible that local volcanic vent zones and buried intrusive feeders could have affected hydrothermal fluid generation and transport.

Field Trip Objective: My experience in the Clementine mine area is limited. The main objective of this mine visit is to compare Clementine area mineralization with nearby better-understood mineralized systems that will also be visited during this field trip (Mystic mine, Armstrong; Newsboy mine, Bickford). Comments from other workers on Clementine area mineralization, structure, stratigraphy, etc., are actively solicited.

SKETCH GEOLOGIC MAP
CLEMENTINE MINE AREA



QT = Quaternary/Tertiary alluvium & colluvium

Tv = Tertiary volcanics; SV = silicic vent

Pg = Proterozoic granodiorite

Ps = Proterozoic schist; XX = exhalite unit

— = fault zone

Scale ≅ 1:24,000   DEW 11/15/90

LOW-ANGLE TECTONIC PHENOMENA

BETWEEN TUCSON AND SALOME, ARIZONA

ROAD LOGS AND DISCUSSIONS

PHOENIX TO WICKENBURG

by

Stanley B. Keith[1], Stephen J. Reynolds[1],

William A. Rehrig[2] and Stephen M. Richards[3]

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From 1981 AGS field trip #7,
Relation of Tectonics to Ore Deposits
in the Southern Cordillera

district in the Heiroglyphic Mountains. In January 1980, Ranchers Mining Development Company announced a significant gold find in the Heiroglyphic Mountains with reported gold-rich intercepts in drill core that assayed as high as 3.46 oz./T. All of the excitement is currently centered on the Mystic claim group (N½, SW¼, Sec. 12, T5N, R1W) about two miles south-southeast of Saddleback Mountain. The claims were originally located by Albert Harding, a retired Mining Engineer from Sun City who began prospecting in the area about 1973. Drilling financed by Mr. Harding has established an indicated 20,000 tons of ore averaging 0.7 oz. of gold per ton with slightly lower values of silver. The block is open on all sides and at depth (below 500 feet). Five foot drill sections assayed as high as 19.11 oz. of gold per ton (Harding report on file at Arizona Department of Mineral Resources in Phoenix). It is interesting that the present gold ore tonnage has been established entirely by drilling; there is no surface indication of high grade gold ore.

The mineralization appears to be localized along a fracture that cuts Precambrian schist. The fracture zone strikes N75°E, dips about 65 to 70° NW and is at least 1,200 feet long and three to five feet wide. A foliated andesite-like dike occupies much of the fracture. Apparently, very little to no quartz is present although calcite stringers and hematite are common. Ranchers now has several drill rigs operating at the property. The Mystic property is part of the old Pikes Peak district that to date has yielded a comparatively small amount of reported production (10,992 pounds of copper, 7,287 pounds of lead, 1,118 ounces of silver and 1,162 ounces of gold from 2,147 tons of ore). Obviously, the future of the district, is much more golden (sic).

1.4

15.6 Roadcuts on both sides of the road expose vertical to steeply southwest-dipping fragmental volcanics and volcanoclastics that have been deformed by several faults parallel to compositional layering.

0.5

15.1 Roadcut on right and most of the roadcuts in bedrock ahead are in Precambrian quartzitic schists that underlie the probably Miocene aged volcanic section in the eastern Heiroglyphics. In this area the volcanic section dies shallowly northeast. Foliation in the quartzitic schist here strikes N40°E and dips 65° SW.

3.1

12 A good view of the White Tanks Mountains, another presumed metamorphic core or crystalline complex, is seen at 9:00 to 9:30.

ledge forming cap dated at 15.9 m.y. by the K-Ar methods Scarborough and Wilt, 1979). The underlying predominantly clastic sediments contain a dolomitic unit that have anomalous radioactivity in cherty portions of the dolomite.

1.8

29 Pyramid Peak at the northwest end of the Deem Hills is at 9:15.

4.3

24.7 'T' Intersection and stop sign. Turn right and follow signs for Lake Pleasant where road curves left about 0.5 miles ahead.

1.7

23 Road ahead drips off uppermost terrace surface (the one we have been traveling on for the last several miles) and descends onto lower terrace levels along the Agua Fria river.

0.7

22.3 Stop sign. Turn left for Wickenburg.

0.3

22 Lake Pleasant turnoff on right.

0.1

21.2 Bridge over Agua Fria river. Roadcuts ahead are in generally flat-lying indurated conglomerates. To the west the conglomerate rests unconformably on probably Miocene age volcanics. To the north, on the west side of Lake Pleasant, the conglomerate rests in angular discordance on a tilted and folded sequence of tuffaceous sediments, minor fluvial fine-grained mudstones, locally interbedded with basaltic flows. One of the basaltic flows gave a K-Ar age of 16.6 m.y. (Scarborough and Wilt, 1979). The relationship of the dated sequence at Lake Pleasant to the volcanic rocks extensively exposed in the Hieroglyphic Mountains is unknown. The above relationships, however, suggest that the conglomerate exposed in the roadcuts on highway 74 represents older 'basin fill' in the senge of Scarborough and Peirce, 1978.

0.8

20.4 Roadcuts here and for next mile are in probably Miocene age volcanics intercalated with conglomerates.

1.6

18.8 Roadcut on left provides a good glimpse of structural and stratigraphic relationships within the Tertiary section. At the west end of the cut reworked waterlain sandy tuffs are intricately cut by small scale normal faults. The tuff sequence is overlain by a thin glassy ashflow and volcanoclastic rocks that are also cut by the normal faults. The entire sequence outlined above is juxtaposed against another section of waterlain tuffs by a southwest-dipping $N50^{o}W$ striking fault. These tuffs are also intricately laced with small-scale normal faults.

At the east end of the cut the waterlain tuffs are overlain by a monolighologic andesitic breccia. The andesitic breccia appears to post-date the intricate normal faulting that cuts the underlying tuff because its base truncates the normal faults.

Similar rocks and structural relationships are exposed in the next several roadcuts ahead.

0.8

18 Saddleback Mountain composed of more mid-Tertiary volcanics is the most southerly and prominant of the prominant knobs south of the highway.

1.0

17 You may have noticed several new appearing claim stacks along the road. These are part of the recent gold rush to the old Pikes Peak

205.6 Glendale Avenue exit.
1.3
206.9 Northern Avenue overpass. After passing overpass notice well-developed steeply-dipping Precambrian age foliation in the Phoenix Mountains schists. Several small mercury deposits composed of cinnabar, metacinnabar, and quartz occur in pockets within quartz-sericite schist. These deposits were first noted in 1916 and have since had a production of less than 100 flasks of mercury (Bailey, 1968).
2.1
209 Shaw Butte (2:30) is at the southern end of the Union Hills. North Mountain is at 3:00 with Lookout Mountain (3:30) is capped by probably Miocene-age volcanics.
2.7
211.7 Bell Road exit.
2.3
214. Hedgpeth Hills (9:30) and Deem Hills (11:30) are also composed of northwest-striking, northeast-dipping probably Miocene-age volcanics on strike with those at Lookout Mountain.
1.0
215 Pyramid Peak at 10:30.
1.0
216 Deer Valley Road overpass. Southeast end of Deem Hills are in near view (11:00).
2.0
218 Happy Valley Road overpass. Union Hills (12:00 - 3:00) consist of Precambrian schist in the northern protions and Precambrian granite locally overlain by probably Miocene-age volcanics in the southern portions.
2.0
220 New River Mountains on skyline at 1:00 are capped by thick flat lying baslats Two of these basalt flows have K-Ar ages of 14.7 and 14.8 m.y. (Scarborough and Wilt, 1979). The flat lying basalt section unconformably overlies (locally discordantly) a sequence of basaltic flows, white tuffs, agglomerates, mudstones and some distinctive very bright red lithic tuffs. One of the tuffs yielded a 21.3 m.y. K-Ar age and was very near a Miocene oreodont fossil find (Gomez, 1978; Scarborough and Wilt, 1979). The Miocene volcanic and sedimentary sequence unconformably overlies older Precambrian schists metavolcanics and granitoid rocks.
0.4
220.4 Interstate crosses aqueduct for Central Arizona Project (CAP) now under construction.
0.6
221 Bradshaw Mountains dominate the skyline at 11:00-12:00 and are composed almost entirely of undivided pre 1.4 b.y. granitic rocks.
2.6
223.6 Lake Plasant-Carefree exit (Arizona State highway 74). Merge right onto offramp.
0.4
Turn left onto State highway 74 for Lake Pleasant and Wickenburg.
0.1
30.8 Overpass over Interstate 17. Heiroglyphic Mountains on skyline at 12:00. Cuesta at 2:00 consists of a northeast tilted block of Miocene volcanics and sediments. The base of the cuesta contains poorly exposed sediments overlain in slight angular unconformity by a basaltic

Geologic Map of the Wickenburg, southern Buckhorn, and northwestern Hieroglyphic Mountains, central Arizona[1]

James A. Stimac, Joan E. Fryxell, Stephen J. Reynolds, Stephen M. Richard, Michael J. Grubensky, and Elizabeth A. Scott

1987
Arizona Bureau of Geology and Mineral Technology Open-File Report 87-9

INTRODUCTION

This report describes the geology of the Red Picacho quadrangle and parts of the Wickenburg, Garfias Mountain, and Wittman quadrangles (Fig. 1). Geologic mapping was completed between January and April of 1987, and was jointly funded by the U.S. Geological Survey and the Arizona Bureau of Geology and Mineral Technology as part of the cost-sharing COGEOMAP program.

GEOLOGIC OVERVIEW

The map area includes the Wickenburg Mountains and contiguous parts of the Buckhorn and Hieroglyphic Mountains (Fig. 1). Adjacent parts of the Vulture Mountains were mapped by Grubensky and others (1987) and adjacent parts of the Hieroglyphic Mountains were mapped by Capps and others (1986). The overall geologic history of the area is complex, but the regional stratigraphy developed in these reports carries well from range to range.

The map area is composed of a metamorphic-plutonic basement unconformably overlain by Tertiary volcanic and sedimentary rocks. The oldest rocks, assigned to the Proterozoic (1.8-1.7 b.y.) Yavapai Supergroup, consist of amphibolite, schist, and gneiss, intruded by granite, leucogranite, and pegmatite. Protoliths for the amphibolite, schist, and gneiss include both volcanic and sedimentary rocks.

Proterozoic rocks are intruded by Late Cretaceous granodiorite, granite, pegmatite, and aplite. Basement rocks are cut by numerous felsic and mafic dikes and sills related to Tertiary volcanism. In places, these dikes account for more than half of the outcrop area.

Crystalline basement rocks are unconformably overlain by Tertiary clastic sedimentary and volcanic rocks. Basal Tertiary deposits usually include a sequence of conglomerate, arkosic sandstone, and thin tuffs. The sedimentary rocks probably represent stream deposits formed shortly before and during early volcanism. Locally, deposition of clastic sedimentary rocks composed almost exclusively of basement lithologies persisted throughout early volcanism, which indicates topographic relief on basement rocks.

Tertiary volcanic and sedimentary rocks of the area can be divided into several temporal-compositional packages of regional extent. Volcanism was strongly bimodal throughout its duration, with basaltic and rhyolitic to dacitic lava flows and related tuffs accounting for at least 90 percent of the eruptive volume of the system. Extensive ash flow tuffs are conspicuously absent in the map area, as they are in the Bighorn Mountains (Capps and others, 1985), northeastern Hieroglyphic Mountains (Capps and others, 1986), and northeastern Vulture Mountains (Grubensky and others, 1987). Rare andesite flows occur interbedded with basaltic sequences.

Early volcanism was dominated by basalt flows, but rhyolitic flows and related tuffs are locally present. Early basalts are overlain by the San Domingo volcanics, a sequence of phenocryst-poor rhyolite flows and related lithic tuffs. This package is in turn overlain by the Hells Gate volcanics, a thick sequence of porphyritic dacite and rhyodacite flows and related tuffs. The volcanic section is cut

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[1]The complete version of this report is presented in OFR 87-9.

by numerous silicic and mafic dikes that served as feeders to the extrusive rocks. Dikes are more abundant in the early erupted basalt and rhyolite flows and tuffs than in the overlying dacite flows and tuffs.

The uppermost dacite flows in the Hells Gate volcanics are interbedded with and overlain by debris flows with clasts derived mainly from the dacite. Many, if not all, of the early debris flows are eruption related. Later debris flows tend to be heterolithologic, and probably formed in response to fault-related tilting and seismic activity.

Debris flows overlying the dacite package are interbedded with olivine- bearing basalts, megabreccia blocks of lower stratigraphic units, and immature fluvial clastic rocks. This complex package is synvolcanic, but grades upward into conglomerate and sandstone typical of post-volcanic sedimentary sequences in nearby ranges. The entire package was deposited in irregular-shaped half grabens that formed during the main episode of extensional faulting.

Structure

Volcanism was accompanied and followed by low- to moderate-angle normal faulting produced by northeast-southwest-oriented regional crustal extension. Major north- to northwest-trending moderate-angle faults, which dip 30 to 50 degrees to the southwest, cut and tilt Tertiary rocks and crystalline basement rocks, producing domino-style repetition of section. The largest of these faults have displacements of several kilometers and produce north to northwest-trending ridges that are usually capped by resistant rhyolite and dacite flows. They cut another set of low-angle faults that dip 5 to 15 degrees to the southwest, and that are common to the eastern Hieroglyphic, Wickenburg, and Vulture Mountains. Northeast- to east-trending complex fault zones probably functioned as boundaries for domains of differential extension and tilting during displacement on both moderate- and low-angle fault sets.

The low-angle faults have fairly irregular surfaces, probably in part due to original corrugations in the faults. They are interpreted as normal faults because they commonly carry tilted Tertiary rocks in their hanging walls, and, where they juxtapose pre-Tertiary crystalline rocks, the intrusive margin of the Cretaceous granite is progressively displaced westward (see cross section B-B').

The change from northwest-striking to north-northeast-striking ridges in the west central Wickenburg quadrangle probably formed as the result of drag on a major low-angle structure that separates basement lithologies from the overlying, steeply tilted Tertiary section. This fault probably has on the order of 5 km of displacement (see cross section C-C').

Evidence that faulting occurred during volcanism includes (1) generally steeper dips on the early volcanic section than on stratigraphically higher units, and (2) fault zones intruded by Tertiary dikes and sills, with local brecciation of dike rocks due to subsequent movement on those faults.

Pre-Tertiary structures in the map area include isoclinal folds within the foliation of the Proterozoic rocks and megascopic open to tight folds that fold the Proterozoic foliation. The foliation-related isoclinal folds are certainly Proterozoic in age, and the megasopic folds are probably also of Proterozoic age.

Mineralization

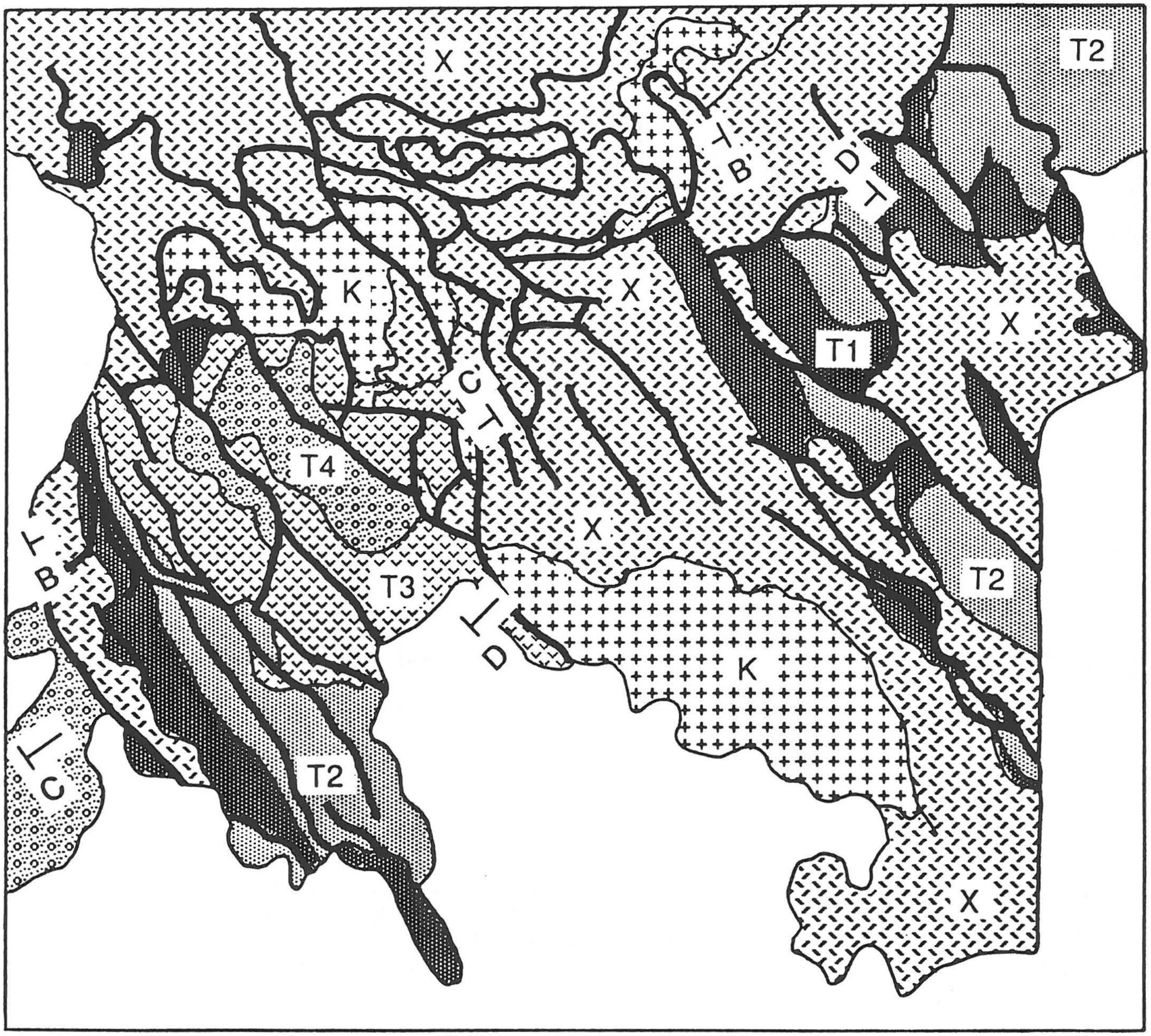
Precious- and base-metal prospects occur in both the Tertiary volcanic and sedimentary rocks and the crystalline basement. Many of the prospects are localized along low- to moderate-angle faults characterized by intense brecciation and quartz, calcite, and iron oxide veining. Such mineralization is middle Tertiary in age. Placer gold occurrences are common in several major drainages and their tributaries. The most productive deposits are in the San Domingo, Little San Domingo, and Ox Wash areas. Proterozoic metachert and metacarbonate lenses, interpreted as exhalites, are also potential prospecting targets for gold. Proterozoic Li-bearing pegmatites occur in the upper San Domingo Wash area.

MIDDLE TERTIARY VOLCANIC AND SEDIMENTARY ROCKS

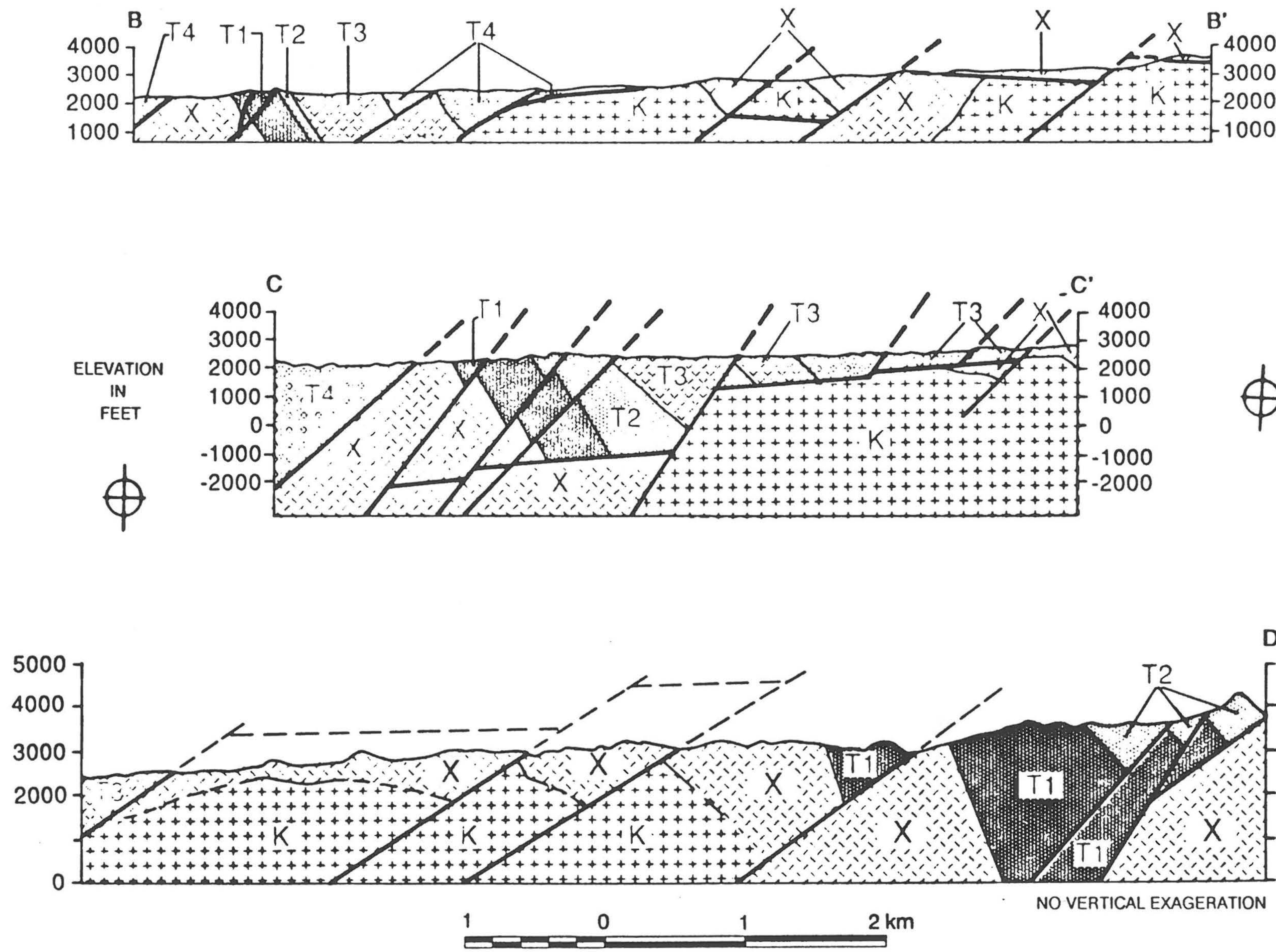
Tertiary rocks of the area overlie crystalline basement and consist of clastic sedimentary rocks, volcanic rocks, debris flows, and fanglomerate and related megabreccia. The volcanic rocks probably range in age from latest Oligocene to early Miocene. The youngest Tertiary rocks are fanglomerates and related megabreccia that accumulated during extensional faulting. Fanglomerate grades downward into a complex sequence of synvolcanic debris flows, megabreccia, clastic sedimentary rocks, thin tuffs, and olivine-bearing basalts. These units are underlain by a series of dacitic to rhyodacitic flows and tuffs, correlative with the Hells Gate volcanics of the northeastern Hieroglyphic Mountains (Ward, 1977; Capps and others, 1986). The Hells Gate volcanics also make up most of the Buckhorn Mountains in the adjacent Garfias Mountain and Copperopolis quadrangles. The Hells Gate volcanics are underlain by the San Domingo volcanics, a series of rhyolite flows and related tuffs. The San Domingo volcanics are interbedded with, and underlain by a series of basalt flows, and conglomeratic to arkosic sandstone lenses. The average thickness of the volcanic pile is roughly 1-2 km.

The volcanic stratigraphy has been subdivided into the following informal units (from youngest to oldest):

1) debrisflows,deposited duringandaftertheHellsGate volcanics;
2) upper basalt flows, deposited during and after the Hells Gate volcanics;
3) upper tuffs, deposited after the Hells Gate volcanics;
4) Hells Gate volcanics,composed of dacite andrhyodacite flows, tuffs, and debris flows;
5) San Domingo volcanics,composed of rhyoliteflows and tuffs;
6) lower basalt, basaltic andesite, and andesite flows; and
7) clasticsedimentary rocks, deposited prior to, during, and after volcanism.



See Fig 3 for Units.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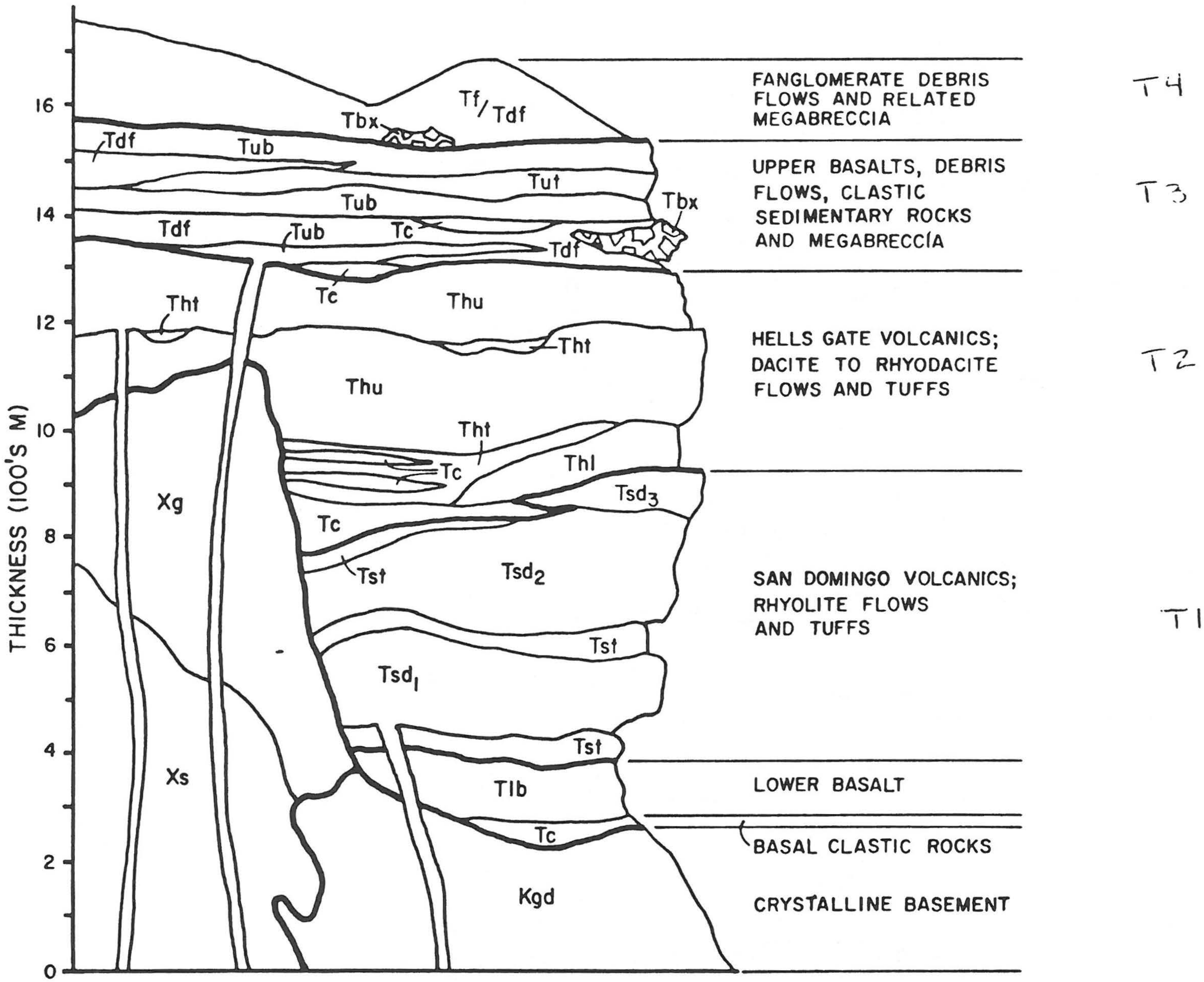

Figure 3. Schematic stratigraphic section for the San Domingo Peak area.

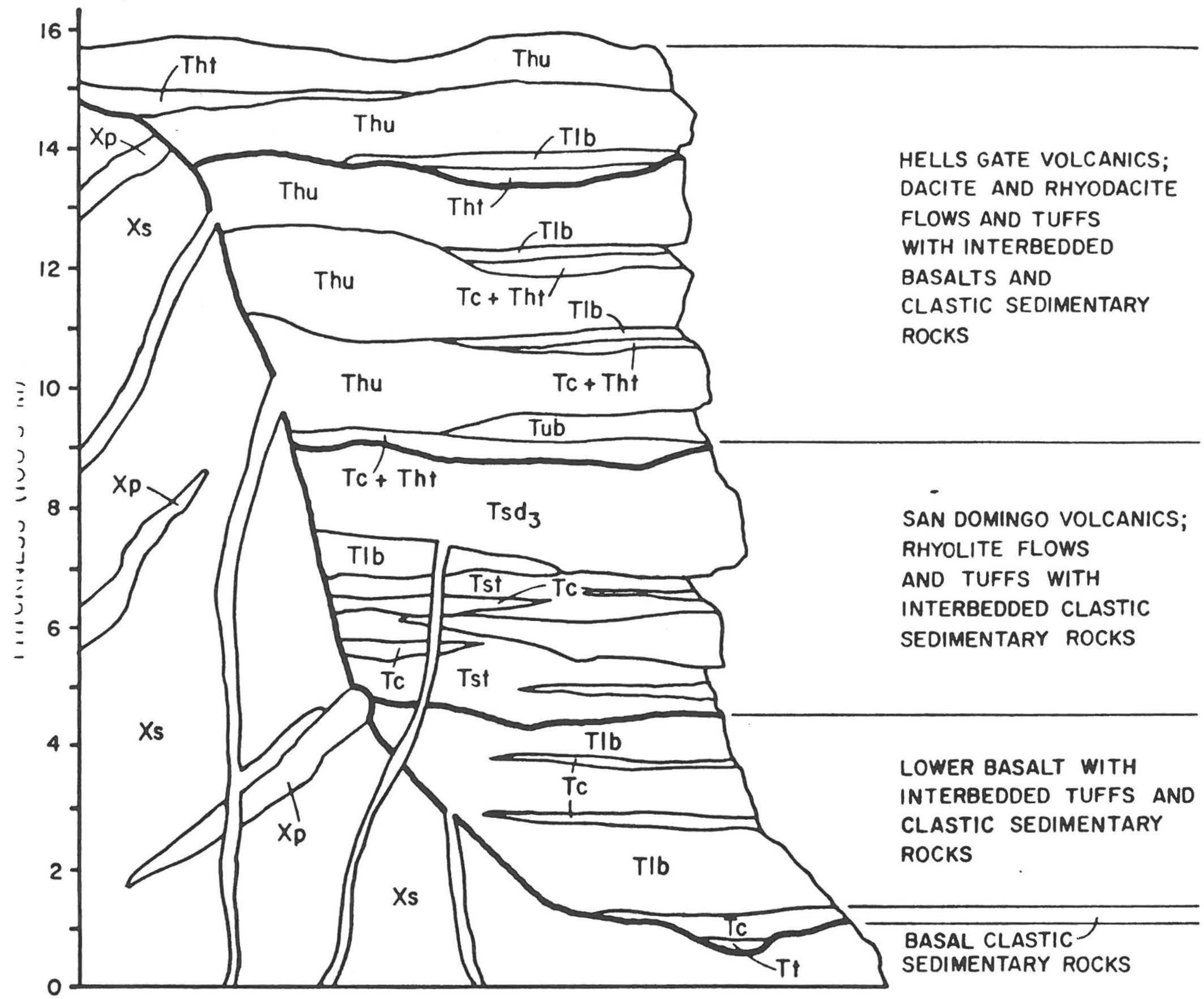

Figure 4. Schematic stratigraphic section for the Red Picacho and White Picacho area.

areas around the Black, Chemehuevi, Whipple, Buckskin, Harcuvar, Harquahala, Picacho, Rincon, and Pinaleno Mtns. They also extend to the west of the exposed windows of middle-crustal mylonitic rocks. Seismic lines west of the Old Woman Mtns. and near the So. Chocolate Mtns. suggest that the middle-crustal mylonitic rocks may continue for distances of at least 100-200 km to the west of the core complexes in California and several 100's of kms west of the Arizona complexes, indicating that the mylonitic rocks do not simply root to the northeast beneath the Colorado Plateau. Rather, a widespread zone of Tertiary reworking of the crust by distributed shear appears present. The regionally subhorizontal character of the reflections at mid-crustal level suggests that individual detachment faults probably descend to a mid-crustal zone of accommodation, rather than cutting through the entire crust. Many of the exposed mylonitic rocks are inclined WRT this accommodation zone, indicating that the regionally extensive mylonitic shear zone was disrupted after its initial formation and portions rotated to the surface during continued simple shear within the middle and lower crust. The three-dimensional interaction of such a regional zone of distributed simple shear is attractive to explain the progressive development of the overall detachment terrane on a crustal scale.

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SUPERIMPOSED DOMINO-STYLE NORMAL FAULTS IN A TERTIARY BIMODAL VOLCANIC COMPLEX, WICKENBURG MOUNTAINS AND VICINITY, CENTRAL ARIZONA

No 143031

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The Wickenburg Mountains, located along the boundary between the Basin and Range and Transition Zone Provinces, contain a suite of early to middle Miocene, high-potassium calc-alkaline volcanic rocks that overlie Proterozoic and Late Cretaceous crystalline rocks. Volcanism was strongly bimodal throughout its duration, with basaltic and rhyolitic to dacitic compositions comprising at least 90% of the volcanic rocks. Early volcanism was dominated by eruption of basaltic and phenocryst-poor rhyolitic lava flows and related rhyolitic lithic-rich tuffs. These rocks are overlain by a sequence of phenocryst-rich dacitic lavas and tuffs. Uppermost dacite flows are interbedded with debris flows, basalt flows, megabreccias, and fluvial clastic rocks that are synchronous with major extensional faulting.

The volcanic rocks are tilted 50°-70° ENE. The volcanic section and underlying Proterozoic rocks are repeated on two sets of NNW-striking imbricate normal faults. One set dips 40°-50° SW, and cuts the other, which is subhorizontal. Bedding-to-fault angles average 90° for the younger set, 60° for the older set, and both sets are consistent throughout the map area. The consistency of bedding attitudes, bedding-to-fault angles, and fault orientations indicates that these faults are planar, not listric. These relationships suggest the following sequence of events. Faulting began early during volcanic activity, although most extension followed the bulk of volcanic activity; faults initiated with NNW strikes and 60°SW dips. As extension progressed, the faults and fault blocks moved through about 30° of rotation. Then, a second set of faults formed, at a similar initial orientation as the first set, and moved through 20°-30° of rotation before extension ceased. Preliminary extension estimates of 130% and 150% are obtained, based on palinspastic reconstruction and on fault rotation, respectively.

GSA Abstracts of Programs 1987 (Phoenix meeting)

CONTRASTING ^{40}AR/^{39}AR THERMOCHRONOLOGY OF MINERALS FROM LOWER PLATE ROCKS OF THE BUCKSKIN-BULLARD-EAGLE EYE DETACHMENT FAULT SYSTEM, WEST-CENTRAL ARIZONA

No 143040

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Subhorizontal mylonitic fabrics with a N60E lineation overprint Precambrian to Tertiary(?) rocks through most of the Buckskin Mountains (BM), but only in the northeast end of the Harquahala Mountains (HM). Both ranges occupy the lower plate of the Buckskin-Bullard-Eagle Eye detachment fault system. Biotite and K-feldspar from the BM yield ^{40}Ar/^{39}Ar age spectra that record early Miocene cooling to argon closure temperature (<300°C) throughout the range, and middle Miocene reheating (<200°C) only in the northeastern BM. Amphibole age spectra in the northeastern BM indicate initial cooling to argon closure temperatures (~500°C) in the Paleocene and minor argon loss in the Miocene. Together these data suggest that (1) the detachment system was active in the Miocene, (2) the mylonitic fabric probably was developed at temperatures

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Fall 1990 Arizona Geological Society field trip
Newsboy gold deposit

Trip Leaders: Fred Bickford and Patti Tuve

The Newsboy gold deposit is located about 12 miles south of Wickenburg, Arizona. It is reached by leaving Route 60 at Morristown and driving two miles southwest on the unpaved Gates Road to the east bank of the Hassayampa River. Final access to the property is via a track across the usually-dry bed of the river. The center of the drill-defined ore body is located approximately 1500 feet beyond a cattle guard at the west bank of the river.

Gold reportedly was first discovered at the site as early as 1868, and various parties have conducted work there in the years since. During World War II, material that was mined from the site for smelter flux also earned gold credits. The ore deposit currently is being developed by Newsboy Gold Mining Company, which is engaged in mine planning and permitting. Knowledge of the ore deposit is derived from surface mapping, examination of limited underground workings, and drilling (reverse circulation and coring).

Lithologies at the site include a basement of dark green Precambrian biotite and chlorite schists overlain by Miocene rhyolite porphyry volcanics. The well-foliated Precambrian schists strike east-west and dip steeply to the north. The overlying felsic volcanics consist of flows, tuffs, and volcaniclastics. Mafic flows have been observed south of the deposit.

The contact between the volcanics and the schist is a shallow-dipping blanket-like breccia as much as 40 feet thick. Mineralization largely coincides with this breccia, which is known as the Newsboy Fault. In addition to the main body of mineralization, a thinner analagous blanket of mineralization locally occurs above the Newsboy Fault entirely enclosed within the volcanics. Precious metals grades are relatively consistent between holes within the drill-defined ore body. The in situ ore resource totals 5.8 million short tons at an average grade of 0.045 ounces per ton gold and 0.88 ounces per ton silver. Measured reserves total 1.8 million tons at an average grade of .048 ounces per ton gold and 1.25 ounces per ton silver. The deposit is largely open to the north and south.

The deposit and enclosing rock units are cut by a series of northwest-trending high-angle faults which result in the Newsboy Fault being progressively offset downward to the east. The deposit is terminated on the west by one of these high-angle faults, which is referred to as the Wash Fault. Mineralized breccia is exposed at the surface along the dry wash for which this fault is named. Several similar faults pass through the deposit east of the Wash Fault. It has been suggested that these faults may have served as conduits for the solutions which mineralized the Newsboy Fault, and the presence of mineralization in at least some portions of the faults can be taken as evidence for this possibility. A set of E-W trending high-angle faults is also present, but these faults are not clearly manifested.

Matrix material makes up a substantial fraction of the total rock volume in the breccia of the Newsboy fault, and black calcite is an abundant constituent of the matrix. Manganese oxide is common on fracture surfaces and more generally disseminated through carbonate matrix material. Several generations of cryptocrystalline silica can be seen. Yellow-green chalcedony is volumetrically most important. Veins of white opaline silica are of more restricted occurrence, and amethyst is seen rarely. Breccia fragments include rhyolite porphyry, carbonate, and rare blocks of Precambrian schist.

A 1988 Westmont Mining Company report distinguished three alteration assemblages associated with the deposit, which were seen as occupying layered zones coincident with or overlying mineralization. The zone of silica alteration (described in the preceding paragraph) encompasses the mineralization. The silica zone is overlain by the "Red Zone," consisting of kaolinite and iron oxide. Whether the iron oxide of this alteration zone represents weathered finely-disseminated pyrite or primary hematite is not known. The uppermost alteration zone is the "White Zone," which consists of an alteration assemblage of quartz, kaolinite, and alunite.

During this field stop there will be opportunities to see all of the major lithologies, exposures of the Newsboy and Wash Faults, and examples of the major alteration assemblages. Because of liability and safety issues, we request that our guests stay well clear of the accessible underground workings during their visit.

GEOLOGY OF THE NEWSBOY GOLD DEPOSIT

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The Newsboy gold deposit is located at the eastern edge of the Vulture Mountains and is along west side of the Hassayampa River. Pre-Tertiary bedrock in the Vulture Mountains consists of Proterozoic crystalline rocks that are intruded by Cretaceous granitoids. These rocks are intruded by Tertiary dikes and overlain by early to middle Miocene sedimentary and volcanic rocks. The Vulture Mountains have been affected by severe Miocene extension, and middle Miocene and older rocks are typically cut by southwest-dipping normal faults and tilted moderately to steeply to the east or northeast (Grubensky, 1989). The Vulture mine gold deposit in the southern Vulture Mountains is related to a Cretaceous granitoid stock (White, 1988; Reynolds and others, 1988; Spencer and others, 1989), whereas many of the smaller base and precious metal deposits in the Vulture Mountains are Tertiary in age.

The eastern third of the Vulture Mountains contain a diverse suite of mineral deposits that are known or likely to be Tertiary in age. These deposits can be broadly divided into two types, as follows: (1) fluorite veins, and (2) variably silicified and/or iron-stained shear zones containing significant amounts of at least one of the following: copper minerals, lead minerals, manganiferous calcite, and gold. Both types of deposits are hosted in some areas by Tertiary volcanic rocks and many are near or along Tertiary faults.

At the Newsboy deposit, Miocene rhyolitic volcanic rocks are juxtaposed against underlying Proterozoic crystalline rocks by a subhorizontal fault that is strongly mineralized (Fig. 1). Faults that extend from the subhorizontal fault upward into the overlying rhyolite are also typically mineralized. Mineralized areas typically contain hematite, black calcite, variably banded chalcedonic quartz, and rare amethyst. Gold is associated with silica. The volcanic rocks in the mine area are variably and commonly pervasively altered over a broad area (most of the area of exposure shown in Fig. 1). Alteration assemblages include quartz-kaolinite-alunite, kaolinite-iron oxide, and silica (Hasenohr and Dummett, 1989). The volcanic rocks were affected by the following sequence of mineralization and alteration: (1) pervasive silicification, (2) deposition of yellowish green chalcedony along faults, (3) formation of veins and veinlets of white, banded, opaline quartz, and (4) deposition of sparse amethyst. Veins and irregular zones of black manganiferous calcite were emplaced after silicification (Hasenohr and Dummett, 1989).

Studies of fluid-inclusion in quartz by E.J. Hasenohr (written commun. to W. Wilkinson, 1990) and by J. Duncan indicate that minimum temperatures of quartz deposition (homogenization temperatures) were between about 180°C and 280°C (Fig. 2). Freezing-point depressions from most inclusions indicate that fluid salinities ranged from less than 1 wt. % equiv. NaCl to about 15 wt. % equiv. NaCl. Freezing point depressions from two pseudosecondary inclusions indicated approximately 20 and 25 wt. % equiv. NaCl. It is not known if low or high salinities were associated with gold mineralization at the Newsboy deposit.

Gold is concentrated in silicified rocks along and for several tens of feet above the basal fault. Drill-hole assays clearly indicate that the anomalous gold concentrations extend locally downward into the footwall Proterozoic rocks (W. Wilkinson, unpublished data, 1990), which suggests that mineralization occurred after most of the movement on the mineralized faults. The Newsboy gold deposit has been estimated to contain 2 to 5 million tons of ore at a grade of 0.04 oz/ton Au (Hugo Dummett, oral commun., 1989).

In general it appears that base- and precious-metal deposits and fluorite veins in the eastern Vulture Mountains, including the Newsboy mine deposit, formed along or adjacent to Tertiary normal faults during or shortly after faulting. Circulation of mineralizing fluids was apparently related to Miocene tectonic and magmatic activity. It is possible that fluorite veins and base-metal dominated deposits in the eastern Vulture Mountains were derived from basin brines, whereas gold was derived from low-salinity fluids related to magmatism. The large range of fluid-inclusion salinities at the Newsboy deposit may be due to mineralization from both types of fluids.

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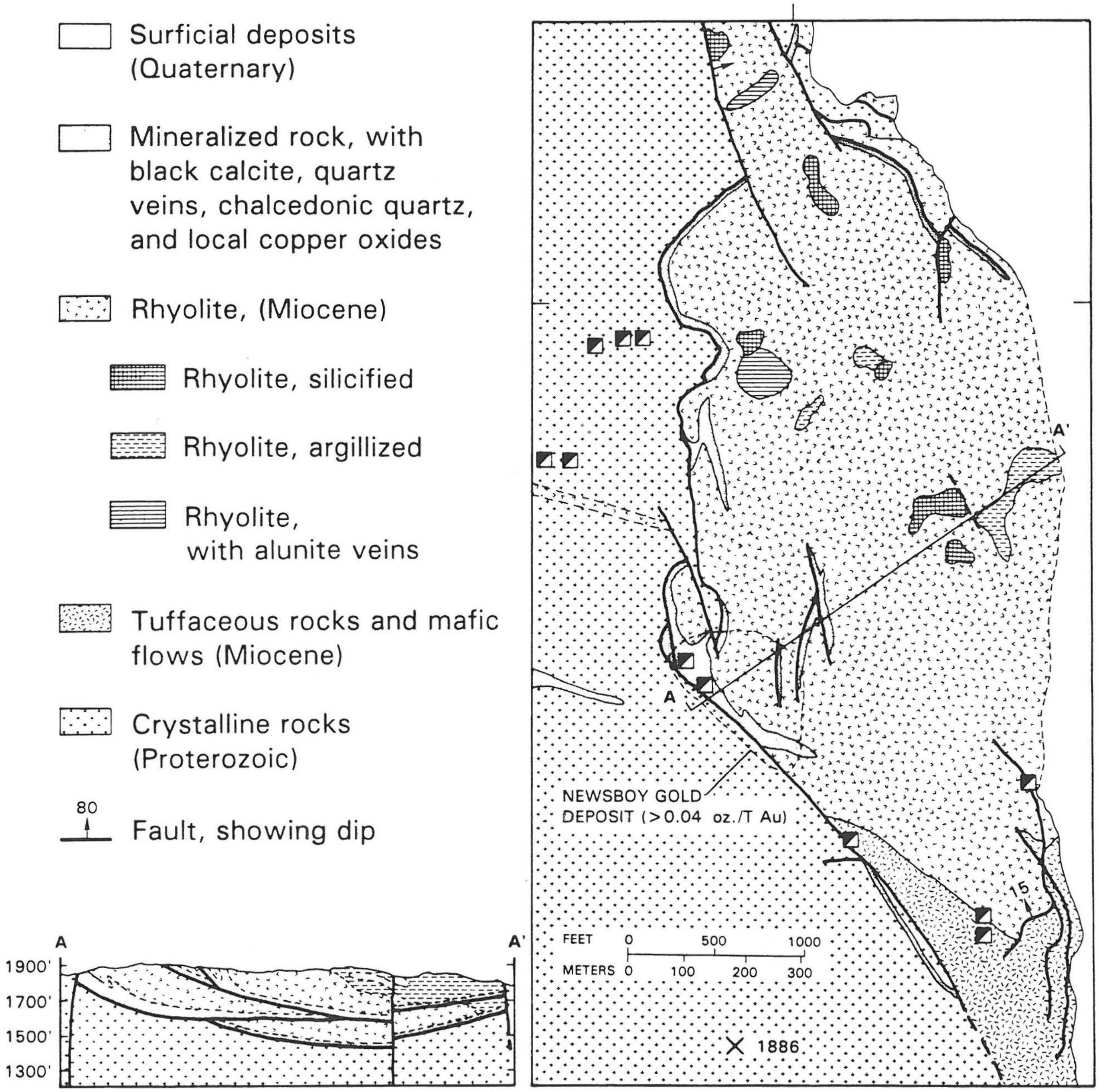


Fig. 1. Geologic map of the Newsboy mine area. Simplified from Zahony (1987).

NEWSBOY DEPOSIT - Fluid Inclusions

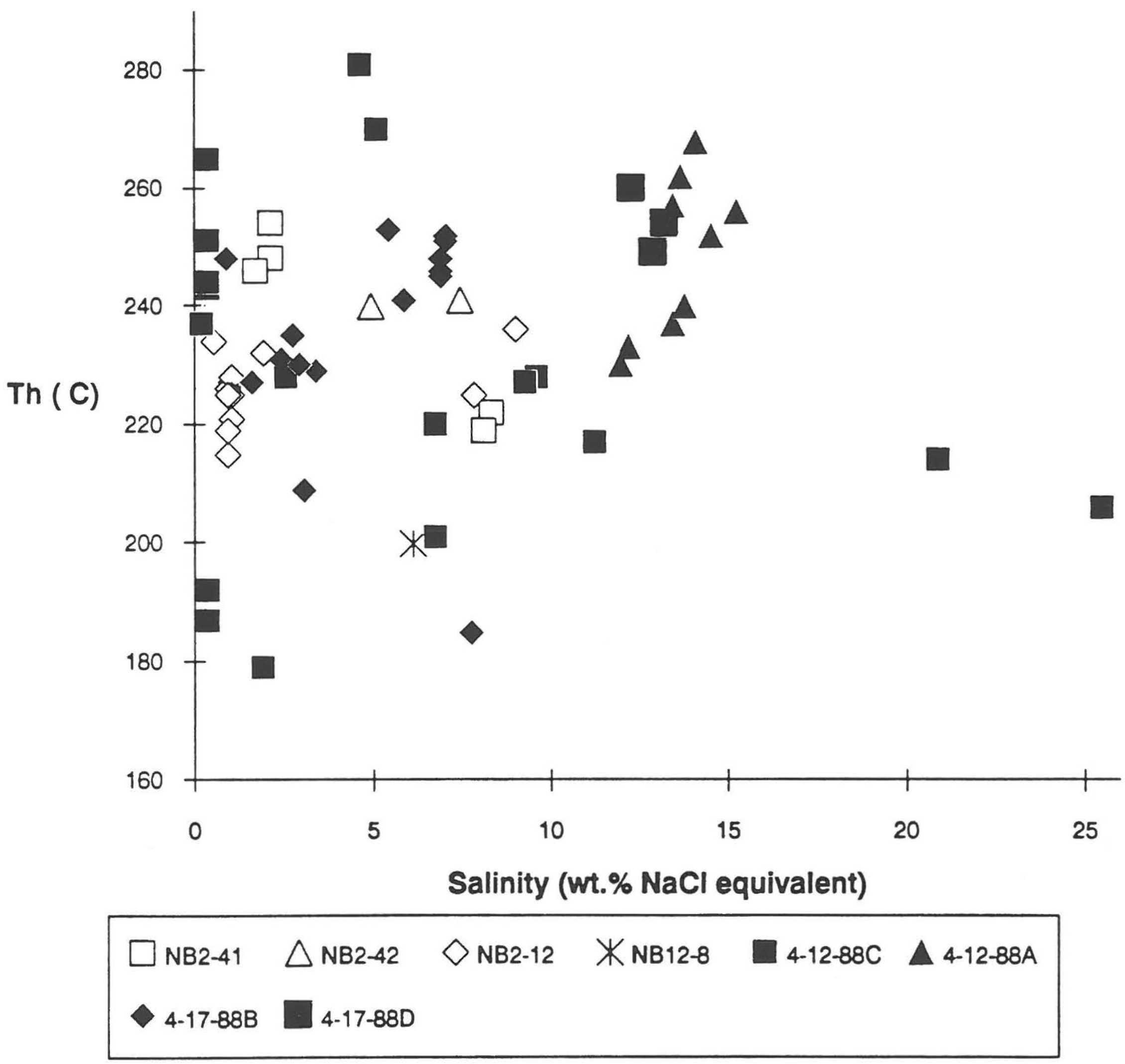
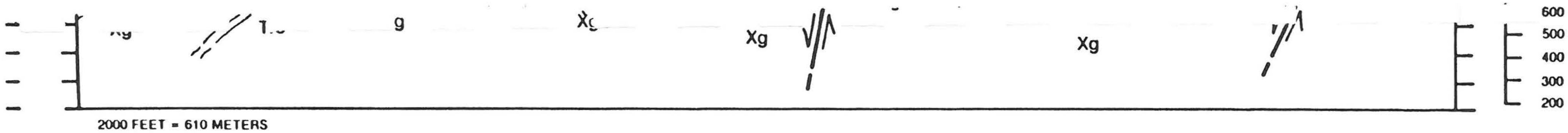
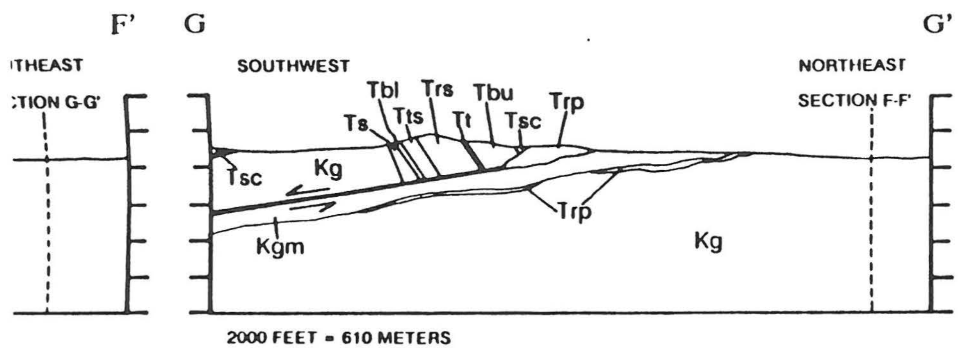
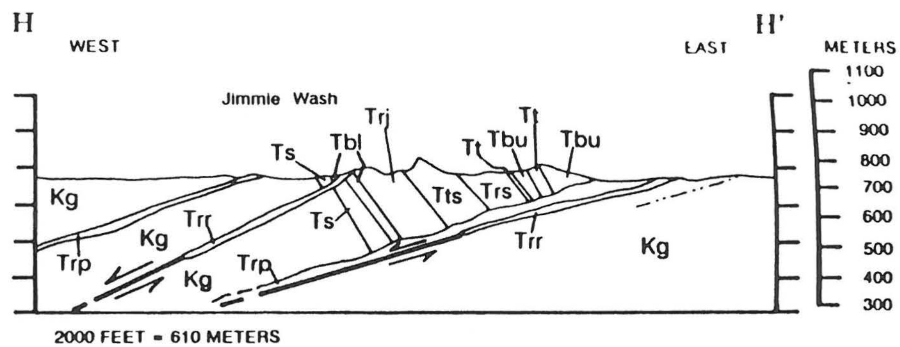
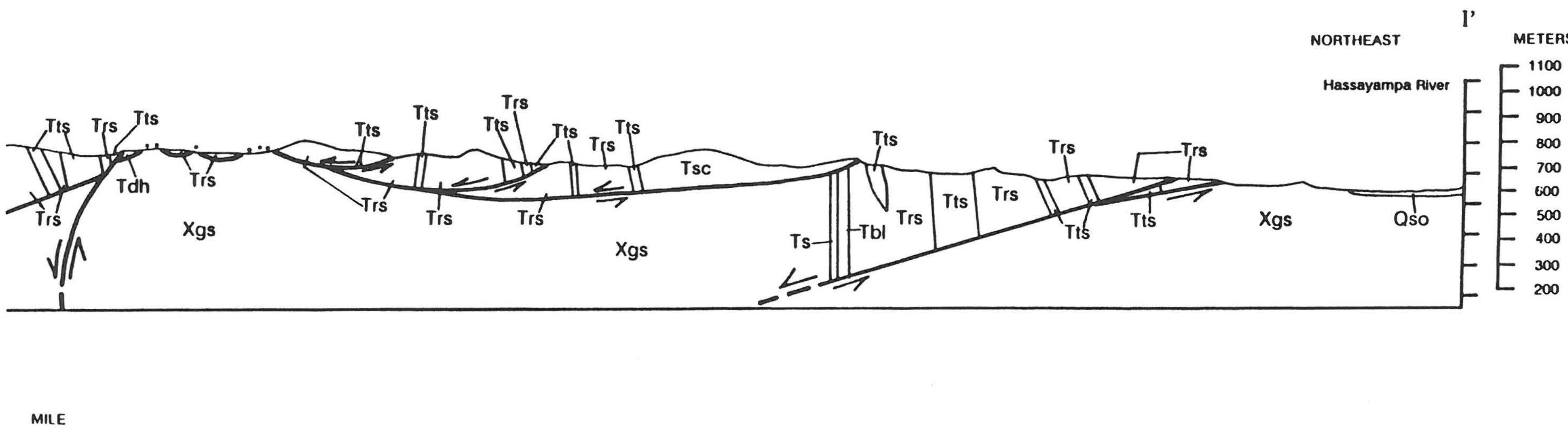


Fig. 2. Fluid-inclusion data from the Newsboy mine. Twenty-two of the 47 inclusions measured by J. Duncan were primary. All 47 are plotted here because primary and secondary inclusions did not differ significantly in homogenization temperature or freezing-point depression (4-88 samples). All 28 fluid inclusions studied by E. J. Hasenohr were primary (NB2 samples; written communication to W. Wilkinson, 1990).









Geologic sections of the Vulture Mountains, from M J Grubensky, AZGS map 27.

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GEOLOGIC MAP OF THE SOUTHEASTERN VULTURE MOUNTAINS, WEST-CENTRAL ARIZONA

by

Michael J. Grubensky and Stephen J. Reynolds

Arizona Geological Survey
Open File Report 88-9

July 1988

INTRODUCTION

The Vulture Mountains are situated in west-central Arizona, between the Big Horn and Harquahala Mountains on the west, and the Wickenburg Mountains on the east. Although a range of low relief, the Vulture Mountains are sufficiently areally extensive in that they cover all or part of eight individual 7.5 minute quadrangles. The geologic map of the southeastern Vulture Mountains (Fig. 1), a product of this study, covers the northern part of the Wickenburg SW 7.5 minute quadrangle. Most of the few precipitous bluffs and ridges of the range are in the eastern quarter of the range, and have roughly 200 m of relief. Detailed geologic mapping in the Vulture Mountains has been limited to the northeastern part (Grubensky and others, 1987). Geochronologic studies of rocks in the central and northern Vulture Mountains (Rehrig and others, 1980) provide the only available K-Ar dates of any of the rocks in the range. This report is considered preliminary and is part of an ongoing project to map and study the entire Vulture Mountains.

The Vulture Mountains are important for three fundamental reasons. The first is that the Vulture Mountains are, at present, largely unmapped. Second, the Vulture Mountains contain an excellent record of the mid-Tertiary structural and volcanic history of the region, which is of general interest to the geologic community. Third, central and western Arizona are of increasing interest to the mining industry because of the potential for undiscovered ore deposits in southwestern Arizona (for example, Bagby and others, 1987). This report is an attempt to meet some of these needs with a new geologic map and a brief summary of the geologic setting of the range. In the course of mapping we have also noted areas where the rocks have been altered and(or) mineralized; areas which may or may not prove to have high mineral potential.

Our understanding of the geologic context of the Vulture Mountains is enhanced by geologic mapping in adjacent ranges conducted by the Arizona Geological Survey (formerly the Bureau of Geology and Mineral Technology). This and other mapping studies have been jointly funded by the Arizona Survey and the U.S. Geological Survey as part of a cost-sharing, cooperative geologic mapping (COGEOMAP) program (see inset, Fig. 1). Base materials for this study included 1:24,000-scale topographic maps and aerial photographs, which were supplied by Ray Brady of the U.S. Bureau of Lands Management.

GEOLOGIC OVERVIEW

The Vulture Mountains are one of several mountain ranges in west-central and central Arizona composed almost exclusively of two pre-Quaternary rock types; (1) pre-Tertiary metamorphic and plutonic rocks, and (2) mid-Tertiary volcanic and sedimentary rocks. The oldest unit in many of the ranges is gneiss and schist similar to rocks of the Yavapai Supergroup, a sedimentary and volcanic sequence that accumulated at the edge of the Proterozoic North American craton. Stratigraphically overlying Paleozoic and Mesozoic supracrustal rocks are preserved in some ranges, but were removed from the Vulture Mountains by pre-middle Tertiary erosion. Cretaceous granitic rocks intrude the Proterozoic crystalline rocks and are the youngest rocks exposed beneath the widespread unconformity onto which a mid-Tertiary volcanic sequence was deposited. The association of Proterozoic and Cretaceous rocks beneath the volcanic rocks throughout central and western Arizona, including the Vulture Mountains, indicates that the substrates of now widely separated mountain ranges have a common geologic history prior to mid-Tertiary deformation.

The petrologic and lithologic diversity of mid-Tertiary volcanic rocks across Arizona is discernible because the rocks postdate regional metamorphic events and have not been buried. Thick packages of calc-alkaline rocks of Oligocene(?) to Miocene age are exposed in most of the Basin and Range Province. The Tertiary volcanic record in most of the mountain ranges in the Transition Zone consists of basalt with lesser amounts of rhyolite, dacite, and latite. Closely spaced rhyolite domes and related thick lava flows and pyroclastic aprons indicate the existence of one or more rhyolitic volcanic centers in the eastern Vulture Mountains (Grubensky and others, 1987). Unlike the adjacent volcanic fields, however, the eastern Vulture Mountains are barren of intermediate lavas.

Mid-Tertiary, post-volcanic, regional extension has since modified the rocks in west-central Arizona. The structure of some ranges, like the Vulture Mountains, consists of numerous, consistently northwest-striking homoclines that dip either to the northeast or to the southwest. Other ranges, including the Big Horn Mountains, have a volcanic section with bedding attitudes that reflect more complex extensional deformation (Capps and others, 1985; Allen, 1985). The structure of the Vulture Mountains is more straightforward.

LITHOLOGY

PROTEROZOIC METAMORPHIC ROCKS

The structurally and stratigraphically lowest rocks of the southeastern Vulture Mountains are Proterozoic metasedimentary and metavolcanic rocks of greenschist to amphibolite facies. These rocks are located in fault-bounded blocks in the eastern Vulture Mountains and also in northeast-dipping homoclines in the Wickenburg and Hieroglyphics Mountains to the east. The protolith for these rocks is considered to be early Proterozoic(?) in age based on lithologic and textural similarity to the Yavapai Supergroup (1.70-1.85 b.y.), which is exposed in the Bradshaw Mountains (Anderson and others, 1971). The metamorphism is probably also early Proterozoic in age, although some metamorphism in the Vulture Mountains could also be Mesozoic in age. Unfoliated granitic plutons of Cretaceous age intrude the schist in the northeastern Vulture Mountains (Grubensky and others, 1987).

Several metamorphic lithologies are present including pelitic and psammitic schist and amphibolite. The schist contains compositional layering defined by alternating bands of quartzofeldspathic and mafic-bearing schist. Compositional banding is on the order of 2 to 10 cm thick and is primarily defined by changes in biotite abundance and the biotite/quartz ratio. Compositional banding does not everywhere parallel foliation. Amphibolites consisting of minor quartz, epidote, plagioclase feldspar, and amphibole are less abundant. Lenses, boudins, and massive irregular-shaped bodies of amphibolite are both concordant and discordant to a strong, east-west striking foliation in the map area. The least abundant lithologies consist of metamorphic assemblages of andalusite+muscovite+ biotite, andalusite+muscovite+quartz, and biotite+muscovite+ quartz. Most of the schist is fine or medium grained: some pelitic schists, however, include anhedral to subhedral porphyroblasts of andalusite up to 1 cm across. The protolith for the quartzofeldspathic schists is probably thin-bedded sandstone, although sedimentary structures other than possible plane bedding are not well preserved. Amphibolites are probably derived from mafic flows and dikes, whereas muscovite schists are likely derived from clays or tuffaceous rocks. Stratigraphic and structural relations between each of these mineralogically discrete assemblages is still uncertain.

The schistose rocks are exposed in structural windows in and along subhorizontal mid-Tertiary normal faults in the southeastern Vulture Mountains. In several places they are intruded by abundant east-west-trending rhyolite dikes and plugs (unit Trs), and the overlying unconformity with Tertiary sedimentary rocks (unit Ts) is repeatedly exposed in adjacent fault-blocks. Precipitous hillsides of schist in sections 7 and

18, T. 6 N., R. 4 W. flank abundant, resistant rhyolitic dikes. A regional metamorphic foliation that is east-west striking and steeply dipping is typical of schists. Lineation directions defined by aligned hornblende phenocrysts or elongated feldspars are less systematic. Unlike Proterozoic rocks in the northeastern Vulture and Buckhorn Mountains, the schists in the map area are not intruded by or associated with fine-grained, quartzofeldspathic gneiss or pegmatites (Grubensky and others, 1987; Jahns, 1952); unmetamorphosed Cretaceous granite and granodiorite of the Wickenburg batholith of Rehrig and others (1980) are also absent.

TERTIARY SEDIMENTARY ROCKS

The stratigraphically lowest Tertiary unit consists of as much as 100 m of red arkosic sandstone and conglomerate of Oligocene(?) and Miocene age. These rocks were deposited on an unconformity that is constrained to be younger than late Cretaceous and older than middle Miocene. The unconformity is regional in extent, overlies rocks as young as Cretaceous granite, and is overlain by rocks as old as late Oligocene in some other ranges (Shafiqullah and others, 1980). The arkosic rocks are, in part, locally derived because they contain clasts of Cretaceous granodiorite and Proterozoic schist, however clasts of Proterozoic quartzite are probably derived from the Buckhorn Mountains. The arkose, although the thickness may be as little as 5 m, is always present at the unconformity unless it has been intruded by rhyolite. The horizon was apparently one of low relief.

The basal arkosic rocks in the map area consist of approximately 10 meters of a fining-upward sequence of conglomerate, conglomeratic sandstone, and arkose with pebbles and cobbles that are between 2 cm and 15 cm in diameter. Clasts of Proterozoic rocks are well rounded and typically matrix supported. Cut-and-fill crossbedding is common on the horizontal scale of a meter as are gravel-filled channels. This sequence includes well-bedded, thickly layered, unsorted conglomerate and thin horizons of well-sorted, coarse-grained sandstone, in part pebbly. The arkose is locally, but dramatically, interbedded with basalt flows of unit Tbl at the common corner of sections 9, 10, 16, and 15, T. 6 N. R. 4 W. There, the arkose is uncharacteristically greenish colored and partly tuffaceous with bedsets that are 3 to 6 m thick. Clasts in this conglomerate are derived solely from unmetamorphosed (Cretaceous?) granitoid and are as large as 15 cm. Plane parallel beds in this unit are approximately 10 cm thick. These rocks are poorly sorted and poorly bedded, and lack obvious channels.

TERTIARY VOLCANIC AND HYPABYSSAL ROCKS

Tertiary volcanic rocks of the southeastern Vulture Mountains are dominated by a sequence of rhyolite at least 1 km thick. These crystal-poor rhyolite flows and domes and associated pyroclastic rocks are now referred to, informally, as the San Domingo rhyolites. The less specific name of San Domingo volcanics was used previous to this report (Stimac and others, 1987; Grubensky and others, 1987), but additional mapping has shown that this unit consists strictly of rhyolite to the exclusion of volcanic rocks of other compositions. K-Ar dates on some rhyolites in the central Vulture Mountains indicate the San Domingo rhyolites are approximately 18 m.y. old (Rehrig and others, 1980). Basalt flows lie above and below the rhyolite sequence. The lower basalt (unit Tbl) is correlative to the Deadhorse basalt, which is dated at approximately 20 Ma (Capps and others, 1985), and the upper basalt is correlative to basalts dated at 14.5 Ma in adjacent areas (Capps and others, 1985; S.J. Reynolds, unpublished data). In two places, the lower basalt is intercalated with crystal-rich dacite (unit Td).

The San Domingo rhyolite complex was erupted through at most 100 m of basalt flows (unit Tbl). These lower basalts are steel-gray, nonresistant, aphyric flows that are uncommonly vesicular. They are interbedded with conglomerate and arkosic sandstone of unit Ts in the northeastern corner of the map area. Locally a parting cleavage has developed in the basalt flows. Scoria is not common. In the southern part of the map area, the lower basalts include at least three varieties: (1) clinopyroxene-olivine-plagioclase-phyric basalts with up to 20% phenocrysts. Clinopyroxene is green, locally altered and present as 1-3 mm euhedral grains, which are singular or as aggregates with plagioclase. Olivine phenocrysts are 1-2 mm across and altered to Fe-oxide. Plagioclase phenocrysts are 1-5 mm euhedral laths or as groundmass microlites; (2) dark gray, aphyric basalt locally including phenocrysts of plagioclase; and (3) olivine-phyric variety that is reddish gray and massive, with a plagioclase microphyric groundmass. Flow thicknesses average between 3 m and 5 m, and flow breccias are only locally developed along flow bases.

Lava flows of the San Domingo rhyolites are characterized by 1-5 mm phenocrysts of sanidine and finer grained biotite set in a devitrified or perlite matrix. Phenocrysts constitute less than approximately 5% of the rock. Rhyolite flows typically have autobrecciated margins and flow-foliated, massive cores. Devitrification of flow matrix to microcrystalline quartz and alkali-feldspar and spherulites between 5 mm and 1 cm are features ubiquitous in the rhyolite flows except for some basal vitrophyres. Interbedded pyroclastic rocks include mostly very well sorted tuffs and lapilli tuffs (air-falls) deposited in beds that are generally 10 cm thick. These are associated with laminated surge-related tuffs with crossbedding, reverse grading, and fine ash-sized grains, and 1-m-thick beds of poorly sorted, unwelded pyroclastic flows. Lithic fragments less than 1 cm are characteristic, except in the western half of section 22, T.6 N., R.4 W., where the tuffaceous rocks have angular fragments up to 1 m across, beds up to 4 m thick, and some welding an autoclastic facies (within a volcanic vent).

Rotation of large fault blocks has provided substantial structural relief through the Tertiary volcanic section. One fault block (including secs. 17, 18, 19, 20,; T. 6 N., R. 4 W.) provides an additional 2 km of vertical section through the schist substrate and a Tertiary rhyolite dike swarm (unit Trs). Several rhyolite dikes that intrude the schist across the width of this fault block grade structurally upward into extrusive, flow banded rhyolite; this fault block, therefore, provides an upturned cross-section through a volcanic center and its hypabyssal feeders. This intrusive network consists of 1- to 20-m-thick dikes, most of which strike east-west, dip steeply, and are, in most places, parallel to the metamorphic foliation in the schist. The Tertiary-pre-Tertiary contact exposed near the Queen of Sheba mine (SE 1/4, sec. 8; T. 6 N., R. 4 W.) has been locally intruded by Tertiary rhyolite dikes. In general, mineralogic and textural differences between and within dikes are very subtle. Locally, individual dikes display sharp zoning between two phases; the marginal (older?) phase is a dark, almost glassy hornblende- and K-feldspar-phyric rhyolite that is separated from the inner phase by a sharp contact or a selvage of schist. The inner phase is typically hematite stained and thoroughly devitrified or altered, such that both hornblende and sanidine are altered to hematite and clays, respectively.

In the northern part of the eastern Vulture Mountains, the tilted volcanic complex is overlain by conglomerate and sandstone associated with the development of half grabens developed on rotating fault blocks. These sedimentary rocks have been removed in most of the map area. Basalt flows of unit Tbu are exposed in isolated pediment outcrops south of the main part of the mountain range. Where unaltered, the flows are plagioclase microphyric basalt or basaltic andesite with local aggregates of clinopyroxene 1-3 mm across. Vesicles and calcite amygdules up to 2 cm across are both common. One flow is underlain by a heterogeneous deposit of unsorted blocks (unit Tdf), which may represent debris flows mapped in adjacent areas (Grubensky and others, 1987).

QUATERNARY SEDIMENTS AND SEDIMENTARY ROCKS

Rocks along the southern margin of the Vulture Mountains are overlain unconformably by poorly to unlithified sediments and sedimentary rocks of Quaternary age that are essentially flat-lying. The Hassayampa Plain includes the area between Black Butte, in the southwestern Vulture Mountains, and the Hassayampa River along the eastern margin of the study area (inset, Fig. 1). Drainages in the eastern half of the map area feed the Hassayampa River directly, whereas runoff from the western half is diverted through a drainage network across the Hassayampa Plain. Isolated outcrops of Tertiary volcanic rocks are present on the northernmost part of the plain. Broad alluvial fans extend southward from the southern flank of the Vulture Mountains. The entire mountain range is one of comparatively low relief amidst the precipitous Harquahala, Big Horn, and Hieroglyphics Mountains. Isolated bedrock exposures suggest that the pediment for the southeastern Vulture Mountains extends at least 3 miles south of the last continuous outcrops within the range.

The Quaternary geology for the western half of the study areas differs from that in the eastern half. The western half is dominated by alluvial fans. West of secs. 32, 29, 20, 17, lies a broad, irregular plain of alluvium with scattered exposures of bedrock pediment. As much as 30 m of poorly lithified gravel (unit Qg) defines a paleoriver channel much broader than the present day Hassayampa River. River. These gravels are exposed 2 miles from the modern Hassayampa River beneath a thin veneer of alluvium and soil. Modern drainages have incised these gravels, which are composed of well-bedded sandy conglomerate and sandstone. Most clasts are light-colored Cretaceous(?) granite and granodiorite. The gravels are characterized by bedform crossbeds, shallow channels, and interbedded, well-sorted, planar laminated sandstone. The components of older river gravels contrast markedly with those of alluvial (Qal units) because of its better sorting, well-rounded clasts, clast-supported nature, and well-developed bedding surfaces. Also, the gravels weather to conspicuous steep-walled arroyos. Interfluves are underlain by poorly developed soils less than 1 m thick that form conspicuous flats, or surfaces, associated with an immature desert pavement. Pavement clasts are primarily of rhyolite. The blufflike topographic expression indicative of the gravels can be traced into areas south of the study area.

Three types of alluvium (subdivisions of unit Qal) are distinguished in the western half of the map. To varying degrees, alluvium of units Qal_o, Qal_m, and Qal_y is incised by modern drainages (units Qs and Qso), and as a result, patterns of drainage and their textures seen in photographs provide information rough criteria for their distinction. The alluvium of unit Qal_o is exposed along the foot of the SE Vulture Mountains and is associated with a relatively large amount of relief within arroyos that dissect it. The deep arroyos in this poorly consolidated alluvium define a high density, dendritic drainage network characterized by well-developed main channels, and short, subsidiary channels. High drainage density suggests that these rocks are less permeable than Qal_y or Qal_m. Many of the modern channels in Qal_o are floored by bedrock.

At the contact of Qal_o and Qal_y, runoff is distributed into a low-density, parallel dendritic, drainage network with shallow gullies. Interfluves in Qal_y are covered by silts and fine-grained sands probably associated with sheet flooding. Few drainages in Qal_y incise down into bedrock.

Map unit Qal_m is less widespread than either Qal_o or Qal_y, and is intermediate in age. The characteristic reddish color of the unit reflects a high proportion of Tertiary rhyolite clasts. Qal_m overlies Qal_o in section 31, T.6 N., R.4 W. and is distinguished from it by its lower density, dendritic drainage pattern, and smooth texture along interfluves. Qal_m, like Qal_o, is rather deeply incised by arroyos.

STRUCTURE

Pre-Tertiary Structure

Proterozoic schists in the southeast Vulture Mountains record one or more dynamothermal, regional metamorphic events of pre-Cretaceous age that have produced moderate-grade metamorphic assemblages. Although protolith grain shapes, phenocrysts, and sedimentary bedforms are not preserved, relict bedding in the metasedimentary rocks is locally preserved as changes in composition and grain size. Bedding has been folded and locally transposed into parallelism with foliation. Amphibolite schists that form lozenge-shaped bodies parallel to foliation are possibly metamorphosed, dismembered mafic dikes. Some mesoscopic layering in schists might be better referred to as compositional banding rather than bedding, which implies a sedimentary origin.

The emplacement of Late Cretaceous plutons (the Wickenburg batholith of Rehrig and others, 1980) crosscuts the metamorphic fabrics, although the plutons locally show a weak flow(?) foliation. Mesozoic fabrics related to either Cretaceous plutonism or tectonism (Reynolds and others, 1980) are recognized in this area; several crosscutting foliations and cleavages have been mapped in the northeastern Vulture Mountains (Grubensky and others, 1987).

Tertiary Structure

A period of Miocene rotational normal faulting occurred after emplacement of the San Domingo rhyolites. The faulting dissects the rhyolite volcanic complex along a duplex of several, sub-parallel, sub-horizontal normal-faults. The Tertiary units are vertical or locally overturned to the west. This duplex is apparently unlike any mapped in Tertiary rocks in west-central Arizona thus far. Klippe of Tertiary volcanic rocks and small fensters into schist through subhorizontal normal faults are otherwise uncommon in a region of high- to moderate-angle mid-Tertiary normal faults. The mid-Tertiary deformation was not associated with metamorphism in the Vulture Mountains because these rocks were and probably have remained at shallow crustal levels throughout the deformation. Miocene faulting has not reoriented the east-west trending foliation in the schist because the axis of rotation was approximately perpendicular to the foliation.

Exposures of subhorizontal faults generally include a resistant upper plate of Miocene volcanic rocks, usually rhyolite flows, and a less resistant lower plate of Proterozoic schist. Rocks in the fault zone were pervasively sheared and cataclasized to a fault breccia. Gouge is uncommon or confined to very narrow zones along fault planes. Upper-plate rocks are typically silicified and pervasively stained with hematite for as much as 10 m above the fault surface, whereas the underlying schists are commonly unmineralized or are recemented with black calcite. Black manganese staining can be present in the upper plate rocks. The striated fault surface is commonly preserved on Miocene rhyolite and usually dips more steeply than the trace of the contact implies, probably because of additional rotation along minor, more closely spaced, later high-angle normal faults with small separation. Lower-plate schists have locally developed a fault-parallel cleavage.

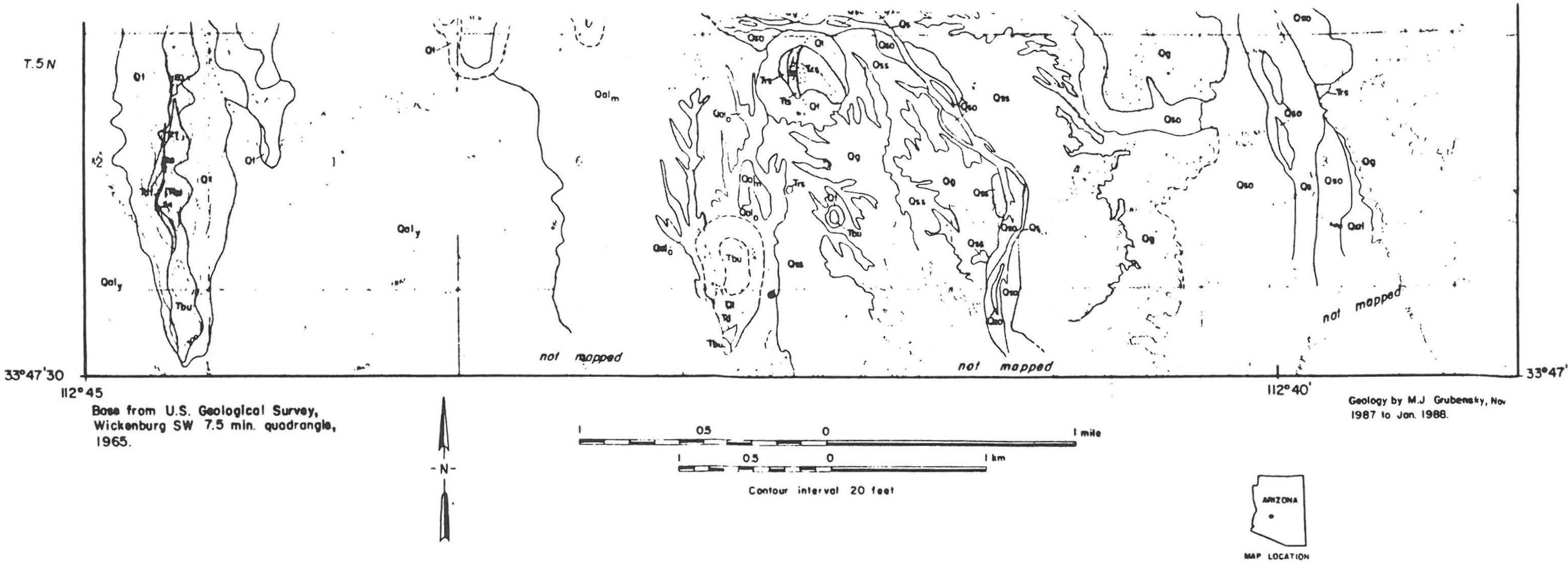
Faulting occurred largely or entirely after deposition of the San Domingo rhyolite based on two observations: (1) debris flows and conglomerates indicative of synvolcanic tectonism are not interbedded with the rhyolite, only with the younger basalts of unit Tbu, and (2) bedding has approximately the same dip within most fault blocks--decreases in dip upsection in some fault blocks are probably inherited from the flanks of a volcanic edifice. Normal faulting continued for probably 5 to 6 m.y., until the eruption of flat-lying younger basalts (unit Tbu) that are dated at approximately 14 Ma. Coarse-grained conglomerates and sedimentary debris flows that fill many of the half grabens, are exposed north of the map area along the Hassayampa River (Grubensky and others, 1987).

The numerous subhorizontal normal faults in the Vulture Mountains are significant because they imply a larger amount of crustal extension than in adjacent mountain ranges. The faults have much shallower dip than in the adjacent Big Horn or Hieroglyphics Mountains, and the Miocene rocks within each fault block in the eastern Vulture Mountains are consistently near vertical to overturned. The present vertical thickness of each fault block is also quite thin, commonly 100 m. Because the lithologic units are vertical and the faults are subhorizontal, the amount of dip separation across several of the larger faults can be measured directly from the geologic map in Fig. 1. The major faults must have 1 to 2 km top-to-the-west motion in order to restore similar volcanic sections between adjacent fault blocks. The total amount of extension across the southeastern Vulture Mountains is approximately the width of the map area (6 km.

The development of flat faults in the eastern Vulture Mountains has been a complex process. The faults probably formed as a series of high-angle normal faults structurally above a regionally developed feature, such as a detachment fault. As the rhyolite flows and tuffs of the Vulture Mountains were extended, beds rotated to moderate eastward dips as faults rotated to moderate westward dips; the angle between faults and bedding remained approximately at right angles during deformation. An additional (secondary) set of younger high-angle faults crosscut the package when rotation along the primary faults had resulted in gentle dips of faults and steep dips of beds. With continued extension, most additional rotation was probably accommodated on the younger, initially high-angle secondary faults (Fryxell and others, 1987). Some beds of volcanic rocks are rotated to vertical or overturned dips as a result of continued extension, and primary faults associated with such beds dip shallowly eastward, although there was little movement, if any, along these faults in this orientation. All generations of faults consistently place younger rocks over older rocks. Late-stage high-angle faults are probably the youngest structures present that are related to Miocene deformation.

ALTERATION AND MINERALIZATION

During the course of geologic mapping, several areas of altered and mineralized rock have been noted. The main types of alteration and mineralization include the following; (1) widespread hematite- and limonite-staining, which may include the presence of Cu-oxide and -carbonate, and relict sulphides; (2) intense silicification, with and without alunite and montmorillonite, and (3) intense or closely spaced veins or irregularly shaped solution-fillings of black calcite. Each of the alteration-mineralization types is shown on the geologic map by a patterned overlay (Fig. 1). The significance of each of these types of alteration and mineralization is uncertain, although a majority of zones of alteration and mineralization in the map area are spatially associated with and probably related to normal-faults. Age relations between types of alteration are unknown. No one lithology seems more favorable for alteration, except hematization is more commonly associated with Tertiary rhyolite.

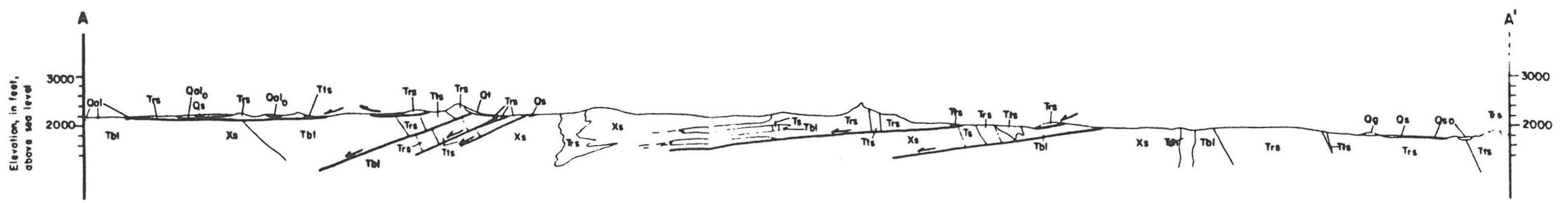


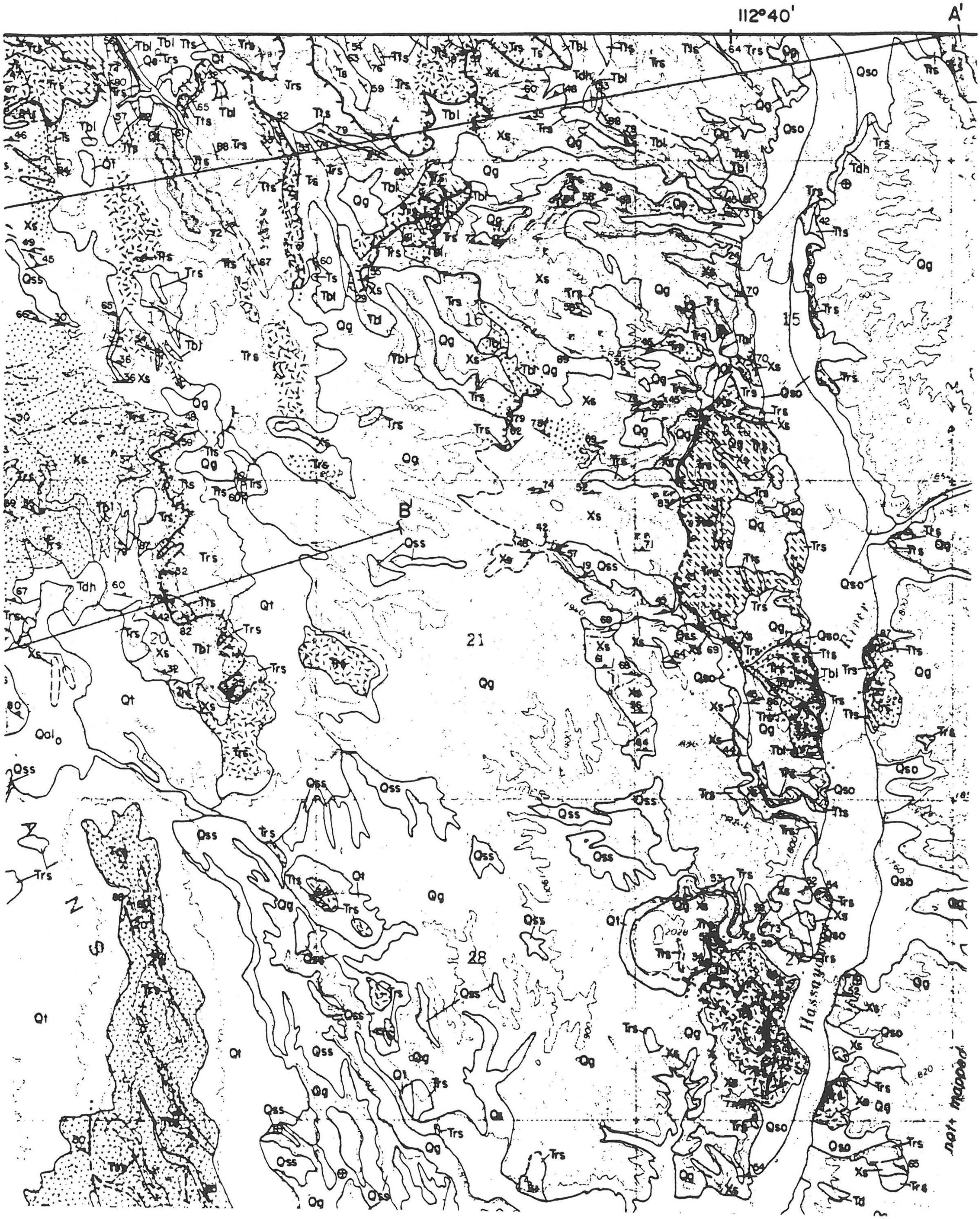
GEOLOGIC MAP OF THE SOUTHEASTERN VULTURE MOUNTAINS, WEST-CENTRAL ARIZONA

by

Michael J. Grubensky and Stephen J. Reynolds

1988





112°40'
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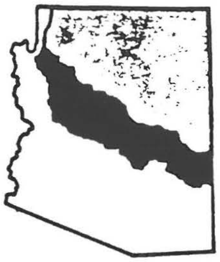

Arizona Geological Survey

ARIZONA GEOLOGY

(formerly *Fieldnotes*)

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Geology of the Vulture Gold Mine

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The Vulture mine in the Vulture Mountains of west-central Arizona is one of Arizona's largest historic gold mines. The mine yielded approximately 340,000 ounces of gold and 260,000 ounces of silver from 1863 to 1942 (White, 1988).

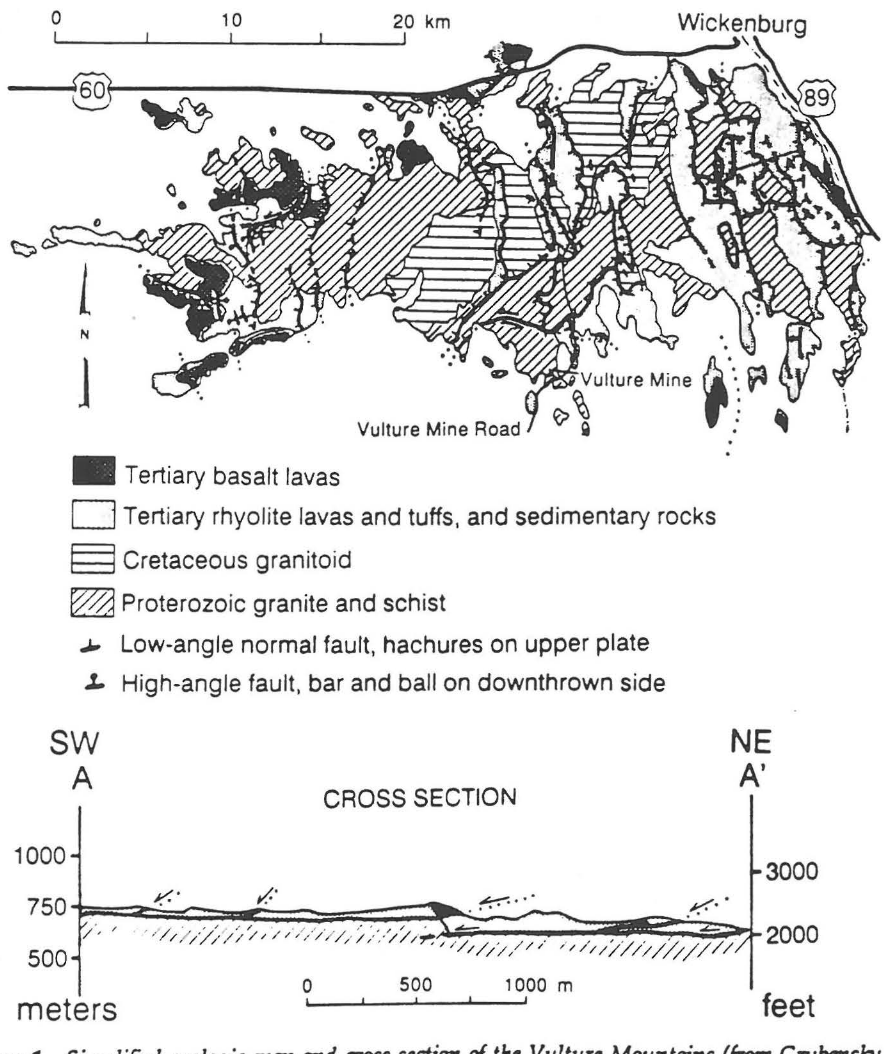


Figure 1. Simplified geologic map and cross section of the Vulture Mountains (from Grubensky and others, 1987; Grubensky and Reynolds, 1988; and M.J. Grubensky, unpublished mapping).

The approximately 1 million tons of ore mined had an average grade of 0.35 ounces per ton of gold and 0.25 ounces per ton of silver. In spite of significant gold production, the deposit has received little geologic study until recently (Reynolds and others, 1988; White, 1988). Recent geologic mapping and laboratory studies by the authors of this article, drilling, and deposit evaluations have led to a much better understanding of the geologic characteristics, age, origin, and evolution of the deposit.

New mapping in the Vulture Mountains was partially supported by the U.S. Geological Survey and Arizona Geological Survey Cooperative Geologic Mapping (COGEOMAP) program. Results of these investigations have implications for exploration strategies in the Vulture mine area and in similar highly extended areas elsewhere in Arizona.

Geologic Setting

Rocks in the Vulture Mountains consist of a variety of Proterozoic metamorphic and igneous rocks, a Cretaceous granite or granodiorite pluton, and lower to middle Miocene volcanic and sedimentary rocks. Large-magnitude, middle Miocene extension, common to most of western Arizona, was accommodated in the Vulture Mountains by movement on numerous listric and planar normal faults. Normal faults and fault blocks were tilted to the east or northeast during extension. Miocene strata now typically dip steeply or are locally overturned to the east or northeast and faults dip gently to the west or southwest (Figure 1).

Geology of the Vulture Mine

Mineralization and alteration at the Vulture mine occurred primarily within and directly adjacent to a north-dipping quartz porphyry dike that extends eastward from a Late Cretaceous pluton and intrudes Proterozoic crystalline rocks (Figures 2 and 3). Moderate to severe alteration of the dike and wall rocks has converted feldspar and mafic miner-

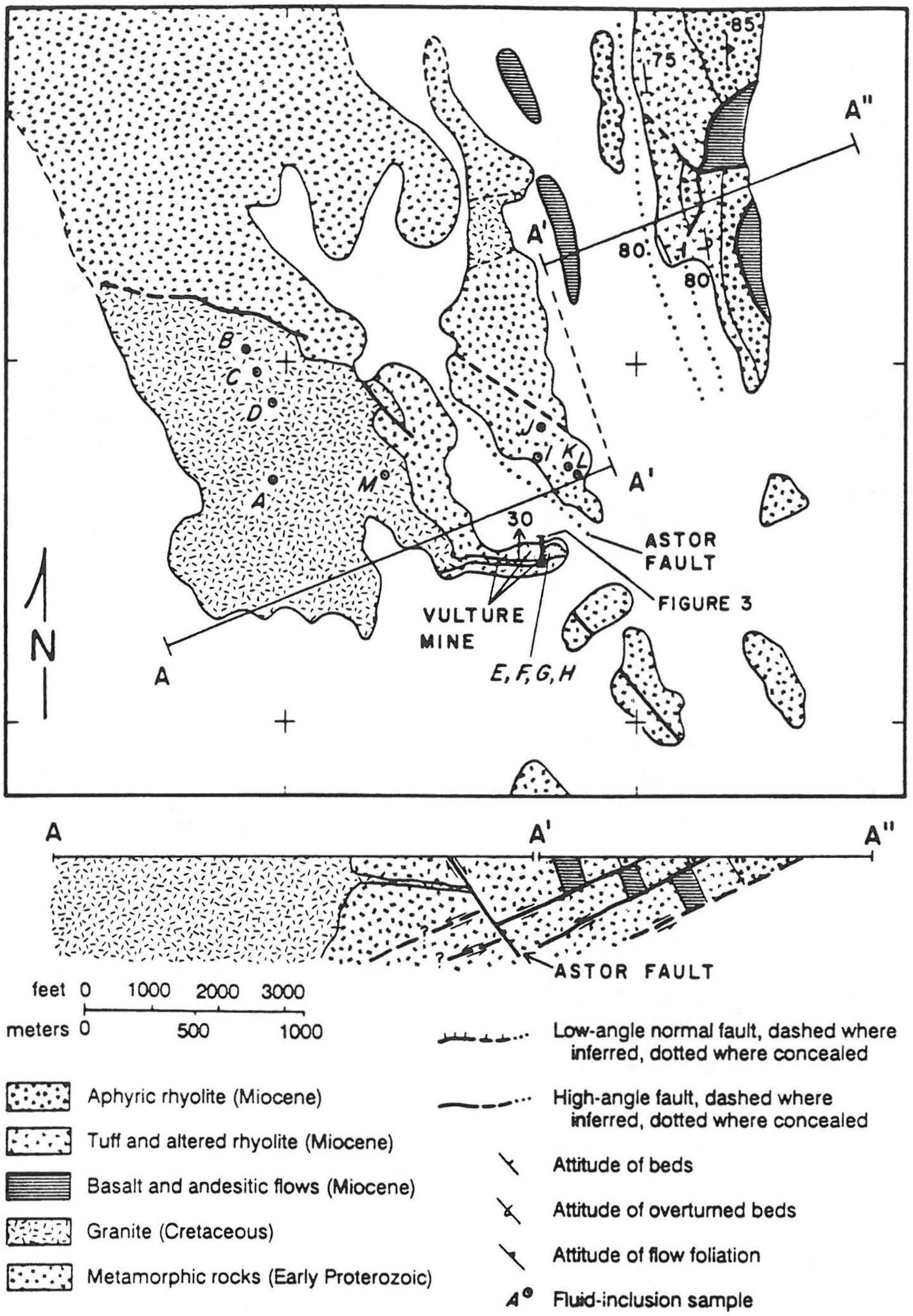


Figure 2. Simplified geologic map of the Vulture mine area and fluid-inclusion sample locations.

als to fine-grained sericite, hematite, and clay minerals. Altered dike rocks commonly consist of quartz "eyes" in a fine-grained matrix of alteration minerals. Gold is concentrated in quartz veins and in silicified and altered rocks within and adjacent to the dike (Figure 3). Gold is present as either native metal or electrum and is associated with pyrite, argentiferous galena, and minor amounts of chalcopyrite and sphalerite. There is a positive correlation among abundances of secondary silica, sulfides, and gold (White, 1988).

The Miocene volcanic rocks northeast of the Vulture mine were deposited on the Proterozoic crystalline rocks that host the Vulture mine gold deposit (Reynolds and others, 1988). The originally horizontal volcanic strata and their crystalline substrate have been rotated 70° to 90° so that bedding is now almost vertical. Rocks exposed in the Vulture mine area, therefore, represent an originally vertical cross section that has been tilted approximately 80° to the east by rotational normal faulting. The map view (Figure 2) represents what was originally a vertical cross-section view; what is visible in a north-south cross section (Figure 3) was originally horizontal.

Conceptual restoration of the rocks of the Vulture mine area to their prerotation orientation reveals the approximate geometry of the ore deposit at the time of mineralization. Mineralization and alteration originally occurred along a north-northeast-trending subvertical dike that projected upward from the structural top of a Cretaceous granitoid pluton (Figure 4A). The association of gold with the dike (Figure 3) and gradation of the dike into the granitic rocks of the pluton indicate that gold mineralization was intimately related to Cretaceous magmatism and dike emplacement. Later erosion and subsequent burial by lower Miocene volcanic rocks (Figure 4B) was followed by structural dismemberment and tilting (Figure 4C) and eventual uncovering by late Cenozoic erosion. The Astor fault (Figure 3), which is probably one of the youngest faults in the area, cuts the deposit and has displaced its down-dip continuation by an unknown amount (White, 1988).

Fluid-Inclusion Characteristics

Fluid inclusions are bubbles of liquid and gas that are trapped inside minerals during mineral formation. The composition of fluids in inclusions that were trapped in mineral deposits at the time of deposit formation reflects the composition of the aqueous fluids from which the deposits formed. One can determine the salinity of the inclusions by measuring the freezing temperature of the trapped fluid. The minimum temperature of the fluid at the time it was trapped can be determined by heating the sample until the two phases (liquid and gas) in the inclusion become one. (This is called the *homogenization temperature.*) Fluid inclusions that formed during precipitation of host minerals are called *primary*, whereas those that formed later along fracture planes are called *secondary*.

Quartz veins are numerous over a broad area around the Vulture mine. Samples of veins were collected from an area (Figure 2) that represents an originally vertical cross section through the Vulture mine and that includes more than 1 kilometer of paleodepth range. Homogenization temperatures of primary and secondary fluid inclusions vary from approximately 200°C to 320°C and calculated salinities vary from approximately 1 to 18 percent NaCl equivalent by weight. Homogenization temperatures and salinities generally decrease with decreasing paleodepth (Figure 5). These fluid-inclusion data reveal the temperatures and salinities of the hydrothermal fluids that were probably undergoing convective circulation above the Cretaceous intrusion and that were responsible for much or all of the mineralization and alteration at the Vulture mine. Greater fluid temperatures at greater depths probably reflect heat from the magma intrusion (now the granitoid pluton) that lay beneath the Vulture mine deposit. Downward-increasing fluid salinities may reflect a downward increase in the proportion of aqueous fluid expelled by the magma during crystallization.

Conclusion

Recent geologic mapping of the Vulture Mountains and adjacent ranges has established that the area has undergone large-magnitude extension as a result of rotational normal faulting (Grubensky and others, 1987; Stimac and others, 1987; Grubensky and Reynolds, 1988; see also Rehrig and others, 1980). Geologic mapping in the Vulture mine area indicates that this area has been faulted and tilted like most of the range and that the Vulture mine gold deposit has been tilted approximately 80° (Reynolds and others, 1988). Drill-hole assay data show that mineralization is associated with a dike that extends from the structural top of a Cretaceous pluton (White, 1988). Fluid-inclusion studies indicate that mineralization at the Vulture mine deposit occurred within a larger system of circulating aqueous fluids in which temperature and salinity increased downward toward a crystallizing magma body.

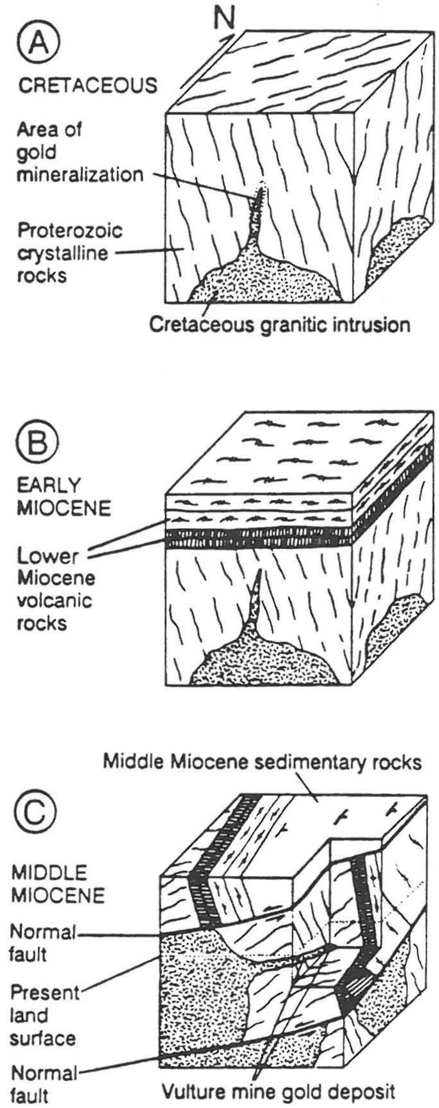


Figure 4 (left). Evolutionary block diagram of the Vulture mine area. Although only one generation of normal faults is shown, rotation probably occurred by movement on two or more generations of normal faults and is more complex than is shown here.

Figure 5 (below). Paleodepth versus salinity (upper diagram) and homogenization temperature (lower diagram) for fluid inclusions from quartz veins in the Vulture mine area. Paleodepth is the distance perpendicular to the approximately vertical disconformity at the base of Miocene volcanic rocks in the Vulture mine fault block. The actual depth of Vulture mine rocks at the time of mineralization was probably 1 to several kilometers.

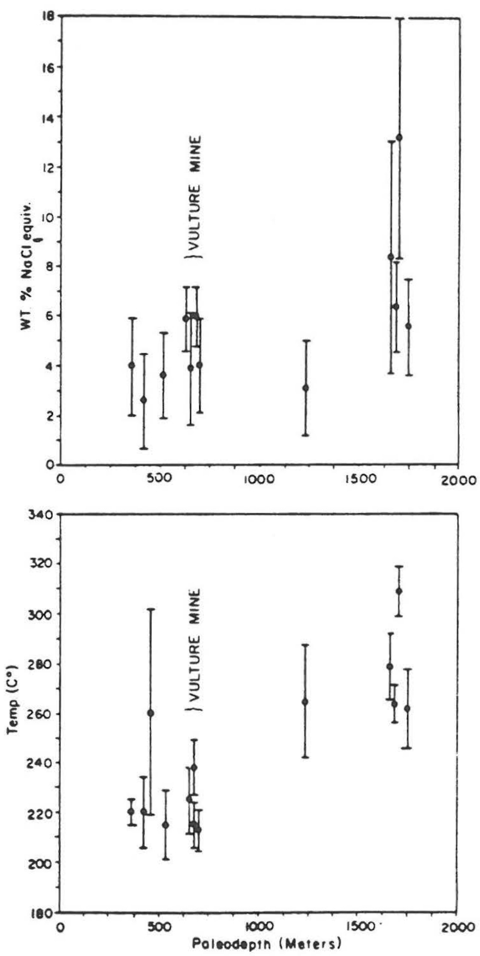
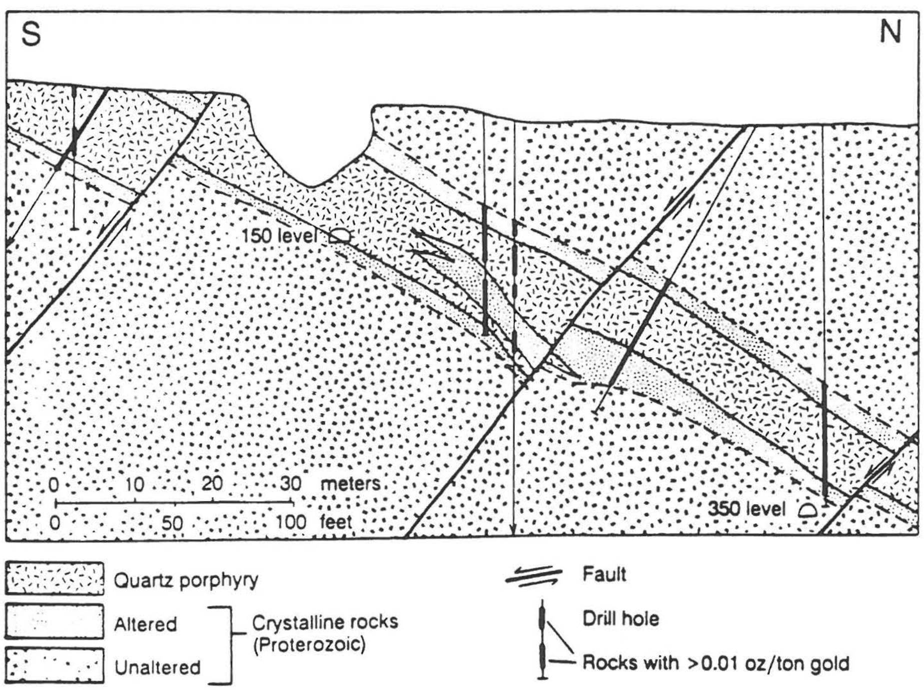


Figure 3 (below). Geologic cross section through the Vulture mine (modified from White, 1988 and unpublished data). See Figure 2 for location.



Recognition of this type of ore-deposit tilting and possible structural dismemberment has implications for exploration strategies in extended areas. Specifically, mineral exploration in highly extended areas characterized by rotational normal faulting may be facilitated by the knowledge that mineral deposits may have been tilted 80° from their original orientation. Such rotation provides a natural laboratory for the study of mineral deposits because the deposits are exposed in what was originally a near-vertical cross section. This type of extensional faulting may also cut an ore deposit into two or more pieces and leave them in shinglelike imbricate fault blocks separated from each other by several kilometers (e.g., Lowell, 1968).

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ROAD LOG FROM WICKENBURG TO THE VULTURE MINE

Joe Wilkins

Geologic Setting of the Vulture Mountains: A Summary

The trip from Wickenburg to the Vulture Mine is a North-South traverse across the Vulture Mountains; an allochthnous sequence of listric normal fault blocks. Basement lithologies occur in a series of subparallel N60E-trending belts including (from north to south) the Laramide-aged Wickenburg "batholith" which intrudes granitic gneisses of Precambrian age and Yavapai Series Schists (see figure 2). The basement rocks are overlain, in part, by Tertiary volcanic and volcanoclastic rocks and cut by North to Northnorthwest-trending dike swarms (Rehrig, Shafiqullah, and Damon, 1980).

As shown on figure 2, the entire lithologic package is cut, rotated, and laterally migrated by a series of NNW-trending, SW-dipping listric normal faults. The resultant extension, WSW-directed, may represent as much as 100% more than the original crustal configuration. In effect, a batholithic-sized mass such as the Wickenburg batholith could be created from what was originally a much smaller stock-like intrusion.

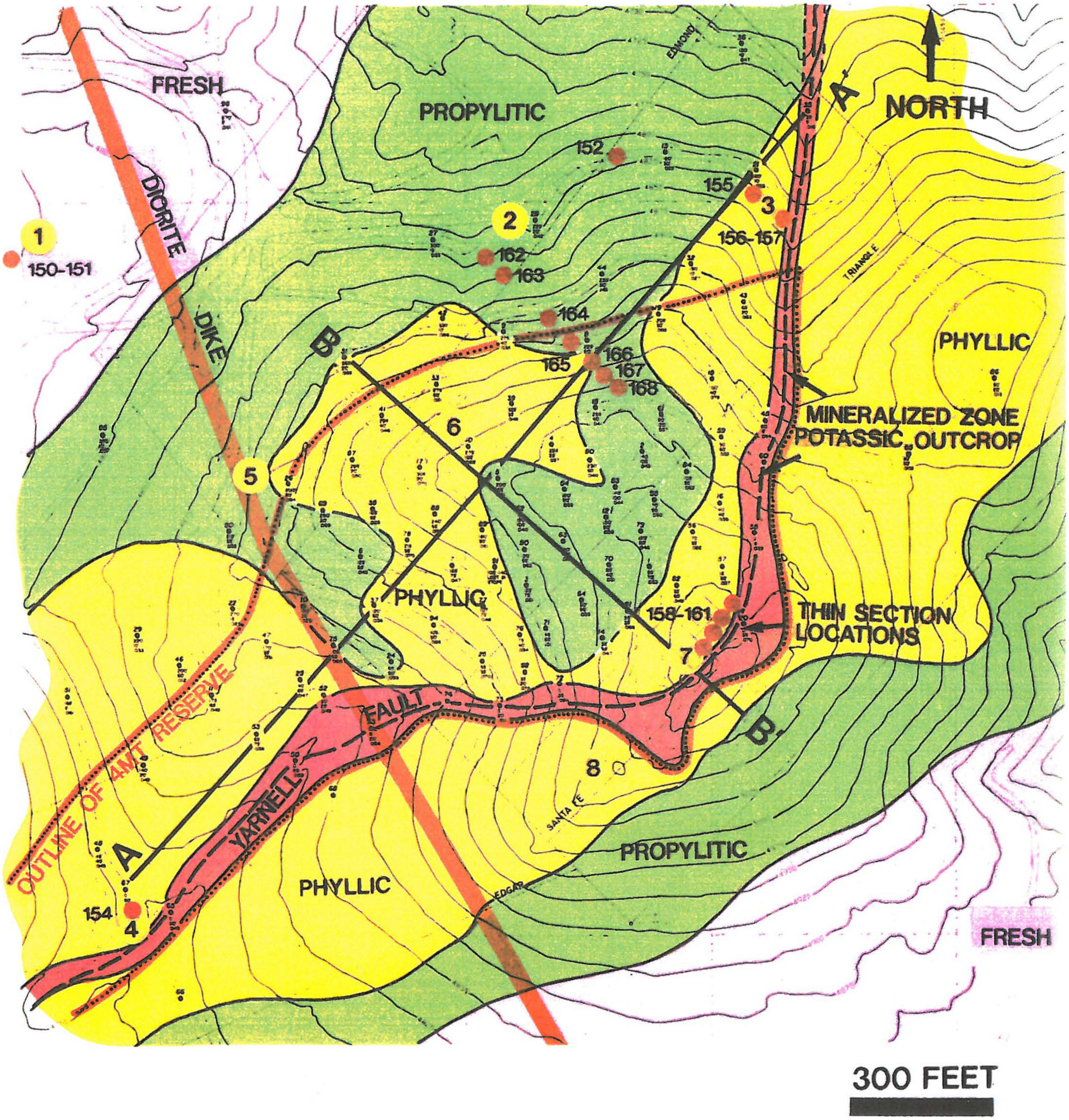
This style of deformation is common to the upper plates of metamorphic core complexes (Coney, 1980). Indeed, core complexes are present NW of the Vultures (the Harcuvar-Harquahala Complex) and to the SE in the White Tank Mountains (Reynolds, 1981, Reynolds and Rehrig, 1980). Alternatively, the stacked listric normal faults suggested by Rehrig and others (1980) cross-sections is similar to the thin-skinned distension documented by Anderson (1971) in NW Arizona-SE Nevada.

Any interpretation concerning the mineralization at the Vulture Mine must address this deformational event which occurred between 15 and 20 m.y. (Rehrig and others, 1980). For instance, all pre-20 million year mineralization events are allochthnous and rotated 50 to 70 from their original positions

Stops 1 and 2 will be orientation stops which provide a view of the listric fault deformation in the Vulture Mountains. Stop 3 will be at the Vulture Mine.

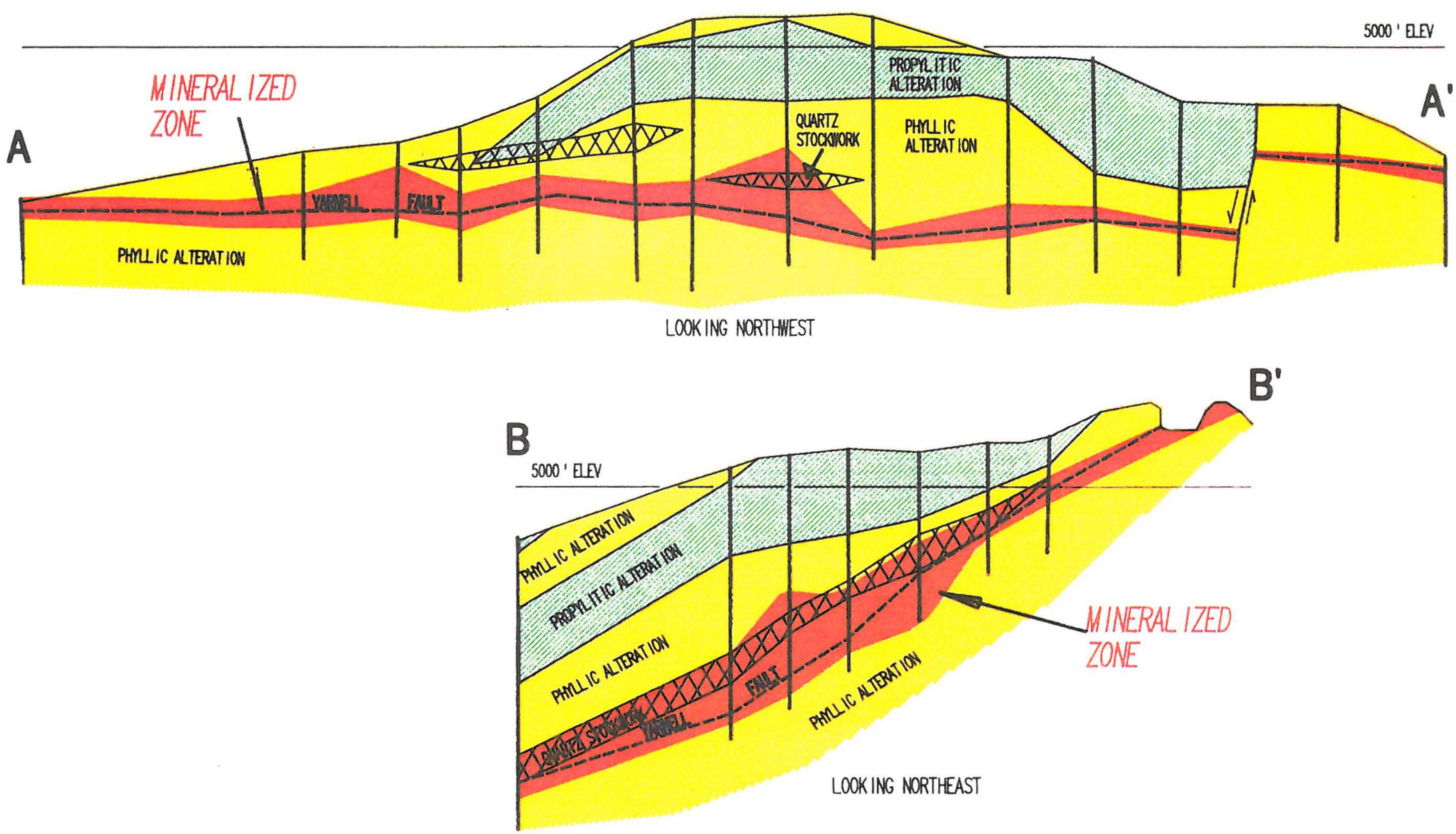
From AGS Spring Field Trip (1985)

FIGURE 2



YARNELL PROJECT
GEOLOGY

FIGURE 3



YARNELL PROJECT GEOLOGIC SECTIONS

Timing of mineralization in the Martinez and Rich Hill metallic mineral districts, west-central Arizona

Ed DeWitt U.S. Geological Survey, MS 905, Denver Federal Center, Denver, CO 80225

SUMMARY

Although tentatively classified as Tertiary in age by Keith and others (1983), vein deposits in the Martinez and Rich Hill metallic mineral districts are most likely Middle Proterozoic in age and related to emplacement of mafic dikes that are chemically and mineralogically identical to ~1.1 Ga diabase in the Sierra Ancha Mountains of central Arizona. Gold-rich veins at the Congress and Alvarado mines parallel mafic dikes that strike northwest and dip shallowly northeast. Hydrothermal alteration related to vein formation has turned the mafic dikes into mixtures of chlorite, biotite, and calcite. At those deposits in the Martinez and Rich Hill districts where mafic dikes are not present (Yarnell and Octave mines), gold-rich veins strike northwest to northeast, dip northeast to northwest, and occupy minor shear zones or fractures that have the same orientation as the mafic dikes in the region. The mafic dikes crop out extensively to the west and northwest, throughout the Weaver Mountains and to the Santa Maria River. To the southeast and east the dikes are less numerous. Similar deposits in northwestern Arizona may include those in the Music Mountains metallic mineral district where gold-rich quartz veins are spatially associated with east-trending, high-angle mafic dikes that cut Early Proterozoic granitic rocks but are truncated by Paleozoic strata of the Grand Was Cliffs (Karen Wenrich, oral commun., 1990).

VEIN SYSTEMS

Quartz veins containing pyrite, galena, minor chalcopyrite, and electrum are typical of deposits in the Martinez and Rich Hill districts (Shaw, 1909; Dinsmore, 1912; Watson, 1918; Staunton, 1926; Metzer, 1938; Herald and Russ, 1985). The veins range from several centimeters to about a meter thick, normally have well-defined walls, and are characterized by very little altered material in the surrounding Proterozoic bedrock. Ratios of precious metals are incredibly constant; very few deposits have Ag/Au ratios less than 0.5 or greater that 1.5. The average Ag/Au of the Martinez and Rich Hill districts is 0.95. The age of mineralization in the districts was assumed only to be Tertiary or older, as rich placer deposits on the top of Rich Hill were assumed to have been derived from the underlying lode deposits.

GEOCHRONOLOGY

In the late 1980's, Echo Bay Exploration Inc. began producing gold ore from a previous unmined part of the Niagara vein structure of the Congress mine. During their mapping and production, the company noted two post-mineral dikes, one mafic and one felsic that cut perpendicularly across the gold-bearing vein on the second development level drift, west of the main haulage decline. The 2-ft-thick, fine-grained, equigranular mafic dike was oriented N. 43°E and dipped 45° southeast. In thin section the dike was composed of intermediate plagioclase, hornblende, clinopyroxene, and minor biotite and calcite. Importantly, this dike was not the "diabasic" main mafic dike at the Congress mine that paralleled and was extensively altered by the vein system, but was a younger dike, oriented perpendicular to the vein system. On the surface, Echo Bay geologists recognized the cross-cutting mafic dike, but were unable to map any significant number of them.

Hornblende was separated from the dike and analyzed by the $^{40}Ar/^{39}Ar$ step heating technique. A plateau date of 103.7 +/- 2.1 Ma was determined for 88.6 percent of the gas from the hornblende (DeWitt, unpub. data, 1989). This mafic dike, which clearly cross-cuts the mineralized Niagara vein in the Congress mine area, is Early Cretaceous and indicates that gold mineralization must pre-date 103.7 Ma. The gold-bearing veins at the Congress and Alvarado mines cut the granodiorite at Yarnell (DeWitt, 1989), which is a 1.4 Ga pluton (J.L. Wooden, unpub U-Pb zircon data, 1990). Therefore, mineralization is younger than 1.4 Ga and older that 103.7 Ma. Obviously, the assumption that vein mineralization at the Congress mine (and therefore in the Alvarado mine in the Rich Hill district--and probably in much of the Rich Hill district, including the Yarnell mine) is Tertiary is incorrect. Further studies are underway by the author to more precisely determine the age of mineralization in the two districts.

The possibility remains that vein mineralization, although spatially associated with the "diabasic" mafic dikes in the Martinez and Rich Hill districts, bay be of a younger age and not genetically related to the assumed 1.1 Ga emplacement of mafic dikes in the region. The author considers this to be a remote possibility, but it cannot be dismissed with the present data.

ACKNOWLEDGEMENTS

I thank Ralph Rupp and Scott Petsel of Echo Bay Exploration for their help in sample collection at the Congress mine.

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convergent with a dextral sense during the Laramide orogeny.

The most convincing evidence for dextral offset comes from slickenlines on a series of sub-vertical faults sub-parallel to the boundary. Slickenlines plunge shallowly indicating strike-slip movement and slickensides show surface fractures characteristic of dextral offset. The strongest trend of slickenlines from all faults in the area indicates a NNE-SSW displacement.

Other evidence for a strike-slip component of movement comes from comparisons with structures found along modern wrench faults such as the San Andreas in California, and the Alpine fault zone in New Zealand. Thrusts and folds occur at left-stepping bends and terminations. Horsts occur between convergent splays and grabens occur between divergent splays. The strata in some grabens has been folded. Folding may be a result of convergence or of drag folding along the faults. Folded strata in grabens may characterize oblique tectonic convergence. Two major faults change dip direction along strike as is typical of strike-slip faults. The faults in the Gunnison area show an anastomosing pattern over a wide zone rather than the narrow zone typical of purely strike-slip faults. Convergence may have increased the width of the fault zone.

The Laramide age is bracketed by faults which cut late Cretaceous intrusions and are overlain by Oligocene tuffs. Most faults cannot be so bracketed in time, but are parallel in trend and style to the few that can be dated.

Maps, cross-sections, and slickenside data consistently indicate dextral oblique convergence between the Colorado Plateau and the North American plate in the Gunnison region during the Laramide Orogeny.

T22C-7 1330h POSTER

A Positive Gravity Anomaly Along the Colorado River Extensional Corridor: Evidence for New Crustal Material?

R.W. Simpson, K.A. Howard, R.C. Jachens (USGS, 345 Middlefield Rd., Menlo Park, CA 94025)
J. Mariano (Dept. of Geosciences, Purdue University, West Lafayette, IN, 47907)

A 150-km long isostatic residual gravity high parallels the west bank of the Colorado River from the Eldorado Mountains in Nevada to the Whipple Mountains in California. It coincides with a belt of metamorphic core complexes that have been interpreted from geologic evidence to mark a corridor of extreme Miocene crustal extension, and it also overlies a mid-crustal upward bulge of higher velocities detected in two PACE seismic refraction profiles across the extensional corridor. Over most of its length, the gravity high has a width of approximately 20 km with an amplitude of 10-20 mGal above background levels on either side. Although gradients seem to require that the top of the source body lie within several kilometers of the Earth's surface, the causative rocks have been difficult to identify in spite of extensive density sampling. Tertiary mafic dikes and small intrusions are exposed along the anomaly in a number of ranges, though usually not in enough volume to explain the amplitude of the anomaly. Where dated, the Tertiary igneous rocks yield ages in the range 22-14 Ma. We speculate that more of these igneous rocks exist in the subsurface and that they were emplaced and uplifted as part of extensional processes that began when the Pacific plate contacted the North American plate. We cannot rule out the possibility that older dense lower-crustal rocks uplifted by the extensional process are causing or contributing to the anomaly, although such rocks are not exposed in significant quantities at the surface. To the west of the Colorado River gravity high, a belt of gravity highs trends south-southeast from the Death Valley region where extension is presently occurring. One gravity high in this belt is associated with an 11.6 Ma diorite intrusion in the Black Mountains adjacent to Death Valley reported by Asmerom and others (1990). They interpreted this intrusion to have been emplaced at mid-crustal levels and brought to the surface by the extensional process. If so, the Death Valley region may provide a modern analog to the Colorado River extensional corridor.

T22C-8 1330h POSTER

Gravity Anomalies in Western Arizona

KEVIN L. MICKUS (Dept. of Geosciences, S.W. Missouri St. Univ., Springfield, MO 65804-0089)

... and a gravity maxima over the Colorado River extensional terrane that is interpreted to be caused by a mid-crustal lens (10-23 km in depth) of dioritic material formed during the main phase of mid-Tertiary extension. The mid-crustal lens is modeled with density of 2.84 g/cc determined from seismic velocities.

T22C-9 1330h POSTER ✶✶

Apatite Fission Track Analyses From Metamorphic Core Complexes and the Transition Zone, Arizona, U.S.A.

David A. Foster, Andrew J. W. Gleadow, and Gordon S. Lister (Victorian Institute of Earth and Planetary Sciences, GPO Box 2729X, Melbourne 3001, Australia)
Stephen J. Reynolds (Arizona Geological Survey, 845 N. Park Ave., #100, Tucson, Arizona 85719, U.S.A.)

Apatite fission track (FT) ages from basement rocks exposed in metamorphic core complexes (MCC) and the Colorado Plateau Transition Zone, west central Arizona, reveal information about heating during the Laramide followed by cooling/unroofing in the middle Tertiary. Seven apatite FT ages from the lower plate of the Buckskin MCC are between 10 ± 2 and 16 ± 3 Ma. Mean confined FT lengths for these samples range from 13.8 to 14.8 μm with standard deviations of 0.7 to 1.5 μm. Two samples from the Whipple MCC, California, give apatite FT ages of 14 ± 2 and 15 ± 1 Ma with mean track lengths >14 μm. Analyses of six samples from the Harcuvar MCC reveal apatite FT ages between 11 ± 2 and 16 ± 2 Ma and mean lengths of 13.6 ± 1.3 to 14.5 ± 0.9 μm. These ages are nearly concordant with published and unpublished K-Ar and $^{40}Ar/^{39}Ar$ ages of biotite and K-feldspar from mylonitic lower plate rocks. The concordant ages combined with mean track lengths >14 μm can only be the result of rapid cooling to below ~80°C followed by residence at or near the surface until the present. Apatite FT ages between Congress and Peeples Valley, AZ increase from 27 ± 2 to 44 ± 4 Ma over an elevation change of 540 meters. Mean FT lengths for these samples decrease from 13.4 ± 1.4 to 12.4 ± 2.2 μm. Track length distributions are unimodal and negatively skewed. An increase in age from 25 ± 2 to 47 ±2 Ma over 560 meters elevation is found between Wilhoit and Preston. Although these two sequences yield similar ages, strongly negative skewed and moderately bimodal length distributions with means of 10.9 ± 3.8 to 12.0 ± 3.1 μm indicate more annealing in the Wilhoit/Preston suite. These two age sequences may represent an age/depth profile developed after the Laramide which was probably uplifted and repeated by Tertiary high angle faulting. We have analyzed apatites from basement rocks collected from beneath the Cambrian unconformity near Cherry, AZ and found ages of 80 ± 5 to 107 ± 11 Ma and bimodal track length distributions with means of 10.2 ± 3.7 to 11.6 ± 3.2 μm. This suggests a high degree of annealing which likely occurred during both the Laramide and Tertiary.

Eos, 1990, v. 71, p 1594

T22C-10 1330h POSTER

A Thermomechanical Model of the Colorado Plateau Lithosphere

Juan Homero Hinojosa (Department of Geological Sciences, The University of Texas at El Paso, El Paso, TX 79968)

The Colorado Plateau (CP) is a coherent and elastically strong lithospheric block surrounded in part by the weaker extensional regimes of the Basin and Range Province and the Rio Grande Rift. The CP has experienced a Cenozoic uplift of about 2 km. The exact physical mechanism responsible for isostatic uplift is still unclear. Previously proposed uplift mechanisms for the CP include, in general, some form of (i) thermal expansion, (ii) crustal thickening, and (iii) phase changes. An alternative thermomechanical uplift mechanism is proposed here. A finite difference solution to both the axisymmetric, time-dependent heat conduction equation with heat sources and the elastic flexure equation has been obtained. Heat flux boundary conditions are used at the base ...

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MIDDLE TERTIARY TECTONICS OF ARIZONA AND ADJACENT AREAS

by
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ABSTRACT

Middle Tertiary tectonics in the Basin and Range Province of Arizona and adjacent parts of southeastern California and southern Nevada were dominated by large-magnitude lithospheric extension accommodated at upper crustal levels primarily by formation of and movement on regional, low-angle normal (detachment) faults. Unidirectional tilting of upper-plate fault blocks over large areas referred to as tilt-block domains reflects the geometry and movement direction of underlying detachment faults. Large displacements on detachment faults resulted in denudation and isostatic uplift of lower-plate mylonitic crystalline rocks that are now exposed in archlike structural culminations known as metamorphic core complexes. Mylonitic fabrics in these complexes formed by ductile shear along the deeper, downdip projections of detachment faults. Crustal extension occurred in the lower crust beneath the Transition Zone, which was probably tilted one to two degrees to the southwest as a result of greater crustal thinning beneath its southwestern margin. Relative elevation changes between the Basin and Range Province and Colorado Plateau occurred in association with tilting of the Transition Zone and were marked by a reversal in drainage direction and formation of many of the basic features of modern Arizona physiography. Crustal extension was accompanied by widespread, dominantly silicic magmatism that migrated from east to west across Arizona. Both extension and the westward sweep of magmatism are inferred to be related to steepening and perhaps disintegration of the subducted lithospheric slab beneath southwestern North America.

INTRODUCTION

The middle Tertiary tectonic evolution of Arizona and adjacent areas was dominated by two processes: lithospheric extension and a resurgence of magmatism following a 10- to 30-Ma period of magmatic quiescence. Both extension and magmatism were related to the evolving plate-tectonic setting of the continental margin of western North America, which is fairly well understood based on marine magnetic-anomaly data and global plate reconstructions (Atwater, 1970; Jurdy, 1984).

Middle Tertiary magmatism and extensional deformation in the Basin and Range Province of Arizona (fig. 1) and adjacent areas overprinted crust that had experienced previous periods of magmatism and compressional deformation. The most significant earlier period of widespread magmatism, compressional deformation, and inferred crustal thickening was in middle to Late Cretaceous and early Tertiary time. The fact that mid-Tertiary tectonism occurred largely in areas that had experienced earlier deformation and magmatism (the Colorado Plateau consistently escaped significant deformation) suggests that the earlier tectonic history of the crust exerted control over the locus of later mid-Tertiary activity. The nature of this

Figure 1. Map of the major physiographic provinces of Arizona.

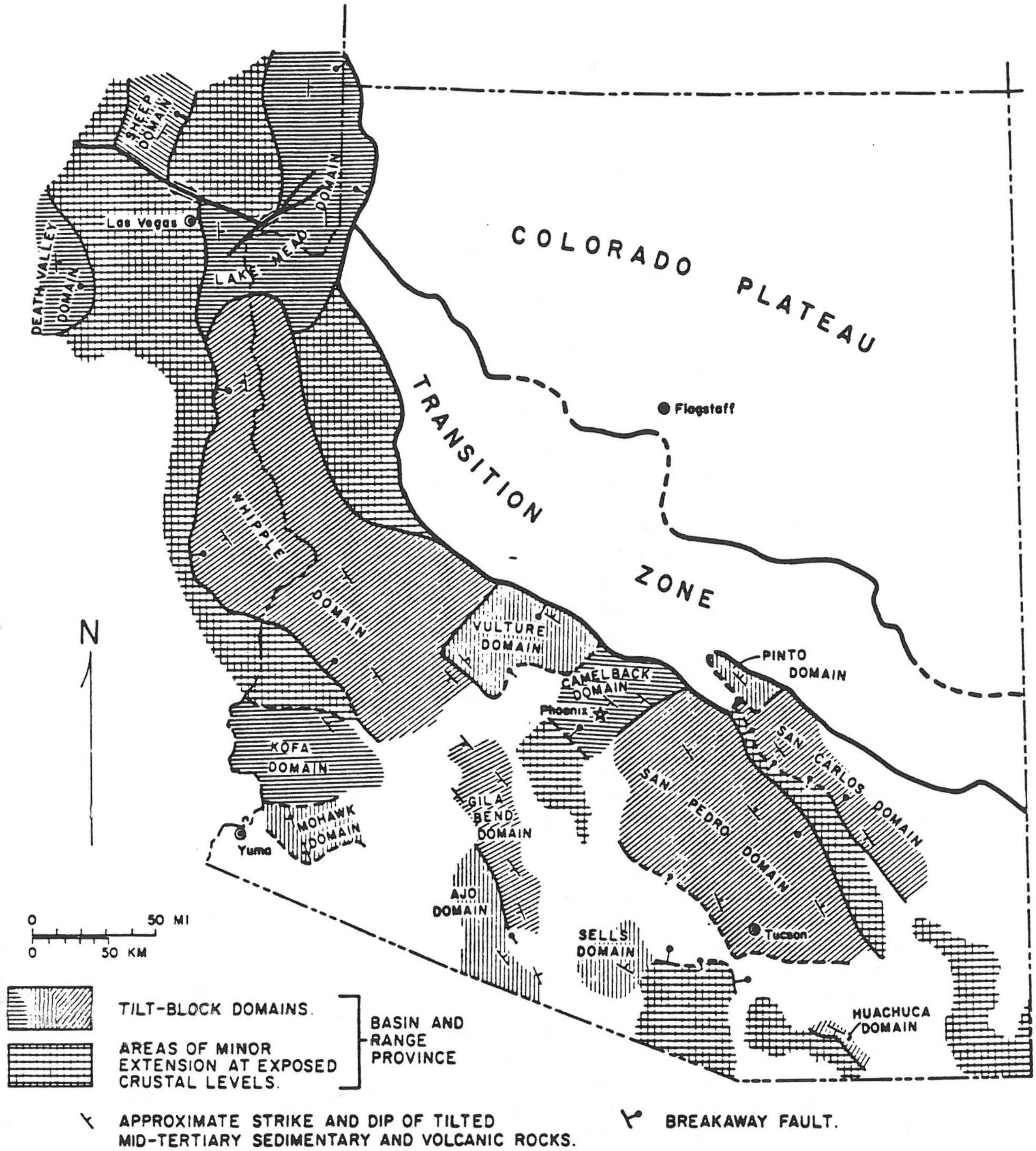

Figure 5. Mid-Tertiary tilt-block-domain map of Basin and Range Province in Arizona and adjacent parts of Nevada and California.

uplifts termed "metamorphic core complexes" (figs. 6, 7; Crittenden and others, 1980). A penetrative, lineated, mylonitic fabric that progressively dies out downward is a characteristic feature of metamorphic core complexes in Arizona. Mylonitic lineation is generally parallel to the direction of upper-plate displacement and distension, and the sense of shear during mylonitization, as indicated by S-C fabrics and other asymmetric petrofabrics (fig. 7; e.g., Berthe and others, 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984), is the same as the sense of shear inferred for the overlying detachment fault based on offset indicators and tilt directions of upper-plate fault blocks (Reynolds, 1985; Davis and others, 1986; fig. 5). The mylonitic fabric ranges from being well developed over the entire uplift to being restricted to a small area along the edge of the uplift. Mylonitic and nonmylonitic rocks within a few tens to hundreds of meters below the detachment fault are fractured or brecciated and contain secondary chlorite, Mountains about 100 km northeast of Tucson (figs. 8, 9; Blacet and Miller, 1978; Rehrig and Reynolds, 1980; Davis and Hardy, 1981). Both faults displace a similar sequence of steeply southwest-tilted upper-plate rocks above a structurally continuous lower plate and are inferred to be correlative. Crystalline rocks of the Pinaleno Mountains are continuous with lower-plate rocks in the Santa Teresa Mountains and are strongly overprinted by a lineated mylonitic fabric at the northeast foot of the range (Swan, 1976; Thorman, 1981; Naruk, 1986). The top-to-the-northeast sense of shear indicated for the mylonites by macroscopic shear-zone geometry and by S-C structures (Naruk, 1986; Kligfield and others, 1984) is consistent with the southwest tilt of fault blocks above the Eagle Pass and Black Rock faults (fig. 9) and strongly suggests that the Pinaleno mylonite zone is mid-Tertiary and related to shear at deeper levels of the Eagle Pass-Black Rock detachment fault.

The Santa Teresa Mountains are structurally continuous to the north with the Mount Turnbull block, which is in the hanging wall of the moderately northeast-dipping Hawk Canyon normal fault (Willden, 1964). Rocks above the fault, including middle Tertiary volcanics and overlying San Manuel-like, postvolcanic fanglomerate, dip approximately 40° to the southwest. This requires moderate tilting of at least the western part of the Mt. Turnbull block by rotational movement above the Hawk Canyon fault. The southwest dip of the Eagle Pass fault is possibly due to rotation above a southeastward continuation of the Hawk Canyon fault or related faults that are now buried under younger basin fill in Aravaipa Valley.

The Hawk Canyon fault and related northeast-dipping normal faults continue to the northwest through the Hayes and Mescal Mountains to the vicinity of Globe. These faults project beneath the Globe Hills and San Carlos area and probably account for the overall southwest dip of Proterozoic and Paleozoic strata in these areas.

Summary of Extensional Tectonics in Southeastern Arizona. In summary, the extensional tectonics of the area north and east of Tucson were dominated by displacement above two major detachment faults, the Eagle Pass-Black Rock detachment fault and the Catalina-San Pedro-Guild Wash-Star Flat-Cloudburst detachment fault. Upper-plate rocks are displaced away from the Galiuro Mountains, and the flanks of the Galiuro Mountains approximately coincide with the inferred breakaway faults for both detachment systems. The mirror-image symmetry of mid-Tertiary structures about the axis of the Galiuro Mountains is further accentuated by younger moderate-angle normal faults that dip away from the Galiuro Mountains and project beneath adjacent ranges (cross section in fig. 9).

Central Arizona

In the South Mountains, a key locality for extension-related deformation in central Arizona (fig. 10), gently dipping mylonitic fabrics with the regionally extensive east-northeast-trending lineation have been dated by U-Th-Pb, Rb-Sr, and K-Ar methods at 25 to 20 Ma (Reynolds and Rehrig, 1980; Reynolds, 1985; Reynolds, Shafiqullah, and others, 1986). A top-to-the-east-northeast sense of shear in the mylonitic rocks matches the east-northeast transport direction of rocks above the overlying South Mountains detachment fault. The kinematic and timing relationships indicate that mylonitization and detachment faulting represent a ductile-to-brittle continuum of simple shear on a gently northeast-dipping, normal shear zone (Reynolds, 1985; Davis and others, 1986). The detachment fault projects in the subsurface to the northeast beneath southwest-dipping Tertiary volcanic and clastic rocks near Phoenix and Tempe and is visible on seismic reflection profiles (Frost and Okaya, 1986). The stratigraphic succession in the upper-plate Tertiary rocks, which are composed of a lower, coarse-grained sedimentary breccia, a middle sequence of fluvial red beds, and upper volcanics dated at 17 Ma, suggests that tectonism began before, and continued after, the local inception of volcanism (Scarborough and Wilt, 1979; Schulten, 1979).

Geologic relationships in the White Tank Mountains to the west of Phoenix (fig. 10) are similar to those in the South Mountains (Reynolds, 1980; Rehrig and Reynolds, 1980). Gently dipping mylonitic fabrics with an east-northeast-trending lineation are moderately well developed in the eastern third of the range and have been overprinted on Precambrian gneiss, Tertiary plutons, and middle Tertiary dikes. The overall sense of shear in the mylonites is interpreted to be top-to-the-east-northeast, although thin, late-kinematic shear zones have the opposite vergence (Reynolds and Lister, 1987). A detachment fault has not been recognized, although chloritic-breccia-style brittle structures are present along the eastern edge of the range. We infer that an unexposed detachment fault, correlative with the South Mountains detachment fault, originally overlay the range and dipped east-northeast beneath the volcanic rocks north of Phoenix.

A higher structural level of middle Tertiary deformation is exposed in the Big Horn, Belmont, Vulture, and Hieroglyphic Mountains. In the western Big Horn Mountains, volcanic rocks dated at 20 to 16 Ma (J. Spencer, unpublished K-Ar data) dip moderately to gently to the southwest and are cut by northeast-dipping normal faults (Capps and others, 1985). Toward the east, in the eastern Big Horn and Belmont Mountains, the volcanics dip moderately to steeply to the northeast and are cut by southwest-dipping, low- to high-angle normal faults. Unconformities within the volcanic sequence indicate that volcanism was synchronous with normal faulting and tilting. Coarse sedimentary breccia and landslide-type megabreccia derived from fault scarps and oversteepened volcanic sections were deposited in the larger half grabens after the main pulse of silicic volcanism. Gently tilted to flat-lying basalts dated at 15 to 15.5 Ma occur north and south of the range and mark the termination of the main episode

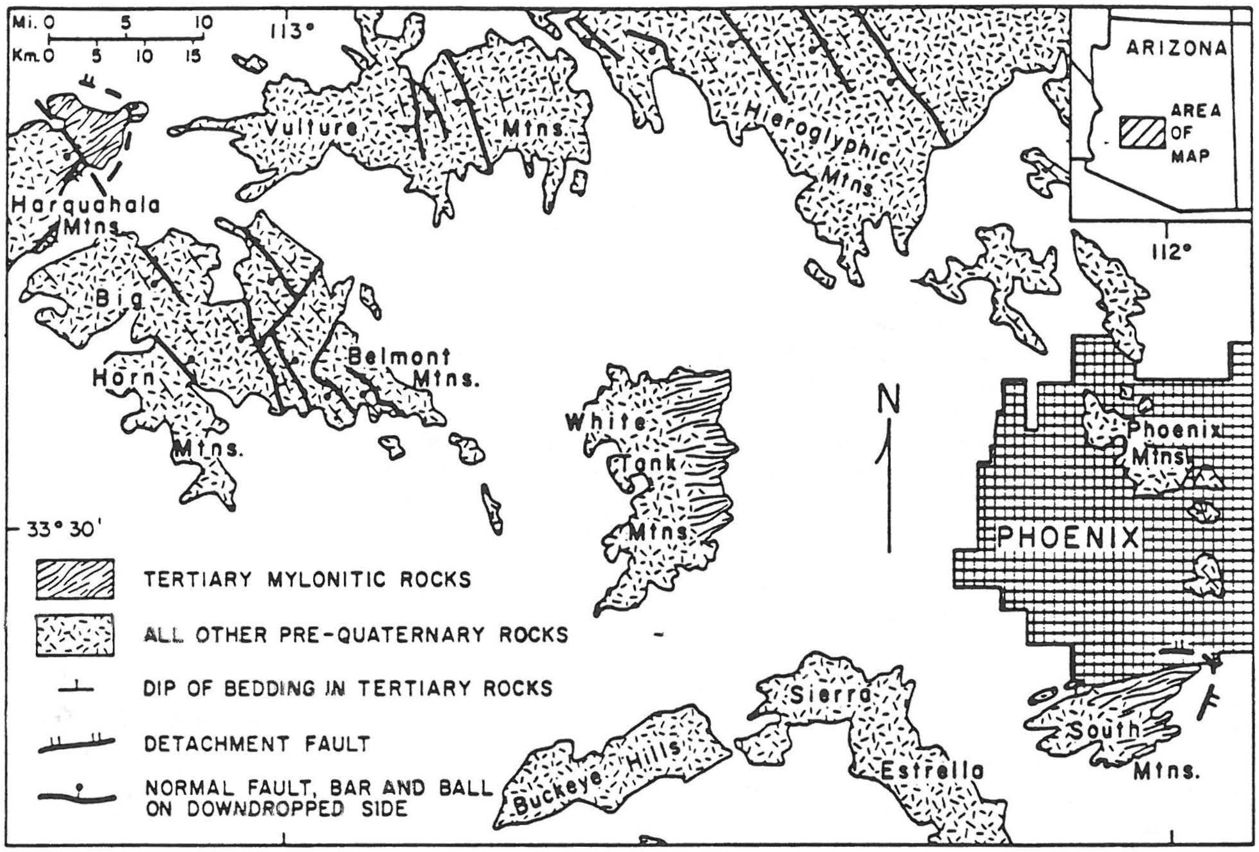

Figure 10. Map of central Arizona showing locations of mountain ranges and major Tertiary fabrics and structures.

of tilting (Scarborough and Wilt, 1979; Shafiqullah and others, 1980).

A nearly identical geologic setting has been documented in the Vulture Mountains to the northeast, where silicic volcanic rocks dated at 26 to 16 Ma dip moderately to steeply to the northeast and are cut by southwest-dipping, low- to high-angle normal faults (Rehrig and others, 1980). Termination of normal faulting and tilting is tightly bracketed by a 16-Ma date on a postfaulting potassic dike and a 13.5-Ma date on flat-lying basalt. Northeast-dipping volcanic rocks and southwest-dipping normal faults continue to the northeast through the Wickenburg and Hieroglyphic Mountains to the southwest edge of the Bradshaw Mountains (Capps and others, 1986; Stimac and others, 1987; Grubensky and others, 1987). Some of the southwest-dipping normal faults in the Wickenburg Mountains are very low angle, have displacements of approximately 3 to 5 km, and truncate higher angle normal faults in the overlying tilted Tertiary rocks (Stimac and others, 1987). The uniform northeast dip direction over the entire region from the central Bighorn Mountains to the Hieroglyphic Mountains suggests several possibilities: (1) the southwest edge of the Bradshaw Mountains is marked by the trace of the breakaway portion of a major southwest-dipping detachment fault or fault system that projects southwestward beneath the Hieroglyphic, Vulture, and Big Horn Mountains; (2) the northeast dip of the Tertiary units is due to movement on southwest-dipping antithetic faults related to a northeast-dipping detachment fault or fault system; or (3) northeast tilting occurred above a regionally southwest-dipping detachment fault or fault system that intersects a regionally northeast-dipping detachment fault or fault system. Northeast-dipping detachment faults in (2) or (3) would possibly link the South Mountains—White Tank detachment fault with the Bullard detachment fault of west-central Arizona. Resolution of these three possibilities is possible only by seismic reflection profiling.

Whipple Tilt-block Domain

One of the most extensive areas of detachment faulting, tilted upper-plate fault blocks, and tectonically denuded mylonitic and nonmylonitic rocks in western North America forms part of western Arizona and adjacent southeastern California and southernmost Nevada. This area composes the Whipple tilt-block domain, an area of approximately 25,000 km² in which Tertiary fault blocks dip predominantly to the west or southwest.

The Whipple tilt-block domain extends parallel to the strike of tilt-blocks (N-S to NW-SE) from the central Eldorado Mountains and northern Black Mountains in southernmost Nevada and northwestern Arizona, respectively, southward along the Colorado River and into west-central Arizona as far southeast as the Big Horn and Little Horn

Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona

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ABSTRACT

The Bullard detachment fault is a gently to steeply dipping normal fault that flanks the Harcuvar and Harquahala mountains of the Basin and Range province in west-central Arizona. The stratigraphy of upper-plate Miocene conglomerates and the regional distribution of upper- and lower-plate pre-Tertiary units indicate that upper-plate rocks were displaced about 50 km to the northeast with respect to the lower plate during middle to late Tertiary time. Normal slip of this magnitude on the regionally northeast-dipping Bullard fault indicates that deep-seated Tertiary-Cretaceous(?) mylonitic gneisses and Mesozoic thrust faults of the lower plate were drawn out from beneath Precambrian rocks along the margin of the Transition Zone of central Arizona during middle to late Tertiary crustal extension. The Transition Zone was, therefore, affected by deep-seated tectonism in both Mesozoic and Tertiary time.

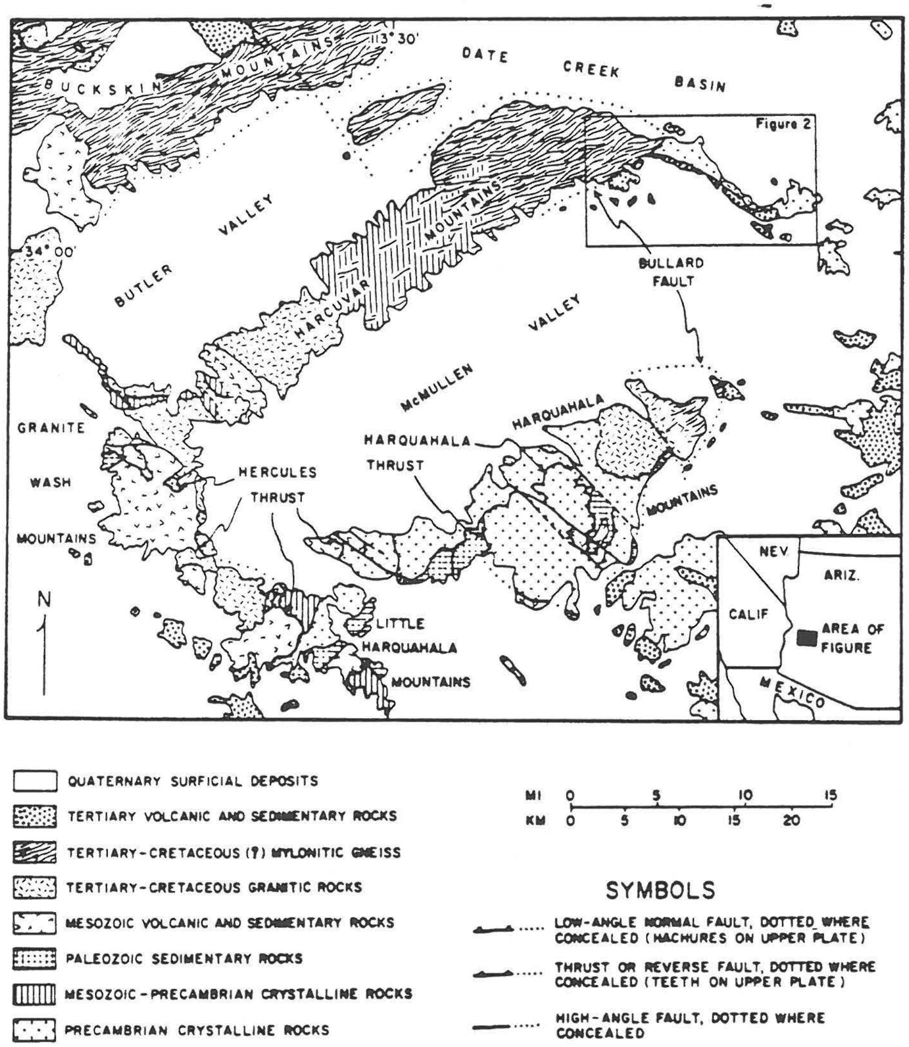

Figure 1. Simplified geologic map of McMullen Valley area. Sources of data include Rehrig and Reynolds (1980), Reynolds (1982), Reynolds and Spencer (1984), and unpublished mapping by S. J. Reynolds, S. M. Richard, and J. E. Spencer.

INTRODUCTION

Current models for the origin of detachment faults[1] associated with metamorphic core complexes can be divided into two groups: those that envision the faults as surfaces of major transport (Wernicke, 1981; G. H. Davis, 1983; G. A. Davis et al., 1983; Reynolds, 1985), and those that consider the fault surface to be an exhumed brittle-ductile transition that has only minor displacement (Rehrig and Reynolds, 1980; Miller et al., 1983). In this paper, we present evidence that the Bullard detachment fault of west-central Arizona accommodated about 50 km of normal slip during middle to late Tertiary crustal extension.

The Bullard detachment fault is a low- to high-angle fault that flanks the northeast ends of the Harcuvar and Harquahala mountains of west-central Arizona (Fig. 1; Rehrig and Reynolds, 1980; Reynolds, 1982). The fault separates upper and lower plates that have undergone dramatically different metamorphic, structural, and thermal histories. Rocks below the fault generally consist of plutonic and high-grade metamorphic rocks that have been complexly overprinted by Mesozoic and Cenozoic metamorphism and ductile deformation. In contrast, upper-plate rocks include highly tilted and faulted middle Tertiary volcanic and sedimentary rocks and Proterozoic metamorphic and granitic rocks that have generally escaped significant Mesozoic and Cenozoic metamor-

[1]The term "detachment fault" is used by us and, in our view, by many other geologists to describe a low-angle normal fault that formed at a low angle, has significant displacement, and is of subregional extent.

phism and ductile deformation. Lower-plate mylonitic rocks have yielded K-Ar biotite ages of 25 and 17 Ma (Shafiqullah et al., 1980; Rehrig, 1982), whereas upper-plate, Cretaceous(?) granite yielded a Late Cretaceous K-Ar biotite age (J. Kirkwood, 1977, oral commun.), which indicates that the upper and lower plates of the Bullard fault had contrasting thermal histories prior to mid-Miocene time. Although regionally the fault has a gentle northeast dip, it dips 50°–70° to the southeast in the eastern Harcuvar Mountains because of original irregularities of the fault surface (megagrooves) or warping during or after faulting.

GEOLOGY OF LOWER-PLATE ROCKS

Rocks below the Bullard fault in the Harcuvar Mountains include Precambrian crystalline rocks and Upper Cretaceous to lower Tertiary granitic rocks (Rehrig and Reynolds, 1980). The Harquahala Mountains also contain extensive exposures of these rock types but are further complicated by south- and southwest-vergent thrusts that place Precambrian crystalline rocks over Precambrian, Paleozoic, and Mesozoic rocks (Reynolds et al., 1980; S. M. Richard et al., mapping in progress). Rocks in both ranges have been widely overprinted by a Cretaceous regional metamorphic fabric and, in the eastern part of the ranges, by a Tertiary(?) mylonitic fabric formed by top-to-the-northeast shear. Foliation in the mylonitic rocks generally dips moderately to gently off the flanks of the range and defines broad, east-northeast–trending antiforms.

The Little Harquahala and Granite Wash mountains contain Mesozoic clastic and volcanic rocks that have been overridden along the Hercules and subsidiary thrusts by a variety of Precambrian, Paleozoic, and Mesozoic rocks (Fig. 1; Reynolds et al., 1980, 1983). Lower-plate Mesozoic rocks are only slightly cleaved and metamorphosed away from the southwest-vergent Hercules thrust but have been converted into schists immediately below the thrust, especially in the Granite Wash Mountains. The thrust sheets and thrust-related metamorphic fabrics have been intruded by large plutons of Upper Cretaceous granodiorite and granite.

GEOLOGY OF UPPER-PLATE ROCKS

Upper-plate rocks in the Harcuvar Mountains include Precambrian crystalline rocks with original Precambrian fabric that has been locally overprinted by a southwest- to southeast-dipping, mylonitic foliation of unknown age and significance (Fig. 2; Reynolds and Spencer, 1984). The Precambrian rocks have been intruded by Cretaceous(?) and lower Tertiary(?) granites and are depositionally overlain by a southwest- to south-dipping sequence of middle Tertiary volcanic and sedimentary rocks. The basal Tertiary unit, an arkosic conglomerate, is overlain by trachytic ash-flow tuffs that yielded a 24 Ma K-Ar biotite age (Brooks, 1984) and a 17 Ma K-Ar whole-rock age (Scarborough and Wilt, 1979). The tuffs are overlain by a 600-m-thick sequence of coarse conglomerate and sedimentary breccia that contains, from bottom to top, the following clast types: (1) well-rounded clasts of reddish quartzite exotic to the region; (2) angular to subangular clasts of porphyritic granite and Mesozoic clastic rocks, and large lenses of sedimentary breccia and granitic megabreccia; and (3) angular to subangular clasts as large as 1 m in diameter of Mesozoic sandstone, conglomerate, and mudstone, most of which are unmetamorphosed and undeformed; a few clasts contain a weakly developed cleavage. The top of the conglomerate contains minor amounts of Mesozoic volcanic clasts and is overlain by andesite flows, one of which yielded a 16 Ma K-Ar whole-rock age (Scarborough and Wilt, 1979).

DIRECTION AND MAGNITUDE OF TRANSPORT ON THE BULLARD FAULT

Significant normal slip on the Bullard fault is suggested by contrasting lithologies and structural styles across the fault. The fault juxtaposes rocks representative of different middle Tertiary crustal levels; it places upper-plate, high-level middle Tertiary volcanic and sedimentary rocks over lower-plate, deeper-level granitic sills and mylonitic gneisses that have yielded middle Tertiary cooling ages.

For several well-documented detachment faults, tilted upper-plate units strike perpendicular to the line of transport and dip in a direction opposite, or antithetic, to the direction of transport (Davis et al., 1980). If this generalization is true for the Bullard fault, then the southwest dip of upper-plate units reflects antithetic rotation during northeast transport of the upper plate relative to the lower plate. The systematic change in attitude of upper-plate mid-Tertiary units along Aguila Ridge (Fig. 2), if

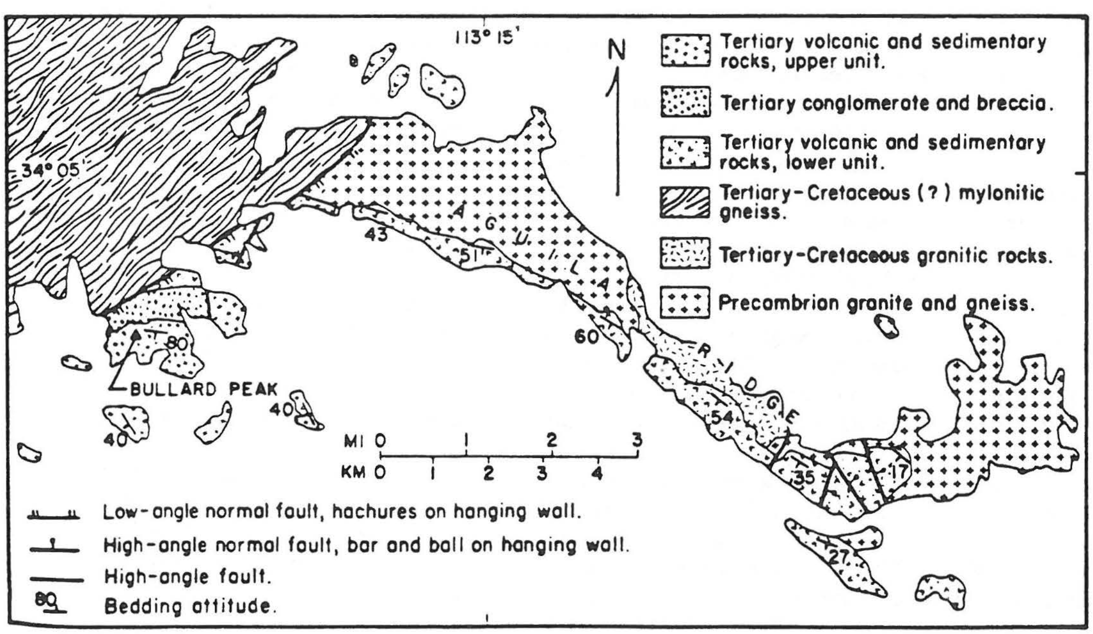

Figure 2. Simplified geologic map of Aguila Ridge, Bullard Peak area, and easternmost Harcuvar Mountains. Areas without pattern are Quaternary surficial deposits. See Figure 1 for location of map area.

interpreted as a large-scale drag structure, also indicates northeast transport of the upper plate (Reynolds, 1982). In addition, relative northeastward displacement of the upper plate is supported by correlation of the Bullard fault with the Whipple-Buckskin-Rawhide detachment fault, which, on the basis of various types of evidence, also displaced upper-plate rocks to the northeast relative to the lower plate (Shackelford, 1980; Davis et al., 1980).

Further evidence of major displacement is contained in the upper-plate sequence of conglomerate and sedimentary breccia. Granitic megabreccia in the conglomerate is composed of porphyritic granite that is lithologically most similar to granites that occur above the Hercules thrust in the Little Harquahala and western Harquahala mountains (Fig. 1), but that is completely dissimilar to any granites we have mapped in the Harcuvar or eastern Harquahala mountains. Correlation of the granite in the megabreccia with granite in the Little Harquahala Mountains is supported by Rb-Sr isotopic analyses that are prohibitive of a Precambrian age and suggestive of a Jurassic age for both granites (P. E. Damon and M. Shafiqullah, 1985, written commun.). Conglomerate that overlies the megabreccia contains large, angular to subangular clasts of unmetamorphosed Mesozoic clastic rocks that are not present in either the Harcuvar or the Harquahala mountains. Regional mapping has revealed that unmetamorphosed Mesozoic clastic rocks are present only in the Little Harquahala Mountains, western Granite Wash Mountains, and ranges farther to the west. Correlative Mesozoic sedimentary rocks occur in windows beneath regional thrust sheets in the western and southern Harquahala Mountains, but they have been strongly metamorphosed. Likewise, clasts of unmetamorphosed Mesozoic volcanic rocks, which are abundant near the top of the Miocene conglomerate, have no source in the Harcuvar or eastern Harquahala mountains, but could have been derived from Mesozoic volcanic rocks that underlie Mesozoic sedimentary rocks in the Little Harquahala Mountains. The angular to subangular nature and large size of the clasts argue against significant sedimentary transport of the clasts prior to deposition. Mesozoic clastic rocks in the Granite Wash and Little Harquahala mountains contain less chert grains and mudstone than some clasts in the Miocene conglomerate, but they nevertheless represent the nearest exposed source of relatively unmetamorphosed Mesozoic rocks.

The strongest evidence for large-scale transport is that the clast stratigraphy of the conglomerate appears to be the inverse of the structural and stratigraphic stacking of the Little Harquahala and Granite Wash mountains. The

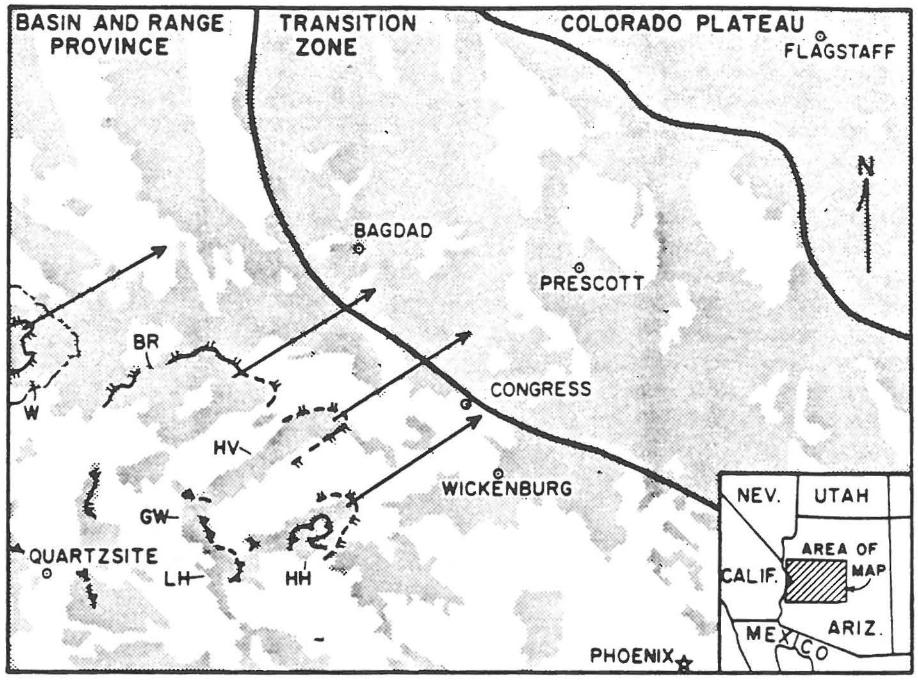

Figure 3. Map showing distribution of pre-Quaternary bedrock exposures (stippled) and major physiographic provinces in part of western and central Arizona and adjacent California. Major faults are shown with same symbols as in Figure 1. Arrows indicate estimated minimum 50-km translation of lower-plate rocks necessary to restore to pre–mid-Tertiary position. Capital letters indicate position of Whipple (W), Buckskin-Rawhide (BR), Harcuvar (HV), Granite Wash (GW), Little Harquahala (LH), and Harquahala (HH) mountains.

stratigraphic succession in the Miocene conglomerate from granitic megabreccia to overlying Mesozoic-clast conglomerate suggests that granite overlay Mesozoic sedimentary rocks in the source area. The presence of granite over Mesozoic sedimentary rocks would be unusual in most geologic settings but is precisely what is observed in the Little Harquahala and Granite Wash mountains where Mesozoic sedimentary and volcanic rocks have been overridden by granitic rocks along the Mesozoic Hercules thrust. The upward increase in abundance of clasts of Mesozoic volcanic rocks in the Miocene conglomerate is interpreted as the result of progressive erosional, and possibly tectonic, unroofing of volcanic rocks that underlie Mesozoic sedimentary rocks of the Little Harquahala and Granite Wash mountains.

We interpret the present-day 50-km distance between the conglomerate and the possible source rocks to be the approximate amount of transport on the Bullard detachment fault. The closest lithologic match to the clasts of Mesozoic rocks actually occurs in Mesozoic sections in the southern Plomosa Mountains, the next range west of the Granite Wash Mountains, but we do not, at present, infer that the fault has 100 km of transport. It is unlikely that Mesozoic sedimentary rocks were originally part of the highest thrust sheet in the Harquahala Mountains, because the thrust sheet and its inferred offset equivalents above the Bullard fault are composed entirely of Precambrian and Mesozoic crystalline rocks; Mesozoic and Paleozoic sedimentary rocks are nowhere observed in the upper plate of the Bullard fault.

Distension of upper-plate rocks results in progressively greater relative displacement on the detachment fault in the direction of upper-plate transport. Displacement on the Bullard fault, therefore, probably increases to 60 or 70 km beneath distended upper-plate rocks identified in the subsurface northeast of the Harcuvar Mountains (Otton, 1981, 1982).

IMPLICATIONS

Our data indicate that detachment faults on the flanks of core complexes do have significant amounts of transport and were not formed as a result of in situ crustal stretching of the lower plate. The restriction of penetrative mylonitic fabrics to the eastern Harcuvar and Harquahala mountains (Fig. 1) indicates that in situ ductile distension of the lower plate, if it occurred, could not have caused more than about 15 km displacement of the upper plate relative to the lower plate. We therefore conclude that most, if not all, of the northeast displacement of upper-plate rocks relative to lower-plate rocks occurred by translation above the Bullard detachment fault.

Geologic mapping and regional geologic relationships indicate that the Bullard fault does not surface to the northeast, but instead projects at depth beneath the edge of the Transition Zone and toward the Colorado Plateau (Rehrig and Reynolds, 1980; Lucchitta and Suneson, 1981; Otton, 1982; proprietary seismic reflection data). If the fault has 50 km of transport and a corresponding original minimum downdip extent of 50 km, then deeper segments of the fault were almost certainly within the ductile regime, even if the fault had a very gentle original dip. Lower-plate mylonitic rocks formed by top-to-the-northeast shear in the easternmost Harcuvar and Harquahala mountains would probably have been within the ductile regime at the inception of faulting and therefore probably represent initial ductile deformation related to movement on the Bullard fault. An original northeast dip of the fault zone is further supported by the restriction of middle Tertiary cooling ages to the easternmost, and therefore structurally deepest, lower-plate rocks. Our data thus reinforce those models that interpret mylonitic fabrics in core complexes as a ductile, deeper seated manifestation of low-angle normal faulting (G. H. Davis, 1983; G. A. Davis et al., 1983; Reynolds, 1985). We interpret lower-plate rocks exposed in the eastern Harcuvar and Harquahala mountains as having been at a depth of 10 to 20 km prior to Tertiary extension, which, combined with the 50 km estimate of transport, requires an original dip on the Bullard fault of about 10° to 20°.

Restoring 50 km of movement on the Bullard fault and correlative Whipple-Buckskin-Rawhide fault places the most northeasterly exposed lower-plate rocks beneath the cities of Bagdad, Congress, and Wickenburg, near the edge of the Transition Zone (Fig. 3). This implies that the Harcuvar core complex, with its Mesozoic plutons, metamorphic fabrics, and thrust faults, was drawn out from under the Transition Zone, a region dominated in outcrop by Precambrian rocks considered by most geologists to have escaped significant Mesozoic tectonism. Restoring Mesozoic thrust sheets of the Harquahala Mountains to a position under the edge of the Transition Zone opens the possibility that a variety of rock types now exposed in the Basin and Range province were underthrust beneath the present-day Transition Zone in the Mesozoic, only to be exhumed by detachment faulting during middle to late Tertiary crustal extension. Thrust-induced crustal thickening in the Mesozoic could have accentuated the Mogollon Highlands of Harshbarger et al. (1957), a Late Triassic to Eocene uplift that is inferred to have occupied parts of the present-day Transition Zone.

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Reviewer's comment

An excellent paper! I wish I'd written it!

Greg Davis