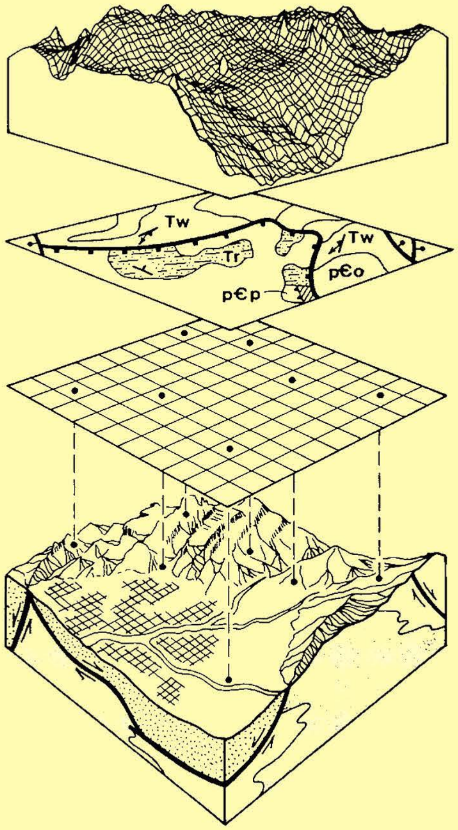
FRONTIERS IN GEOLOGY AND ORE DEPOSITS OF ARIZONA AND THE SOUTHWEST

Arizona Geological Society and the University of Arizona 1986 Symposium



FIELD TRIP GUIDEBOOK
3

Precious Metal Mineralization,
Stratigraphy, and Tectonics
In Southeastern California

March 17-19 1986

Leaders: W. Wilkinson and C. Wendt (NICOR), J. Wilkins (St. Joe Minerals), G. Haxel (U.S.G.S.)

Coordinator: J. Wilkins

ARIZONA GEOLOGICAL SOCIETY
TUCSON, ARIZONA

Cover preparation by Beverly Morgan, modified from J. Mehulka and P. Mirocha, AGS Digest Volume XVI

ARIZONA GEOLOGICAL SOCIETY

P.O. BOX 40952, UNIVERSITY STATION
TUCSON, ARIZONA 85719

To: Field Trip Participants

Welcome to Arizona and the 1986 Arizona Geological Society Symposium "Frontiers in Geology and Ore Deposits of Arizona and the Southwest." As field trip chairman I would like to wish you an enjoyable and informative conference and a worthwhile field trip experience.

The field trip committee set out many months ago to provide field exposure to a broad spectrum of geological disciplines. The results include trips to recent precious-metal discoveries, areas of new and developing stratigraphic and structure concepts, industrial mineral resources, lithologic features significant to the petroleum potential in the Southwest, geologic hazards in the community, and an opportunity to attend trips from previous Arizona Geological Society meetings. We hope you find your chosen field trip as exciting as we intended.

At this time of very limited support from industry, it is especially important to acknowledge the personal efforts of so many. I include in those the planning and follow through of the field trip committee, the many hours of preparation by the trip leaders, and the commitment of the trip coordinators to a smooth-running trip. A special thanks goes to Maggie Morris of the University of Arizona Conference Department for the transportation, lodging, and meal arrangements.

Please enjoy the Southwest and remember this week of field trips and meetings as a step toward the frontiers of the future.

Best regards,

Parry D. Willard

Parry D. Willard
Field Trip Chairman

Field Trip Committee

Annon Cook
Norm Lehman
Beverly Morgan
Jon Spencer
Erick Weiland
Joe Wilkins Jr.
Jan Wilt

ITINERARY

FIELD TRIP 3

PRECIOUS-METAL MINERALIZATION, STRATIGRAPHY, AND TECTONICS IN SOUTHEASTERN ARIZONA

General Leaders:	William H. Wilkinson and Clancy J. Wendt (Nicor), Gordon B. Haxel (USGS), Joe Wilkins Jr. (St. Joe Minerals)
Coordinator:	Joe Wilkins Jr. (St. Joe Minerals)

Monday, March 17, 1986

4:00 pm	Depart from University of Arizona, front of Student Union. Travel to Yuma, Ariz.
8:00 pm	Arrive and check in at Stardust Resort Motor Inn,* Yuma, Ariz. (602-783-8861)

Tuesday, March 18, 1986

7:00 am	Depart from Stardust Motel
8:15 am	Stop 1. Gavilan Hills—a walking tour (4 hours)
12:15 pm	Return to vehicles. Lunch*
2:00 pm	Stop 2. Overview of Mesquite mine
3:15 pm	Stop 3. Cargo Muchacho Mountains—visits to American Girl, American Boy, and Padre-Madre mines
5:15 pm	Return to Yuma
7:00 pm	Steak fry* at Stardust Resort

Wednesday, March 19, 1986

7:00 am	Check out and depart from Stardust Motel
7:30 am	Stop 1. Overview of Picacho Basin
8:00 am	Stop 2. Traverse to examine structural behavior of rocks along the detachment fault
9:15 am	Stop 3. Traverse through Winterhaven Formation onto the detachment fault
10:30 pm	Stop 4. Exposure of cataclastic ledge
11:15 pm	Stops 5 and 6. Picacho mine. Lunch* between stops
1:30 pm	Depart for Tucson
6:00 pm	Arrive in Tucson. Stops at Holiday Inn (Broadway) and University of Arizona

*Included in fees.

Drivers:	David Young	Gail Liebler
	Mark Bradley	Bob Smith

Field boots required. If possible, bring hard hat and safety glasses for mine tours.

BACKGROUND MATERIAL

Geologic Road Logs

1979 Arizona Geological Society Spring Field Trip

Tucson-Yuma-Quartzsite-Buckeye. With side trips to the Marine Corps Gunnery Range and the Silver mining district.

Peter H. Dohms, New Jersey Zinc Co., Tucson
Peter G. Dunn, Quintana Minerals Corp., Tucson
Lucy E. Harding, University of Arizona, Tucson
Richard J. Lundin, Wallaby Enterprises, Tucson
Daniel J. Lynch, University of Arizona, Tucson
Stephen J. Reynolds, University of Arizona, Tucson
John E. Teet, New Jersey Zinc Co., Tucson

TUCSON TO YUMA VIA INTERSTATES 10 AND 8

Distance: 224.3 miles

(by D. J. Lynch)

Milepost
256 Grant Road on-ramp to Interstate 10. Starting point.

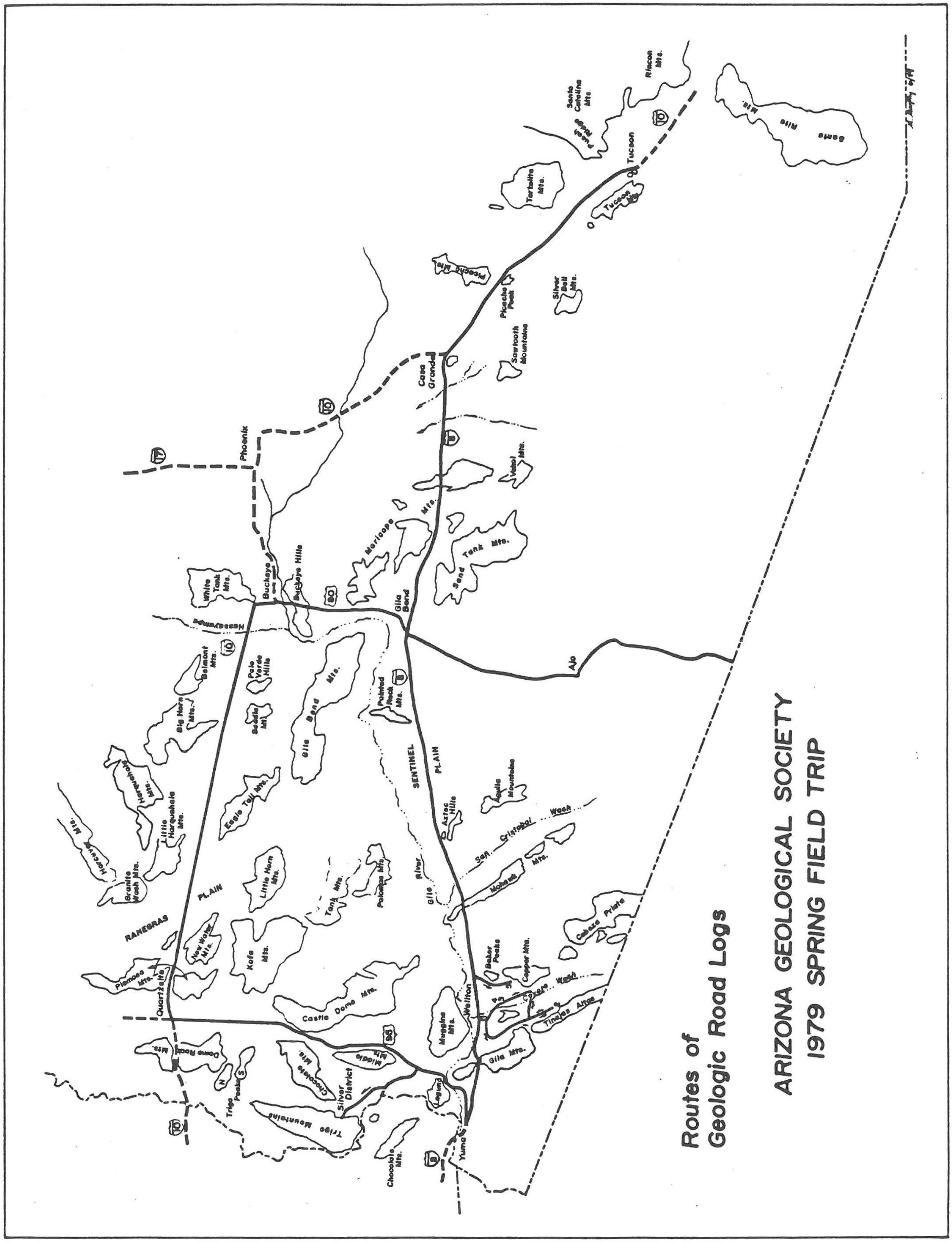
16 miles

TO
MP 240 Tucson Mountains and Catalina Mountains

Pusch Ridge and the forerange of the Catalina Mountains lie to the north of this section of freeway. Details of structure are easily seen from the road while traveling northwest. Layering of the Catalina gneiss is warped into a broad anticlinal structure, which is seen to plunge gently to the west. Opposing dips on the limbs are most easily observed from the north section of road. The rocks of Pusch Ridge are alternating layers of dark, biotite augen gneiss and light-colored muscovite granite. Although the K/Ar ages from these rocks fall within the Cenozoic, all of the rocks were formerly thought to be older Precambrian with their argon clocks reset by a mid-Tertiary thermal event. Recent work (Reynolds, pers. comm.) suggests that the dark layers are mylonitized Oracle Granite and the light layers are 50 m.y.-old granite sills intruded at the close of the Laramide and then mylonitized by the event that created the Tortolita-Catalina-Rincon metamorphic core complex.

As you proceed past the end of Pusch Ridge, the erosional amphitheater developed on the Catalina granite will come into view . Intrusion of this pluton 25 m.y. ago was probably responsible for resetting the argon clocks.

To the west of the freeway are the Tucson Mountains, a complex series of intrusions and lava flows which rest on Cretaceous rocks. Rocks of the southern end are rhyolites and monzonites, which have radiometric ages ranging between 50 and 72 m.y., within the time span of the Laramide orogeny. Sentinel Peak ("A" Mountain) and Tumamoc Hill, directly west of Tucson, have a well-exposed section of mid-Tertiary lava flows interbedded with


Routes of
Geologic Road Logs
ARIZONA GEOLOGICAL SOCIETY
1979 SPRING FIELD TRIP
Tucson
Santa Catalina Mts.
Rincon Mts.
Tucson Mts.
Tortolita Mts.
Picacho Mts.
Picacho Peak
Silver Bell Mts.
Sawtooth Mountains
Casa Grande
Phoenix
Buckeye
Buckeye Hills
White Tank Mts.
Maricopa Mts.
Vekol Mts.
Sand Tank Mts.
Gila Bend
Ajo
Hassayampa
Belmont Mts.
Palo Verde Hills
Gila Bend Mts.
Painted Rock Mts.
Saddle Mt.
Big Horn Mts.
Harquahala Mts.
Little Harquahala Mts.
Eagle Tail Mts.
SENTINEL PLAIN
Aguila Mountains
Aztec Hills
San Cristobal Wash
Mohawk Mts.
Gila River
Palomas Mts.
Tank Mts.
Little Horn Mts.
Granite Wash Mts.
RANEGRAS PLAIN
New Water Mts.
Kofa Mts.
Plomosa Mts.
Quartzsite
Castle Dome Mts.
Baker Peaks
Copper Mts.
Cabeza Prieta
Coyote Wash
Tinajas Altas
Wellton
Muggins Mts.
Gila Mts.
Dome Rock Mts.
Trigo Peaks
Chocolate Mts.
Middle Mts.
Silver District
Laguna
Trigo Mountains
Yuma
10
17
8
80
95

volcaniclastic and sedimentary rocks, which range in age from 27.6 ± 1.2 m.y. (Turkey Track porphyry) to 23.7 ± 0.5 m.y. (the basaltic andesite that caps Tumamoc Hill) (Eastwood, 1970; Phillips, 1976; Shafiqullah and others, 1978).

The Safford Peak group, which lies beyond Ina Road, contains a coarse conglomerate, which rests uncomformably on Cretaceous rocks. This is one of the oldest of the widespread Oligocene conglomerate units found in southern Arizona, its age (39.4 ± 1.3 m.y.) determined on an andesite flow contained in the sequence. The ridges of this mountain group are formed of 28.5 ± 1.9 m.y.-old andesite, and Safford Peak, the highest point, is made of a 25.1 ± 0.9 m.y.-old dacite intrusion. (Ages from Eastwood, 1970.).

9 miles

MP 249 Rillito River

The Rillito River and streams tributary to it are the major drainages for the northern Tucson basin as well as the eastern and southern slopes of the Catalina and Rincon Mountains. Cienega Creek rises in the Sonoita valley east of the Santa Rita Mountains and flows northward to join Pantano Creek in Cienega Pass. Pantano Creek joins the Rillito River northeast of Tucson, and the Rillito joins the Santa Cruz River a few hundred meters west of this bridge. The Tucson basin is drained by rivers that flow around its periphery rather than down the center of the valley.

2 miles

MP 247 Canada del Oro Wash

This creek flows southward out of Canada del Oro, a graben valley that separates the high Catalina Mountains on the east from the lower Tortolita Mountains on the west. Both the Tortolita and Catalina mountain fronts are highly embayed and pedimented indicating a lack of tectonic activity along the basin margin faults during Quaternary time. Since mid(?)-Pleistocene time, large alluvial fans that once buried the Catalina pediment have been partially eroded away resulting in the exhumation and deep dissection of the pediment. Geomorphic, soil, and stratigraphic evidence show that the predominant factors controlling the Quaternary geomorphic evolution of this intermontaine valley have been nontectonic. Climatic change, stream and drainage basin piracy, and other geomorphic variables affecting sediment supply, stream discharge, and aggradation or degradation have influenced the evolution of this landscape (McFadden, 1978).

7 miles

MP 240 Rillito (Cement Plant)

The Arizona Portland Cement Company makes cement out of lower Paleozoic rocks quarried from Twin Peaks (visible to the southwest at 8:00). Several low, isolated bedrock hills can be seen at 1:30. They are composed of altered quartzite, possibly Apache Group, separated by a fault from Oracle(?) Granite at a depth of 80 m. Four drill holes spaced 300 m in cardinal directions from the outcrop hole encountered the granite beneath alluvium at depths ranging from 50 to 120 m without passing through the altered quartzite.

This suggests a buried pediment having a gentle slope to the southwest beneath this area.

8 miles

MP 232 Marana Air Park Road—Pinal County Line

Ragged Top, a mountain with a distinctive irregular skyline, is at 9:00. Biotite from the Ragged Top rhyolite yielded a K/Ar age of 25.6 ± 1.0 m.y. (Eastwood, 1970). The hill at 1:30 is composed of gneiss. Owlhead Butte north of the Tortolita Mountains is at 3:00. Directly ahead is Picacho Peak to the left of the highway and the Picacho Mountains to the right.

7 miles

MP 225 Red Rock Road

Northward from this point, the view is increasingly dominated by Picacho Peak. It has the classic shape of an exhumed volcanic neck, but it actually is a fault-bounded block from the flank of a volcano. Although the flow units cannot be easily differentiated, apparent dips to the right (northeast) can be seen in some planar elements of the rocks. The structural complexity of this peak is typified by the unexplained 50-meter-long block of Oracle Granite found near the summit.

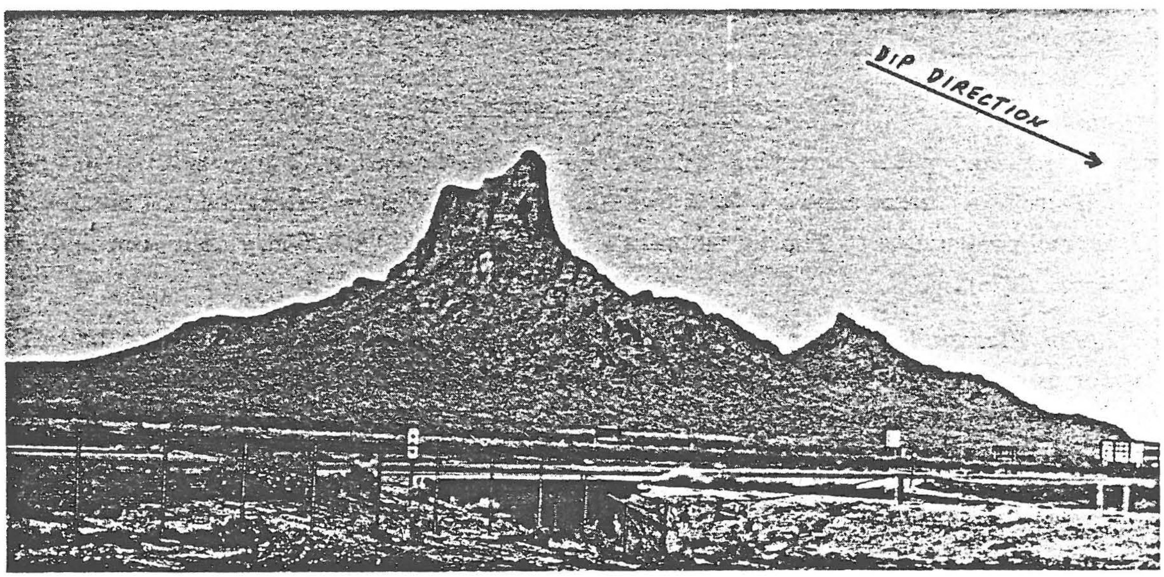


Fig. 1. Picacho Peak. Apparent dip of planar elements in the lava flow sequence is parallel to the "dip direction" line. A coherent block of Oracle Granite underlies the concave slope to the left of the summit.

Three isolated mounds of black-appearing rock occur in the pass and are best seen from near the interchange. The most distant outcrop of this rock lies atop a gneissic ridge extending southeastward from the Picacho Mountains and may not be easily located. This dark-red, aphanitic trachyte is the most potassic of the alkaline rocks of Picacho Peak, having a K_2O content of 12.5%. All the other trachytes and trachy-andesites have combined alkali contents greater than 7.5%, and many of the units are ultra-potassic

($K_2O/Na_2O>10$). The ultrapotassic trachytes are autobrecciated, having fractured during the last stages of flow movement. This dark-red to purple color and pervasive autobrecciation are characteristic of all the ultrapotassic rocks in the state.

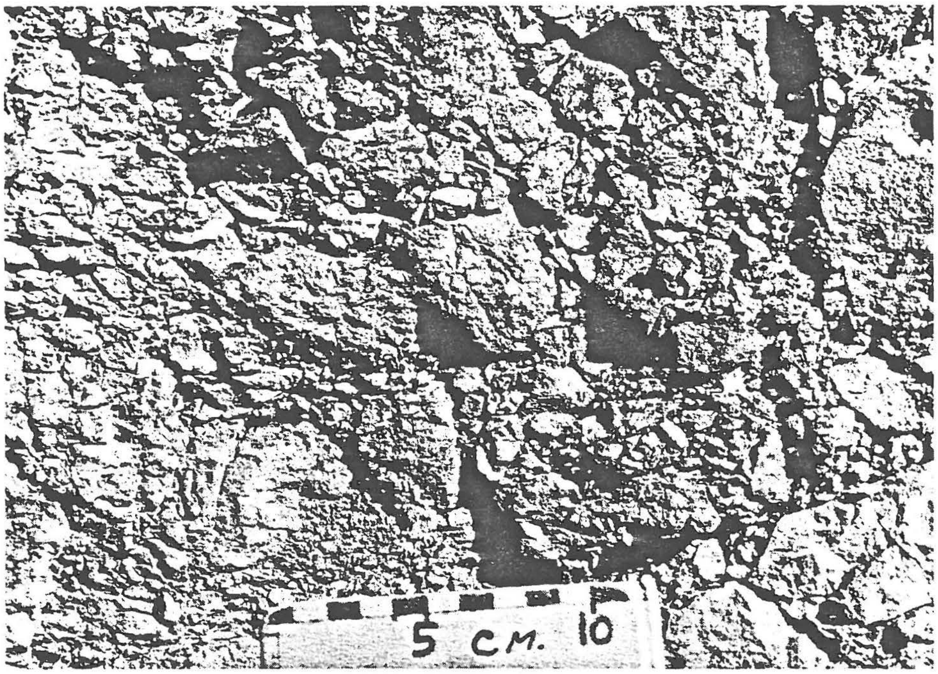


Fig. 2. Autobrecciated ultrapotassic trachyte at Picacho Peak

Four K/Ar dates between 22.2 and 22.6 m.y. have been determined on the lava flows from the peak massif. The ultrapotassic trachyte is 20.7 ± 0.5 m.y. old (Shafiqullah and others, 1976).

The Picacho Mountains north of the pass are composed in their southern half of gneiss which resembles the Catalina gneiss, although this rock has not been studied in detail. The northern half is granite of a probable Laramide age.

9 miles

MP 216 Earth Fissure

A large earth fissure, striking parallel to the Picacho Mountain front, crosses the highway and railroad at this point. The Picacho basin has dropped more than a meter since 1951 when the cracking began. Subsidence of the Picacho basin is attributed to compaction of sediments upon withdrawal of ground water, but the site of ground breakage is probably close to the eastern basin margin fault. Highway and railroad crews must make repairs every few months.

The Exxon exploratory drill hole is about 10 km north of here. The hole is 3,100 m (10,100 ft) deep. A bed of halite 25 m thick was encountered at a depth of 650 m (1,200 ft), and an additional 1,830 m (6,000 ft) of anhydrite with shale stringers lies beneath the halite. A volcanic unit at a depth of 2,800 m (9,700 ft) is trachyte probably related to the Picacho

Peak rocks and has a K/Ar age of 14.66 ± 0.34 m.y. (Shafiqullah and others, 1976; Peirce, 1976).

16 miles

Interstate 8 to Yuma. Keep right—mileposts change

Road passes north of the Arizola Mountains, which are composed of gneiss.

2 miles

MP 177 Rest Area

6.5 miles

MP 170.5 Santa Cruz Wash

North of the Tucson Mountains, the Santa Cruz River becomes disseminated and poorly defined. Major flood discharges passing through Tucson spread out in these broad basins and either sink into the sediment or evaporate. Dumps of the Sacaton mine can be seen at 3:00 across the valley.

7.5 miles

MP 163 Santa Rosa Wash

From here, the road climbs the alluvial surface to the Vekol Mountains. The upper reach of this surface is a pediment developed on granite bedrock. To the south of the road, mid-Tertiary basalt flows, partially eroded, lie atop alluvial fan deposits, which have been mostly removed. On basalt-capped Table Top Mountain as well as on the promontory northwest of it the basalt is separated from the Precambrian Apache Group by several meters of alluvium.

14 miles

MP 149 Outcrop

The Precambrian granite in this outcrop is almost completely weathered to grus. The relief on this old surface is preserved beneath the basalt that covers it.

4 miles

MP 145 Basalt Outcrop

This basalt is designated on the state map as Quaternary basalt, as is the basalt that covers the crest of the Sand Tank Mountains to the southwest. Both are obviously much older but have not been radiometrically dated.

4 miles

MP 141 Outcrop

Note the baked zone beneath the basalt above the fanglomerate.

22 miles

MP 119 Gila Bend Turnoff

3.2 miles

Intersection of State Highway 85

A road log for this route through Ajo to Lukeville and from Why to Tucson along State Highway 86 by Stanton B. Keith has been published by the Arizona Bureau of Geology as Bulletin 183.

13.8 miles

MP 102 Painted Rock Road Intersection

A broad, low basalt cone is located directly south of this intersection at 9:00. This easternmost volcano of the Sentinel Peak volcanic field with its extremely low aspect ratio (height to width) is typical of cones of this field.

3 miles

MP 99 Painted Rock Mountains and Sentinel Peak Volcanic Field

Rocks of the Painted Rock Mountains closest to the highway are autobrecciated ultra-potassic trachyte flows cut by trachyte dikes. (Cretaceous andesite on the state geologic map). A fine-grained latite(?) intrusion covered by trachyte and alkali rhyolite ash-flow units occupies the northern part of the range.

The highway crosses basalt flows from here to MP 80. The flow units are thin and all of the source cones, except Sentinel Peak, are so low as to be nearly impossible to identify from the highway. The thin lava flows that cover such a wide area and the low cones around source vents indicate basalt of low viscosity. Gas content of this lava may have been so minimal or able to escape so easily that cinder and agglutinate, which form steep cones around source vents in the other Arizona volcanic fields, did not form here.

The flows lie atop well-sorted sediments deposited by the Gila River prior to 3 m.y. ago. The river now flows through a gap between the northern Painted Rock Mountains and the Gila Mountains and has cut a channel through the basalt into the underlying sediments.

14 miles

MP 85 Rest Area

This rest area is constructed on a basalt flow giving an excellent opportunity to examine the surface. Some festoon flow banding can still be seen in the air photos of these flows. All of the small flow-top features have been eroded away leaving a lag surface of basalt cobbles.

The closest mountain range to the southwest is the Aztec Hills. This rock is identified as Mesozoic granite (MAgr) on the state geologic map and is lumped with the Gunnery Range batholith. These rocks have not been investigated in detail, but their lithology is different from that of the Gunnery Range granite.

Directly south of this rest area can be seen the broad basalt mesa of the northern Aguila Mountains. The mesa is capped by a series of 3- to 5-meter-thick basalt flows, which dip about 5° N. This surface is broken by closely spaced normal faults, which strike parallel to the regional structural grain, N. 30° W. They can be easily traced into an older andesite-latite volcanic center south of the mesa. This basalt is identified as Quaternary on the map but is probably older than 10 m.y. The volcanic center to the south, labeled Cretaceous, is probably mid-Tertiary and contemporaneous with the silicic volcanic rocks of the Ajo area.

11 miles

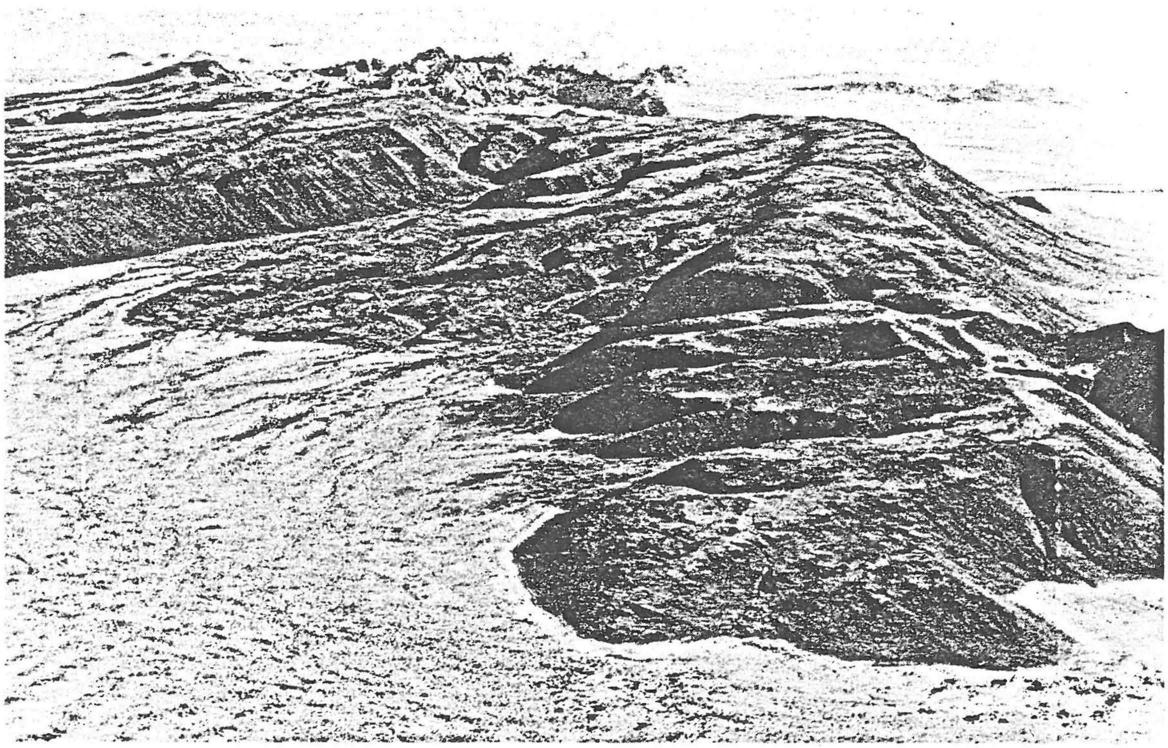


Fig. 3. Faulted and dissected surface of the northern Aguila basalt mesa. The older volcanic center can be seen beyond the far end of the mesa. Photograph courtesy of W. C. Tucker, Jr., Southwestern Exploration Associates, Inc., Tucson.

MP 74 Aztec

Beyond Aztec is the San Cristobal Valley. The Air Force M-X missile test trench is on the west side of this valley next to the Mohawk Mountains.

6 miles

MP 68 Dateland Air Force Station Foundations

8 miles

MP 60 San Cristobal Wash

6 miles

MP 54 Mohawk Mountains Road Cuts

Precambrian gneiss is exposed in this road cut. Tops of the Mohawk sand dunes can be seen from the western slope of this range.

Fig. 4. Eastern flank of the Mohawk Mountains seen from the south. The line that defines the mountain front by connecting the ends of the spurs appears straight, but the actual mountain front is embayed by pedimentation and is quite sinuous. This mountain front is no longer tectonically active. Photograph courtesy of W. C. Tucker, Jr., Southwestern Exploration Associates, Inc., Tucson.

12 miles

MP 42 Tacna Interchange

The dark hills located both north and south of here are composed of mid-Tertiary sedimentary rocks, which will be examined in detail in the Baker Peaks area south of the freeway.

11 miles

MP 31 Wellton Interchange

Geologic road log for the Marine Corps Gunnery Range begins just south of this exit and proceeds south.

North of Wellton are the Muggins Mountains, site of uranium exploration. Bones of an early Miocene(?) camel *Stenomylus arizonesis* were collected from a site 6 miles northeast of Wellton (Wood, 1956).

9 miles

MP 22 Rest Area

Examine the fine-grained sediments across the fence.

1 mile

MP 21 Gila Mountains

The rock here is described as Mesozoic on the state map. Eldred Wilson thought its metamorphism was related to emplacement of the granite to the south, which he considered to be Mesozoic. Two K/Ar ages on biotite separates from this gneiss (199 and 319 m.y.) are wildly discordant and obviously reset (Eberly and Stanley, 1978). Careful observation of the rock in the vicinity of MP 19 shows it to be an angular fanglomerate with a red matrix and containing diabase dikes, rather than being solid gneiss. At MP 18, younger fanglomerate of similar clast size and shape but lacking the red matrix is exposed.

Beyond MP 17, the freeway crosses the Plain of Yuma to the Colorado River terraces in Yuma. The hill in the far distance is Pilot Knob in California. Zircon Pb dates of around 1700 m.y. have been reported for this rock. Knobs of granitic rock in Yuma, which are described on the map as being part of the Gunnery Range batholith (MZgr), are of entirely different lithology. Eberly and Stanley (1978) report a K/Ar age of 39.5 m.y. However, L. T. Silver (written commun., 1968, cited in Olmsted and others, 1973) obtained a 1440-m.y. uranium-lead date on zircon from a porphyritic quartz monzonite in a road cut on US 95 just east of the railroad overpass in Yuma.

10.3 miles

Yuma. Business Loop. Exit 9.

End of log.

MARINE CORPS GUNNERY RANGE

Distance: 62.8 miles

(by D. J. Lynch and R. J. Lundin)

Wellton Interchange, MP 31 on Interstate 8

This road log covers features located on the U.S. Air Force Gunnery Range R2301. Permission to enter this range must be gained in writing from the Commandant, U.S. Marine Corps Air Station, Yuma. Although this part of the range is used primarily for computer-scored air-to-air fighter tactics and ground access to civilians is easy to obtain, the range may occasionally be closed for live firing exercises, and aircraft will sometimes use this area to jettison live bombs in an emergency. Don't pick up anything that looks like military hardware while on the range.

Cumulative mileage

0.0 Cross Wellton Interceptor canal south of Interstate 8. Begin mileage count.

1.5 miles

1.5 Road turns to cross levee; stay on main road.

1.0 mile

2.5 Buildings on left (if not, you're lost—go back to levee).

0.4 mile

2.9 T intersection at 14th Street; turn right (west).

4.0 miles

6.9 T intersection at Camino del Diablo; turn left (south). The Gila Mountains are to the west and south; Wellton Hills to the east-southeast.

1.0 mile

7.9 Enter Gunnery Range here

Low gneiss inselbergs, stone building, road intersection to right.

The inselbergs project from a broad pediment which extends northward from the foot of Sheep Mountain. The Sheep Mountain scarp is easily seen south of this place. It lies behind the dark hills with the prominent white pegmatite veins, which can be reached by this road. All of the visible bedrock here is Precambrian gneiss and schist. Schenker (1977) divided the thin alluvial cover into four units based on their surface appearance and other geomorphic criteria. Q-1, the oldest, is a poorly sorted fanglomerate, which is now deeply dissected and lacks terraces. It is probably more than a million years old and may represent deposits from the last pulse of tectonic activity in the area. Q-2 and Q-3 alluvium fills the valleys cut into Q-1. Q-2 is an older alluvium with a well-developed B soil horizon indicative of deposition in a humid, cool climate, perhaps during the latest glacial event. The three Q-2 terraces identified represent individual surfaces of aggradation in interpluvial periods of reduced rainfall and, perhaps, higher temperatures.

Q-3 is bar-and-swale alluvium having an arid soil profile with a calcium carbonate horizon. Four subunits of Q-3 have been mapped on the basis of their desert varnish and thickness of carbonate layer. Q-4 constitutes the most recent stream deposits, and it lacks both soil development and desert varnish. The road beyond these inselbergs crosses a broad sheet-wash plain of Q-4.

4.1 miles

12.0 Power pole next to road—mileage check.

1.5 miles

13.5 STOP #1. View Sheep Mountain scarp to west

The Sheep Mountain scarp shows many of the characteristics of an active mountain front, including the linear base, triangular facets on the ridges, and steep alluvial cones at the mountain front. However, this scarp is not developed along an active mountain-front fault but rather along a shear zone, which is parallel to the contact of the Gunnery Range batholith about 4 km to the south. Traverses across the shear zone show mylonite gneiss with foliation parallel to the zone but no fault. The shear zone can be followed into the Gila Mountains to the west where it becomes broader and disappears within a few kilometers

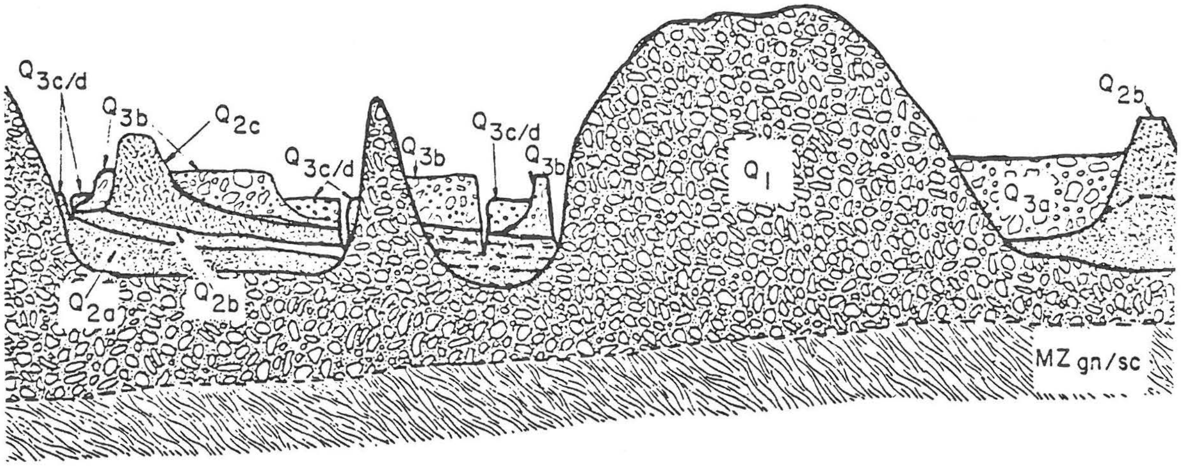


Fig. 5. Alluvial units on the pediment north of the Sheep Mountain scarp—from Schenker (1977)

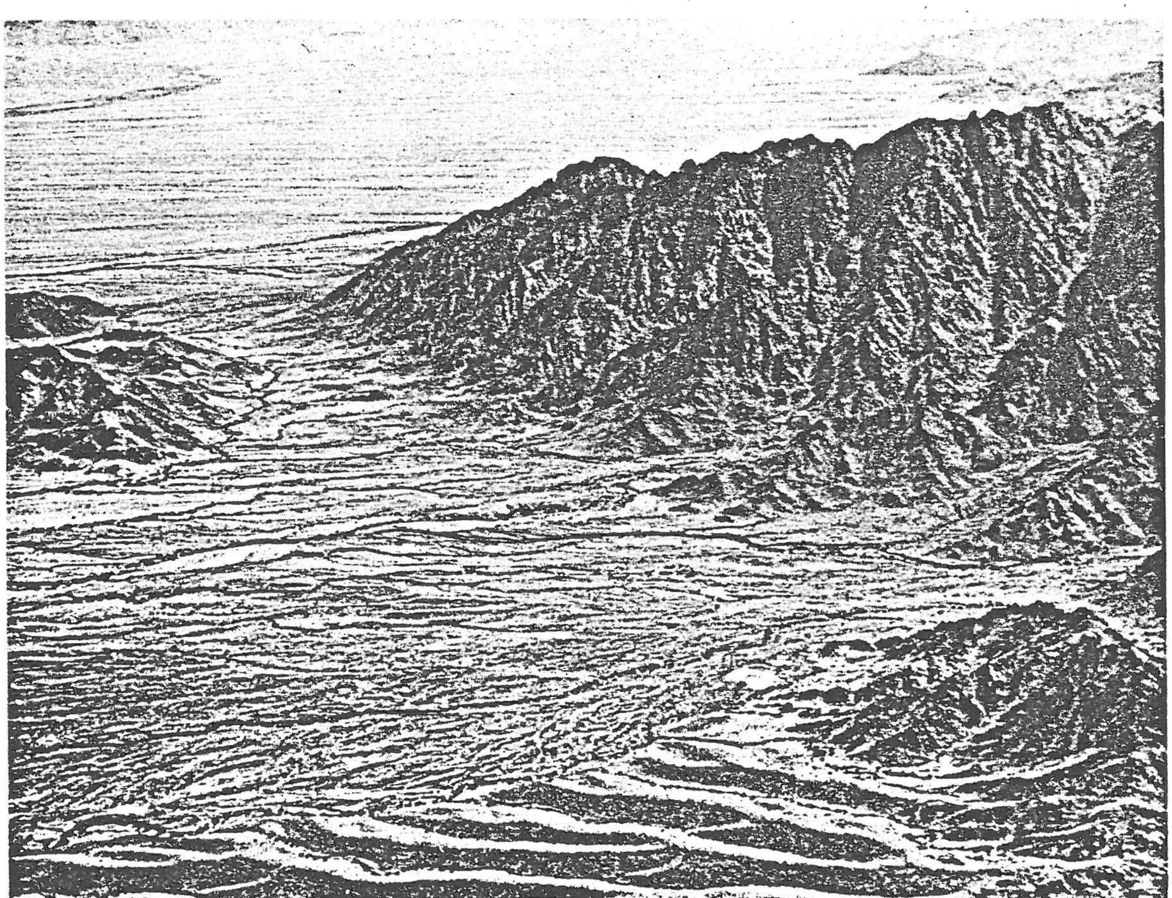


Fig. 6. Sheep Mountain scarp. The straight mountain front, triangular facets, and alluvial cones can be seen in this view. Schenker's Q-1 alluvium forms the dissected surface in the foreground.

of the mountain front. This scarp has resulted apparently from relatively recent erosion along a structural weakness related to emplacement of the batholith

South of this scarp is the contact between the light-colored Gunnery Range granite and the dark-colored Precambrian gneisses. Unpublished K/Ar ages determined on biotite from this granite correspond to the end of the Laramide orogeny between 50 and 55 m.y. ago. These are probably cooling ages.

1.8 miles

15.3 Good road turns to the right toward the Air Force test station; go straight ahead.

0.9 mile

16.2 Road intersection. This road is dragged periodically to detect footprints of illegal aliens walking up the valley. We will return to this point. Copper Mountains 9:30-10:30, Cabeza Prieta Mountains 10:30-11:30, Raven Butte 1:00.

3.0 miles

19.2 Road to right (west) leads to Cipriano Pass.

2.2 miles

21.4 Road to right—turn off to Raven Butte. The tracks are prominent; do not drive on the desert surface beyond the tracks because the damage is long lasting.

2.9 miles

24.3 STOP #2. Base of Raven Butte

Raven Butte, as seen from a distance, appears to be a large basalt plug. Its shiny black surface contrasts markedly with the tan-white granite that forms the mountain west of it and the desert floor around it. Less than a quarter of its bulk is basalt; the rest is an armor of basalt boulders covering granite slopes beneath. This stop is near the south ridge, the only place where this armor is stripped away to expose the internal structure.

Granite bedrock forms the lower part of the pedestal. Grus alluvium containing rounded granite boulders up to 1 m rests on the bedrock pedestal and separates the granite from the basalt. Although this depositional contact is exposed only in this place, for a total length of 5 m, the rest of the butte suggests that this contact is either a buried pediment or a surface of low relief. The grus above probably represents a mountain-front alluvial fan.

The lowermost lava flow rests on and preserves the old fan surface. Another 2 m of grus alluvium above this lava flow indicates no change in the depositional environment after its eruption. Nine more flows cover this thin layer of alluvium without break. Lack of alluvium between the flows may indicate insufficient time between eruptions or a change in the depositional environment, possibly due to the accumulation of lava on the fan surface.

Raven Butte is joined to the Tinajas Altas mountain massif by a sharp granite ridge. A shear zone is located a few meters to the west of the lowest basalt outcrop.

The basalt armor consists of boulders weathered out of the massive centers of the flows.

Fig. 7. Raven Butte. The appearance of great flow thickness results from a basalt-boulder armor covering the lower slopes. A step block can be seen on the east side where the flows have slid down 110 m. The break is on a line connecting the easternmost spurs of the mountain range which may correspond to the valley margin fault. The hummock of debris at the base of this block suggests that it may be a simple landslide block and may not be related to basin-and-range faulting.

These boulders are nearly free of internal stresses as evidenced by the extreme difficulty encountered in attempting to break one open. They are attacked only by surficial weathering, which gives them a very long life in this arid environment.

Numerous basalt-covered hills akin to Raven Butte are found in this desert. Three of them may be easily seen to the southeast of Raven Butte, the largest being Tordillo Mountain. Raven Butte is the only one that is almost completely boulder armored; the others exhibit their internal structures much more clearly. Each has buried a remnant of desert identical to that surrounding them. In addition, other desert geomorphic features have been buried by andesite lava flows in the Cabeza Prieta Mountains. Lynch has inferred that arid climatic conditions similar to those active today were characteristic of this region at the time of eruption 10 to 17 m.y. ago (see Shafiqullah and others, this volume).

Geomorphic aspects of equigranular granite weathering in an arid environment are well illustrated in the vicinity of Raven Butte. The irregular nature of the mountain front with its many re-entrants shows it to be an inactive front. Mountain slopes meet the flat desert floor at a sharp angle over most of the front save where major drainages exit from the

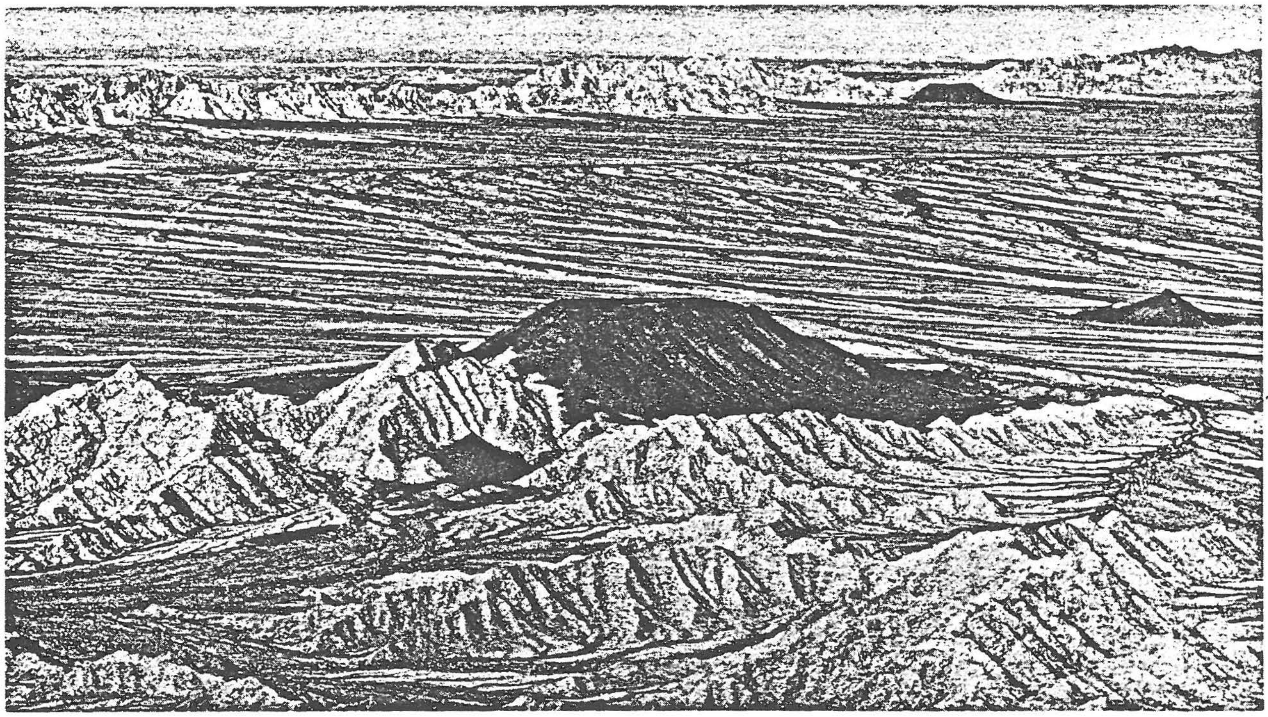


Fig. 8. Tordillo Mountain. This mountain and the basalt remnant north of it are features similar to Raven Butte, seen in the far background. In this part of the Cabeza Prieta Mountains, filling of these arid-climate erosional features is more obvious than at Raven Butte.

mountains. This results from surface weathering of the granite into small grains. Violent rainfalls from convective storms sweep the slopes and carry the detritus to the desert floor where the flow spreads out distributing the detritus. Retrace route back to Camino del Diablo.

2.9 miles

27.2 Intersection with Camino del Diablo; turn left (north).

5.3 miles

32.5 Intersection with cross valley road; turn right (east). Copper Mountains directly ahead, Wellton Hills 9:00, Raven Butte 3:00, Cabeza Prieta Peak 1:30.

2.0 miles

34.5 Coyote Wash, west branch.

0.3 mile

34.8 Coyote Wash, main channels. Coyote Wash is the main drainage in the Lechugilla Valley. It is an anastomosing channel system in the nearly horizontal center of the valley where the western channel drains the west side and the eastern channel drains the east side with few clearly defined connections between the two channel systems.

0.7 mile

35.5 Wrecked Aircraft in the Road. This is a private aircraft, not a military crash site.

2.2 miles

37.7 Road intersection. Turn left (north).

0.7 mile

38.4 Biotite gneiss is intruded by pegmatites in stringers. Schlieren in the gneissic fabric are oriented northwest.

5.0 miles

43.4 View to the northwest of gold-silver prospects along the contact of the granite-biotite gneiss and later pegmatite dikes. The dikes are visible along the ridge line and are iron stained so as to show a color contrast. According to S. B. Keith (1978), metal production from these prospects has been small.

0.7 mile

44.1 STOP #3

Look at pegmatites in biotite-granite gneiss.

0.9 mile

45.0 STOP #4

Look at mineralization and rock types at the Poor Man mine (see S. B. Keith, 1978, for description).

0.2 mile

45.2 Leave Wellton Hills.

3.7 miles

48.9 Intersection with main road to Gunnery Range. Wellton-Mohawk Canal on right. Turn right.

0.2 mile

49.1 Cross Wellton-Mohawk Canal.

0.6 mile

49.7 Turn east onto Interstate 8.

7.0 miles

56.7 Exit from the Interstate at the Roll exit. Proceed south.

0.5 mile

57.2 Intersection of Roll exit at Avenue 35-E. Antelope Hill outcrops of mid-Tertiary sediments similar to those at Baker Tanks to the north. Go south on dirt road.

1.1 miles

58.3 Continue straight ahead.

0.9 mile

59.2 Continue to the left fork.

1.0 mile

60.2 Outcrops on east side of road are arkose with large clasts of granitic and gneissic material.

0.2 mile

60.4 Cross wash.

0.1 mile

60.5 Well-developed pediment surface.

0.5 mile

61.0 Take right fork of road. Granite gneiss in outcrop.

0.8 mile

61.8 STOP #5. Pavilion at Baker Tanks

The stream channel here provides an excellent exposure of a mid-Tertiary conglomerate unit that is probably contemporaneous with clastic rocks of eastern and central Arizona given the names Pantano, Helmet, and Locomotive. At this exposure, the rock is clearly a conglomerate having well-rounded, some nearly spherical, clasts contained within a well-sorted matrix. A few of the clasts exceed 50 cm in diameter, and they are entirely contained within a

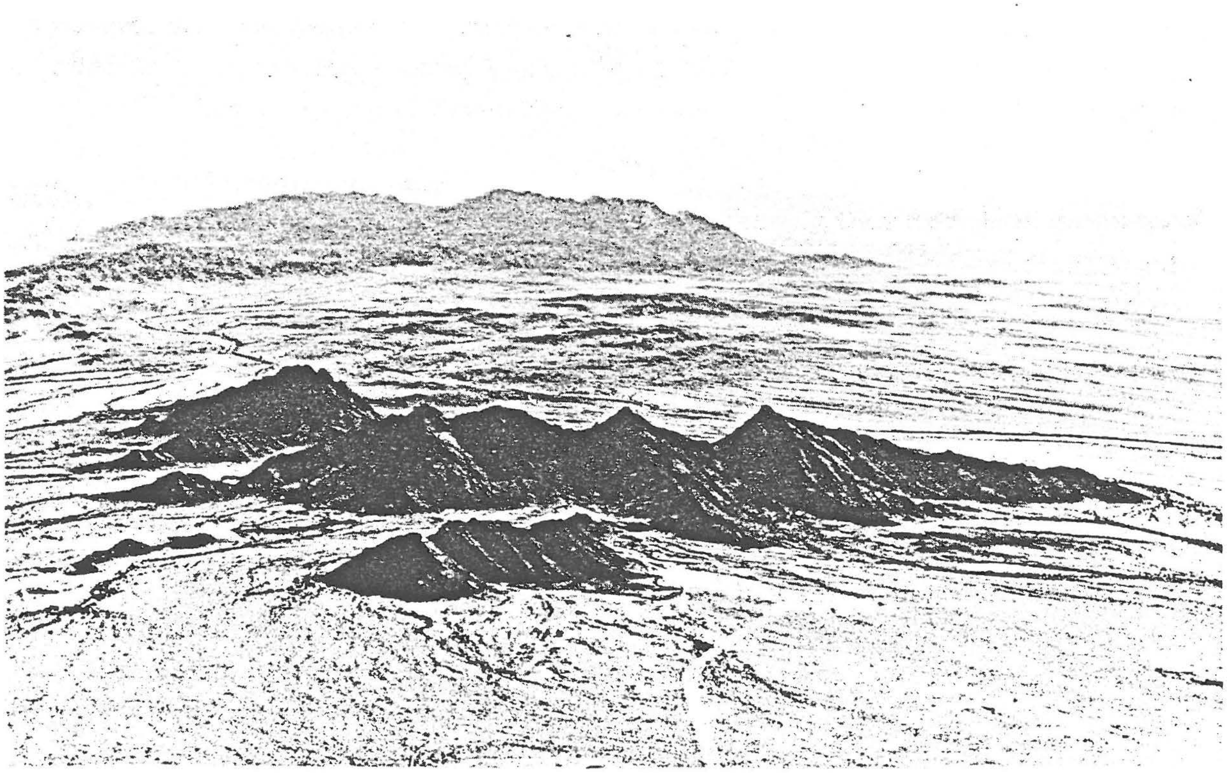


Fig. 9. Exhumed pediment south of Baker Peaks. Baker Peaks (in the foreground) are composed of the sedimentary rock to be examined at the last stop. Copper Mountains are beyond the pediment to the south.

sand matrix. Discontinuous layers of poorly sorted, more angular material contained within this deposit look much like the bar-and-swale deposits of the surrounding desert. Rounding and sorting indicate some transportation from the source locality, and the size of the clasts requires a high-energy depositional environment. As a first approximation, depositional conditions may have been similar to those active today in this region (see Shafiqullah and others, this volume).

Approximately one mile east of this locality, in the same stream channel, the fragmental material is significantly different. All of the clasts are angular, sorting is nonexistent, and a matrix is not always easy to identify. The trip planners gave this rock the name "hypabyssal fanglomerate" because of its resemblance to brecciated plutonic rock, but the discontinuous layers of well-sorted sand show it to be a true fanglomerate composed of material moved only a short distance from its source.

The provenance of these deposits is unclear, but the close proximity of fanglomerate to conglomerate is further evidence of similarity between their depositional environment and that active today. Tectonic activity in mid-Tertiary time undoubtedly created mountains that were eroded and the material was transported to local basins. The following Basin and Range disturbance has largely obscured these basins, and the deposits are only found in the present mountain blocks. These beds were tilted during the transition from the mid-Tertiary orogeny to the Basin and Range disturbance in much the same manner as the Pantano fanglomerates found east of Tucson.

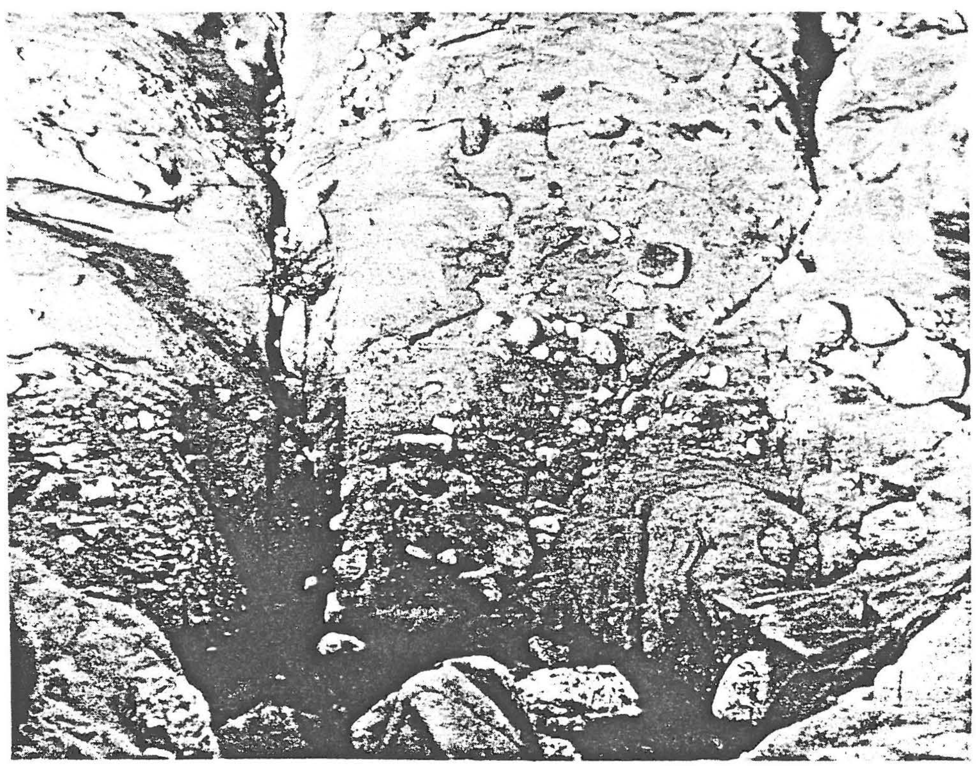


Fig. 10. Kinter(?) formation at Baker Tanks. Large, rounded boulders of gneiss and granite are contained within a well-sorted arkosic sandstone matrix.

A mid-Tertiary age is assigned to these beds because of their lithologic similarity to known mid-Tertiary clastic units in other parts of the state, their steep dips in this mountain block, and their tentative correlation with Miocene beds of the Muggins Mountains to the north where lower Miocene camel bones were found (Wood, 1956). Casual searching of the area around Baker Tanks failed to find any clasts of the 50+- m.y.- old Gunnery Range granite that crops out 25 km to the south.

Baker Tanks and environs are part of a large exhumed pediment. This part of the southern Basin and Range province has been tectonically inactive for many millions of years, an excellent environment for pedimentation. Exhumation of this one is probably due to downcutting of the nearby Gila River rather than to uplift of the mountain block.

End of log.

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THE PELONA-OROCOPIA SCHIST AND VINCENT-CHOCOLATE MOUNTAIN THRUST SYSTEM, SOUTHERN CALIFORNIA[1]

Gordon Haxel
U.S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025

John Dillon
Alaska Division of Geological and Geophysical Surveys
P.O. Box 80007
College, Alaska 99708

ABSTRACT

The Pelona-Orocopia schist (=the Pelona, Orocopia, and Rand Schists) crops out in the southeastern corner of California and in southwesternmost Arizona, along the southern San Andreas fault system in the central Transverse Ranges, and along the Garlock fault. Metamorphism of the Pelona-Orocopia schist occurred in Paleocene (or Late Cretaceous) time; the age of the Pelona-Orocopia protolith is unknown. The lower-greenschist- to lower-amphibolite-facies schist is predominately metagraywacke, with subordinate metapelite, metabasite, ferromanganiferous metachert, marble, and meta-ultramafic rock. These oceanic rocks are tectonically overlain, along the mylonite-marked Vincent-Chocolate Mountain thrust, by nappes consisting of Precambrian through Mesozoic gneissic and granitic rocks. These sheets of continental crust are interpreted as pieces of a single (hypothetical) regional allochthon which extends from southwesternmost Arizona to the western Mojave Desert. Overthrusting is inferred to have been toward the northeast. In several areas which have received detailed study, metamorphic grade and grain size within the schist increase upward toward the thrust, and lineation in the cataclastic and retrograde rocks at the base of the upper plate is parallel to lineation in the schist. These relations indicate that metamorphism of the Pelona-Orocopia schist took place beneath the upper plate of the Vincent-Chocolate Mountain thrust and was broadly contemporaneous with movement along the thrust.

A palinspastic reconstruction of southern California prior to 300 km of late Cenozoic right slip along the San Andreas fault system shows that the Pelona-Orocopia schist lies largely along and beneath the eastern margin of the Cretaceous Sierra Nevada-Salinia-Peninsular Ranges batholithic belt; the schist is thus spatially distinct from the Franciscan Complex of western California. The Pelona-Orocopia schist is apparently unrelated to any of the other widespread tectonic-lithologic units of southeastern California and adjacent areas. The presence of the oceanic rocks of the Pelona-Orocopia schist in their present tectonic position in southern California seems anomolous. The Pelona-Orocopia protolith may have accumulated outboard of a continental margin, in southern California or elsewhere, and been subsequently tectonically trapped inboard of the continental basement that now lies to the west of the Pelona-Orocopia schist. Alternatively, the protolith may have accumulated in an ensimatic intracontinental basin within southern California.

INTRODUCTION

The Paleocene (or Upper Cretaceous) Pelona, Orocopia, and Rand Schists have long been one of the least understood elements of the geology of southern California. Field and petrologic studies completed in the decade since the summary by Ehlig (1968) have added to our knowledge of the geologic history of the schists, confirmed the conclusion of Ehlig (1958) that the metamorphism of the schists is closely related to the overlying Vincent-Chocolate Mountain thrust system, and extended the known distribution of the Orocopia Schist southeastward into the southwestern corner of Arizona. However, the significance of these schists and their protolith in the tectonic evolution of southern California and adjacent areas is still uncertain.

In this paper we summarize the evidence for correlation of the Pelona, Orocopia, and Rand Schists (collectively, the Pelona-Orocopia schist) with one another; describe the geology of the Pelona-Orocopia schist and the Vincent-Chocolate Mountain thrust system; discuss the tectonic setting and possible subsurface distribution of the schist; outline the uncertainties regarding the paleogeographic significance of the schist; and conclude with some suggestions for future study. In describing the schist we emphasize the terranes with which we are most familiar: the Orocopia Schist of the southern Chocolate Mountains (Dillon, 1976) and the Picacho-Peter Kane Mountain area (Haxel, 1977) northwest and north of Yuma, Arizona, and the Pelona Schist of the eastern San Gabriel Mountains, to which we have been introduced by Perry Ehlig.

THE PELONA-OROCOPIA SCHIST

Distribution and Lithology

The Pelona Schist occurs on either side of and within the greater southern San Andreas fault system (Crowell, 1975a) in the central Transverse Ranges (Fig. 1) from the area of Mount Pinos (schist body 3, Fig. 2, Table 1) southeast to the north side of San Gorgonio Pass (8). One body of the Pelona Schist occurs as a sliver within the Garlock fault zone in the southwestern Tehachapi Mountains (4); the Rand Schist (5) crops out south of the Garlock fault in the Rand Mountains. The Orocopia Schist forms a discontinuous belt, east of the San Andreas fault, extending from the Orocopia Mountains (9) southeast through the Chocolate Mountains (10, 11) to the Picacho-Peter Kane Mountain area (12) and thence eastward at least as far as Neversweat Ridge (15) in

[1]The stratigraphic nomenclature used in this report is from several sources and may not necessarily follow the usage of the U.S. Geological Survey.

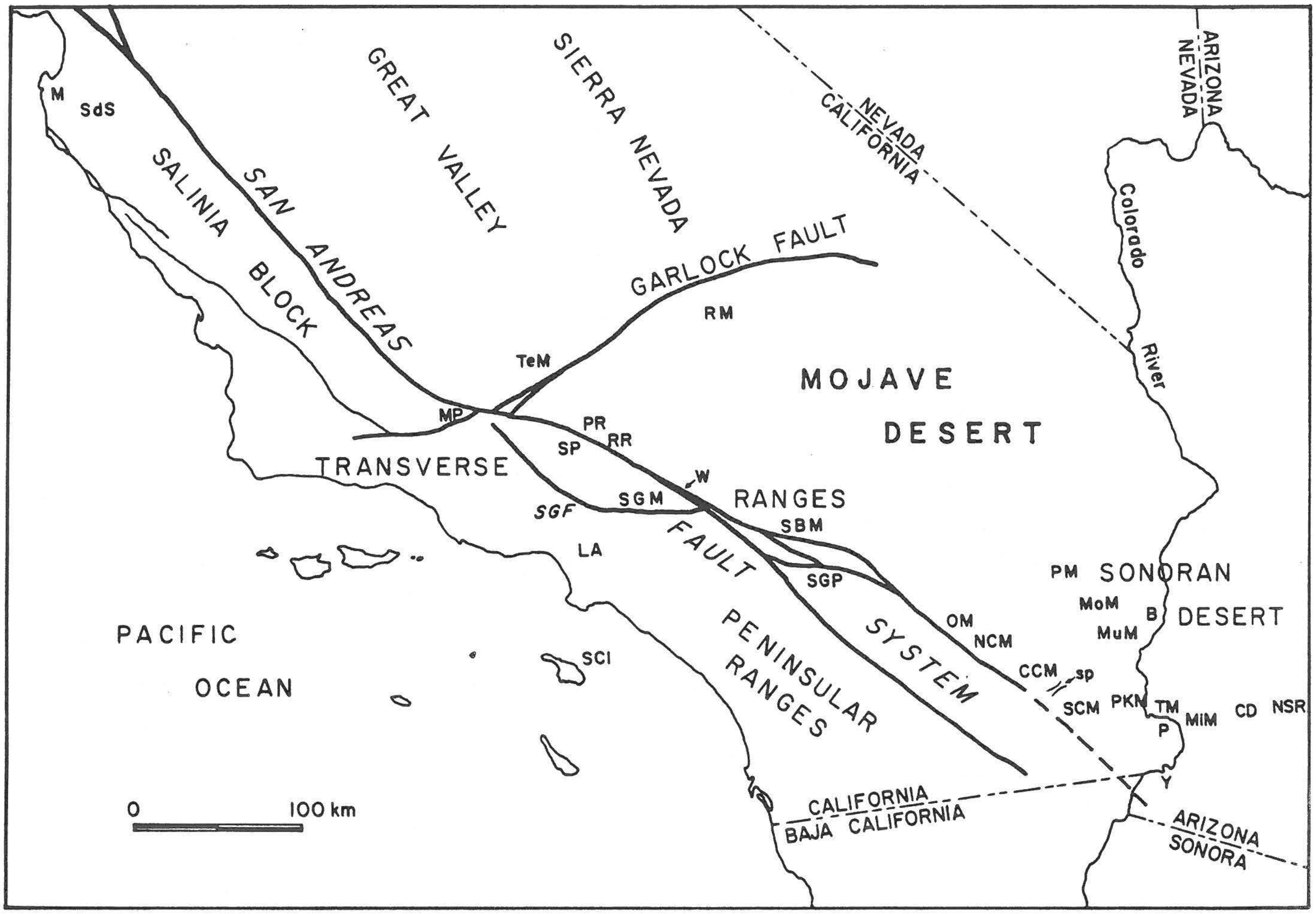

Figure 1. Index map showing most of the geographic features and localities referred to in the text. CCM, central Chocolate Mountains; CD, Castle Dome Mountains; LA, Los Angeles; M, Monterey; MiM, Middle Mountains; MoM, McCoy Mountains; MP, Mount Pinos; MuM, Mule Mountains; NCM, northern Chocolate Mountains; NSR, Neversweat Ridge; OM, Orocopia Mountains; P, Picacho; PKM, Peter Kane Mountain; PM, Palen Mountains; PR, Portal Ridge; RM, Rand Mountains; RR, Ritter Ridge; SBM, San Bernardino Mountains; SCI, Santa Catalina Island; SCM, southern Chocolate Mountains; SdS, Sierra de Salinas; SGF, San Gabriel fault; SGM, San Gabriel Mountains; SGP, San Gorgonio Pass; sp, Salvation Pass; SP, Sierra Pelona; TeM, Tehachapi Mountains; TM, Trigo Mountains; W, Wrightwood; Y, Yuma.

central Yuma County, Arizona.

These fifteen schist bodies are considered to be correlative because each body is characterized by most or all of the following features (Ehlig, 1968; Haxel, 1977; references in Table 1):

(1) The most abundant rock type is a monotonous but distinctive light- to dark-gray, flaggy quartzo-feldspathic schist, with a little interlayered mica schist, characterized by ubiquitous flysch-like compositional layering (Fig. 3) derived from sedimentary bedding. This gray schist (of Ehlig, 1958) is predominantly metagraywacke, probably in part volcaniclastic, with a little metapelite and meta-arkose.

(2) Subordinate to minor rock types are, in order of decreasing overall abundance, metabasite as greenschist, albite amphibolite, amphibolite, or, very locally, garnet amphibolite; ferromanganiferous metachert; siliceous marble; and meta-ultramafic rock as antigorite serpentinite, very coarse grained actinolite-rock, talc-actinolite schist, or, locally, talc-rock.

(3) Two distinctive "index minerals" are present: porphyroblasts of gray to black albite, the color of which is due to included graphite, and aggregates of bright green fuchsite (chrome muscovite).

(4) Most of the schist bodies are overlain by thrust sheets of gneissic and granitic rock (Fig. 2).

(5) The schist bodies are only very sparsely intruded (see below) by Mesozoic granitic rocks (Ehlig, 1968; see also Ross, 1976). In contrast, Mesozoic plutons are common in the thrust sheets overlying the schist; these plutons are truncated by the thrusts.

Table 1. Pelona-Orocopia Schist Bodies

Number (Fig. 2)	Location	Name of schist	Metamorphic facies of schist	Name of thrust	Rocks of upper plate	References
1	Sierra Pelona(*)	Pelona	gsf, aea, amp	Vincent	PC gn, mig, an-sy; Mz gr	Muehlberger and Hill, 1958; Dibblee, 1961a; Crowell, 1962; Ehlig, 1968; Harvill, 1969; Graham, 1975; Graham, and England, 1976
2	Portal and Ritter Ridges, Quartz Hill	Pelona	amp, aea	--	---	Evans, 1966, 1978; Ross, 1976; Dibblee, 1967
3	Mount Pinos, Mount Abel	Pelona	gsf or aea	no name	gn, mig, gr-gn, gr; Mz gr	Crowell, 1962
4	Tehachapi Mountains	Pelona	gsf, aea, amp	no name	gn, gr	Wiese, 1950; Crowell, Ehlig, and Dillon, reconnaissance 1973
5	Rand Mountains(*)	Rand	gsf, aea	Rand	Pz(?) gn; Mz gr	Vargo, 1972; Hulin, 1925; Dibblee, 1967; Ehlig, 1968
6	Eastern San Gabriel Mountains (southwest of San Jacinto fault)	Pelona	gsf	Vincent	PC gn, mig; Pz(?) gn; Mz gr	Ehlig, 1958, 1968, 1975a, b
7	Blue Ridge to Crafton Hills (between San Jacinto and San Andreas faults)	Pelona	gsf	Vincent	gn	Ehlig, 1968; Noble, 1954
8	North side of San Gorgonio Pass	Pelona	aea	Vincent	gn	Allen, 1957; Dibblee, 1964
9	Orocopia Mountains(*), Mecca Hills	Orocopia	gsf, aea	Orocopia	PC gn, mig, gr-gn, an-sy; Mz gr	Crowell, 1962, 1975c; Raleigh, 1958
10	Central Chocolate Mountains	Orocopia	aea?	Chocolate Mountain	PC(?) gn, mafic gn, gr-gn	Murray and Crowe, 1976
11	Southern Chocolate Mountains	Orocopia	gsf, aea, amp	Chocolate Mountain	PC(?) gn, mafic gn, gr-gn; Mz gr	Dillon, 1976
12	Picacho-Peter Kane Mountain area, California; Trigo Mountains, Arizona	Orocopia	aea, amp	Chocolate Mountain	PC(?) gn, gr-gn	Haxel, 1977
13	Middle Mountains, Arizona	Orocopia	?	Chocolate Mountain	gn	Dillon and Haxel, reconnaissance, 1974
14	Castle Dome Mountains, Arizona	Orocopia	?	?	?	Dillon and Haxel, reconnaissance, 1974
15	Neversweat Ridge, Arizona	Orocopia	?	?	?	Crowell, Ehlig, Dillon and Haxel, reconnaissance, 1973

NOTE.--Schist bodies 1 through 9 as in Ehlig (1968, Fig. 1). Areas (1-11) not designated as Arizona are in California. Asterisks (*) designate the type locality for each schist. Abbreviations: gsf, greenschist facies; aea, albite-epidote amphibolite facies; amp, amphibolite facies; gn, gneiss; gr, "granite"; gr-gn, granitic gneiss; mig, migmatite; an-sy, anorthosite-syenite complex; Pz, Paleozoic; Mz, Mesozoic; PC, Precambrian based on U-Pb isotopic age determinations by L. T. Silver and coworkers (1971; oral commun., 1974, 1978); PC(?), probable or possible Precambrian based on lithologic correlation by the authors or by Jennings and Strand (1969) or Rogers (1967). Metamorphic facies are from the references cited and P. L. Ehlig (written commun., 1978).

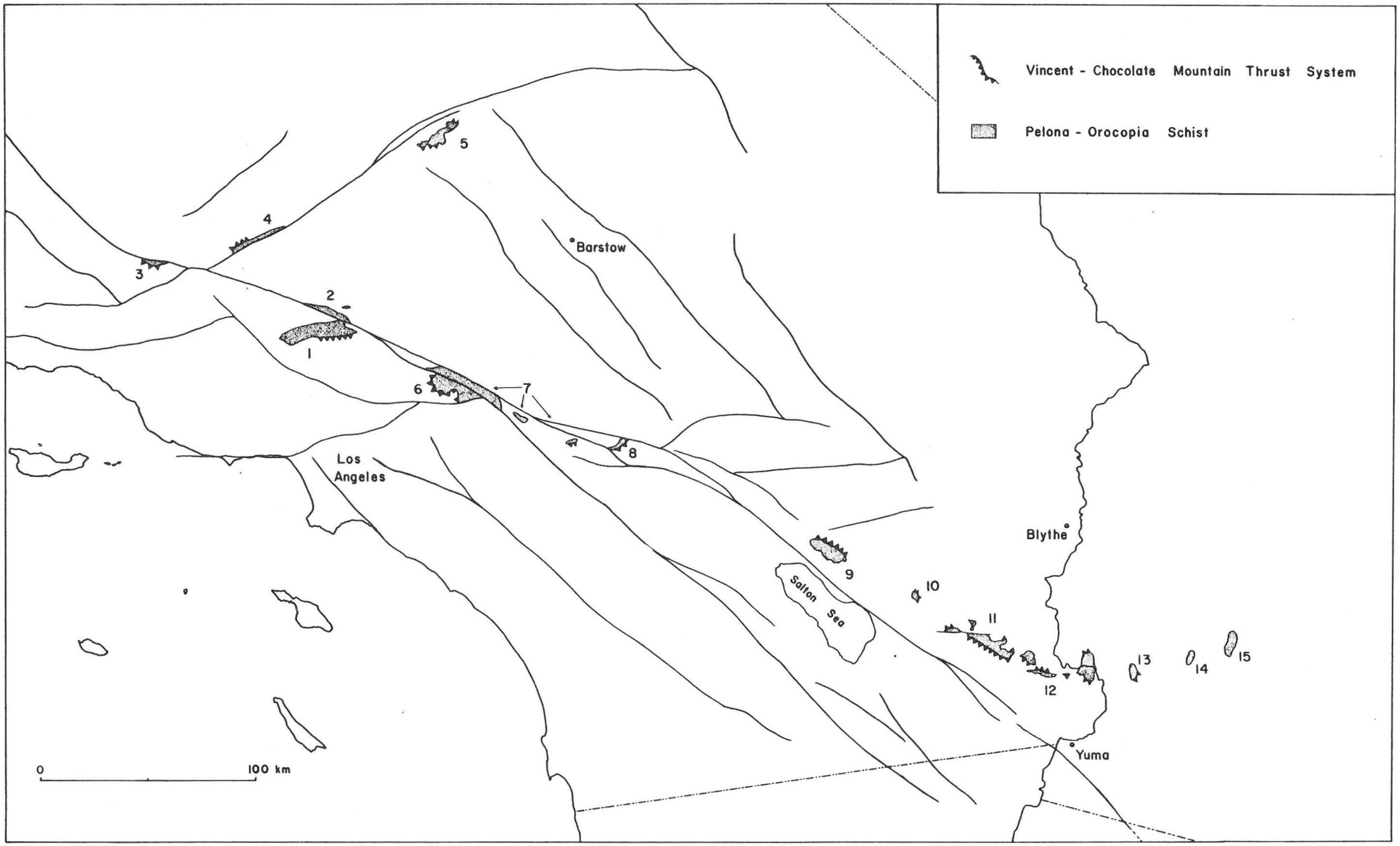

Figure 2. Distribution of the Pelona-Orocopia schist and Vincent-Chocolate Mountain thrust system (after Jennings, 1973; Ehlig, 1968; Dillon, 1976; Haxel, 1977) and Cenozoic strike-slip faults (after Jennings, 1973; Crowell, 1975a) in southern California and southwesternmost Arizona. Schist bodies are numbered as in Table 1; schist bodies 1 to 9 are the same as shown by Ehlig (1968, fig. 1). Some of the smaller schist bodies are shown slightly exaggerated in size and the geometry of most of the thrust faults is simplified.

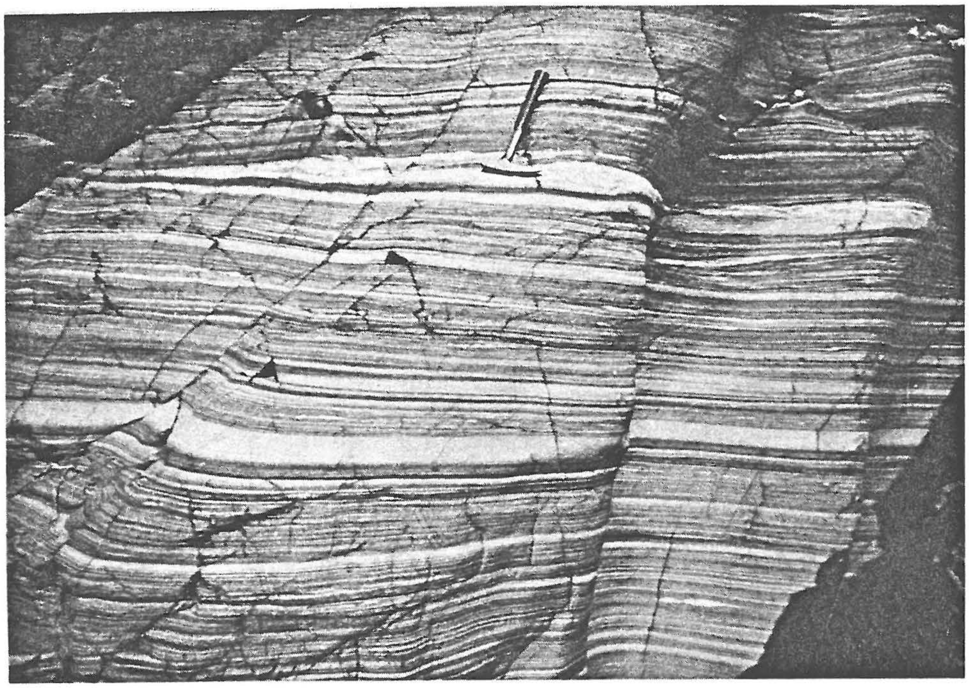

Figure 3. Compositional layering in the Orocopia Schist of the Trigo Mountains, Yuma County, Arizona. Small white lentils are quartz. Hammer is 32 cm long.

The informal name "Pelona-Orocopia schist" used herein to refer to the Pelona, Orocopia, and Rand Schists together is not intended to replace these formal stratigraphic names.

The abundance of the various subordinate and minor rock types varies widely from one schist body to another. For example, metabasite and metachert make up about 15 percent and 10 percent, respectively, of the Pelona Schist of the Mount Baldy area (schist body 6; Ehlig, 1958), but gray schist alone makes up more than 95 percent of the outcrop area of the Orocopia Schist of the Picacho-Peter Kane Mountain area. Metabasite occurs both as thick (up to 200 m) layers, and as thin, discontinuous layers and lenses. In most areas metachert and marble are commonly, though not exclusively, spatially associated with metabasite. Metachert is considerably more abundant than marble. Both rock types occur singly, in layers typically 0.1 to 3 m thick, and in sequences, up to 10 m thick, of interlayered and partially intergradational metachert and marble. The actinolite-rich meta-ultramafic rocks occur as decimeter- or meter-size pods and lenses and as small dikes. Serpentinite forms a few irregular bodies up to several hundred meters across. Veins and pods of milky-white quartz are common in the schist.

The schist of Sierra de Salinas (Ross, 1976), which crops out southeast of Monterey, California, is lithologically fairly similar to the Pelona-Orocopia schist and closely resembles the Pelona Schist of Portal and Ritter Ridges and Quartz Hill (schist body 2; Ross, 1976), which is, however, somewhat atypical of the Pelona-Orocopia schist as a whole (Evans, 1966). The schist of Sierra de Salinas and the Pelona-Orocopia schist differ in that the schist of Sierra de Salinas is intruded by several large Cretaceous granitic plutons and locally contains sillimanite, scapolite, or brucite (Ross, 1972b, 1976). This higher temperature of metamorphism may account for the apparent absence in the schist of Sierra de Salinas of fuchsite and megascopically visible black albite. In some of the schist of Sierra de Salinas inclusions of graphite within plagioclase are visible in thin section (D. C. Ross, written commun., 1977). The most outstanding difference is that the decimeter-scale compositional layering that characterizes the Pelona-Orocopia schist is not well developed in the schist of Sierra de Salinas, which has only a thicker and cruder layering. Although the schist of Sierra de Salinas and the Pelona-Orocopia schist as a whole have had distinctly different metamorphic histories, their protoliths appear to have been fairly similar, and the protolith of the schist of Sierra de Salinas may have been a facies of the Pelona-Orocopia protolith.

The Vincent-Chocolate Mountain Thrust

All of the larger bodies of Pelona-Orocopia schist, and most of the smaller ones, are tectonically overlain by Precambrian, Paleozoic(?), and Mesozoic plutonic granitic rocks and amphibolite- to granulite-facies orthogneiss and paragneiss along regionally low-dipping thrust faults marked by cataclastic rocks (Fig. 2). These faults are variously named the Vincent, Orocopia, Rand, and Chocolate Mountain thrusts (Table 1) and, as explained below, are interpreted as segments of a single thrust or thrust system, here referred to as the Vincent-Chocolate Mountain thrust.

The Chocolate Mountain thrust (Figs. 4, 5) is a single remarkably sharp planar surface which, in the best of outcrops, can be located to within a few millimeters. Straddling the thrust surface is the thrust zone, which consists of rocks, of both the upper and lower plates, that are texturally distinct, in the field, from rocks further from the thrust (Fig. 6). The cataclastic and retrograde rocks at the base of the upper plate range in thickness from only a few meters to several hundred meters. The part of the thrust zone below the thrust surface consists of a zone, zero to several tens of meters thick, of

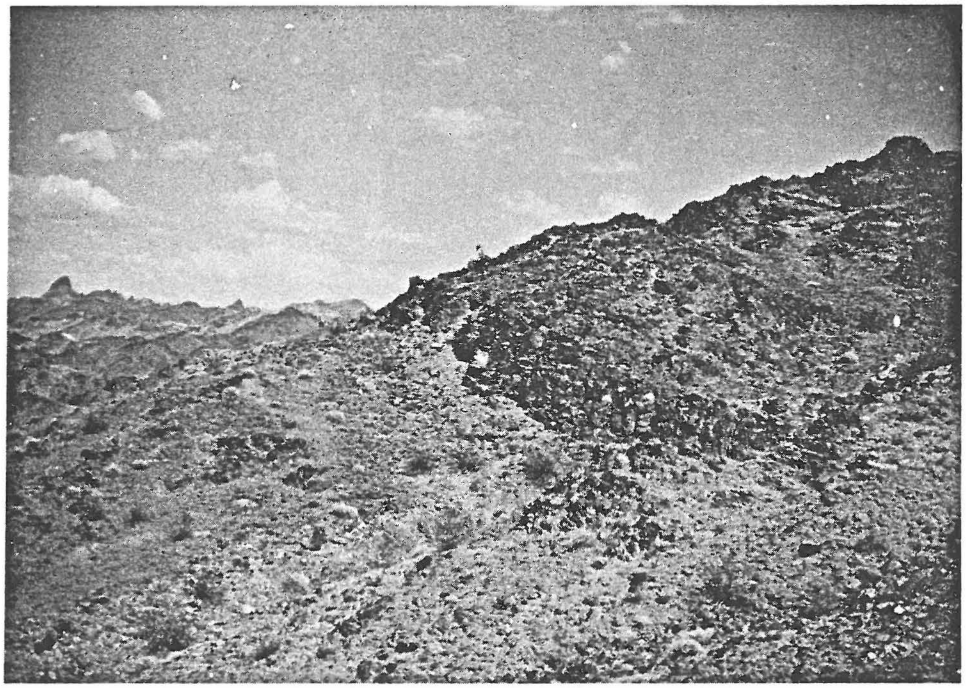

Figure 4. Chocolate Mountain thrust zone, 3 km southwest of Picacho, California. From upper right to lower left: Precambrian banded gneiss, cliff composed of mylonite and ultramylonite at base of upper plate, thrust at base of cliff, Orocopia Schist below thrust. Geologist on center skyline provides scale.

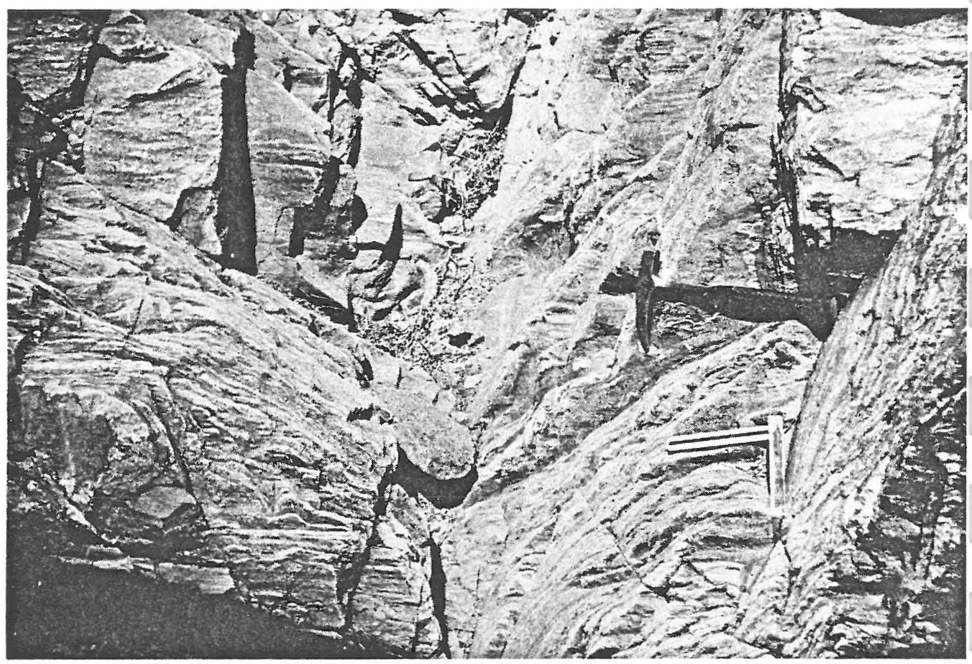

Figure 5. View looking downward on an outcrop of the Chocolate Mountain thrust (at hammer) showing parallelism of lineation in protomylonitic gneiss above thrust and metabasite schist of Orocopia Schist below thrust. Southern Chocolate Mountains, 2.5 km northeast of Mary Lode mine. Hammer is 32 cm long.

Orocopia Schist that is notably coarser grained than, and grades structurally downward into, the normal schist further below the thrust. Locally this coarse schist has protomylonitic (Higgins, 1971) textures in thin section, but in most areas the schist appears to be crystalloblastic right up to the thrust. Lineation in the normal schist, in the coarse schist, and in the cataclastic and retrograde rocks above the thrust are all parallel to one another (Fig. 5).

The Chocolate Mountain thrust zone contains scattered to locally abundant mesoscopic drag folds, most of which occur in the cataclastic rocks near the base of the upper plate. Some of these drag folds are isolated S-folds or Z-folds which have a unique vergence (sense of rotation; sense of asymmetry). Figure 7 shows the orientation and vergence of drag folds measured at some 25 localities along the 80-km length of the southern Chocolate Mountains and Picacho-Peter Kane Mountain area, from Salvation Pass southeastward to the Colorado River. From the collective asymmetry of these drag folds we infer, using the method described by Hansen (1967), that the direction of overthrusting along the Chocolate Mountain thrust was approximately northeastward.

Roughly northeastward overthrusting along the Vincent thrust in the eastern San Gabriel Mountains is suggested by the orientation and sense of overturning of a macroscopic synform in the underlying Pelona

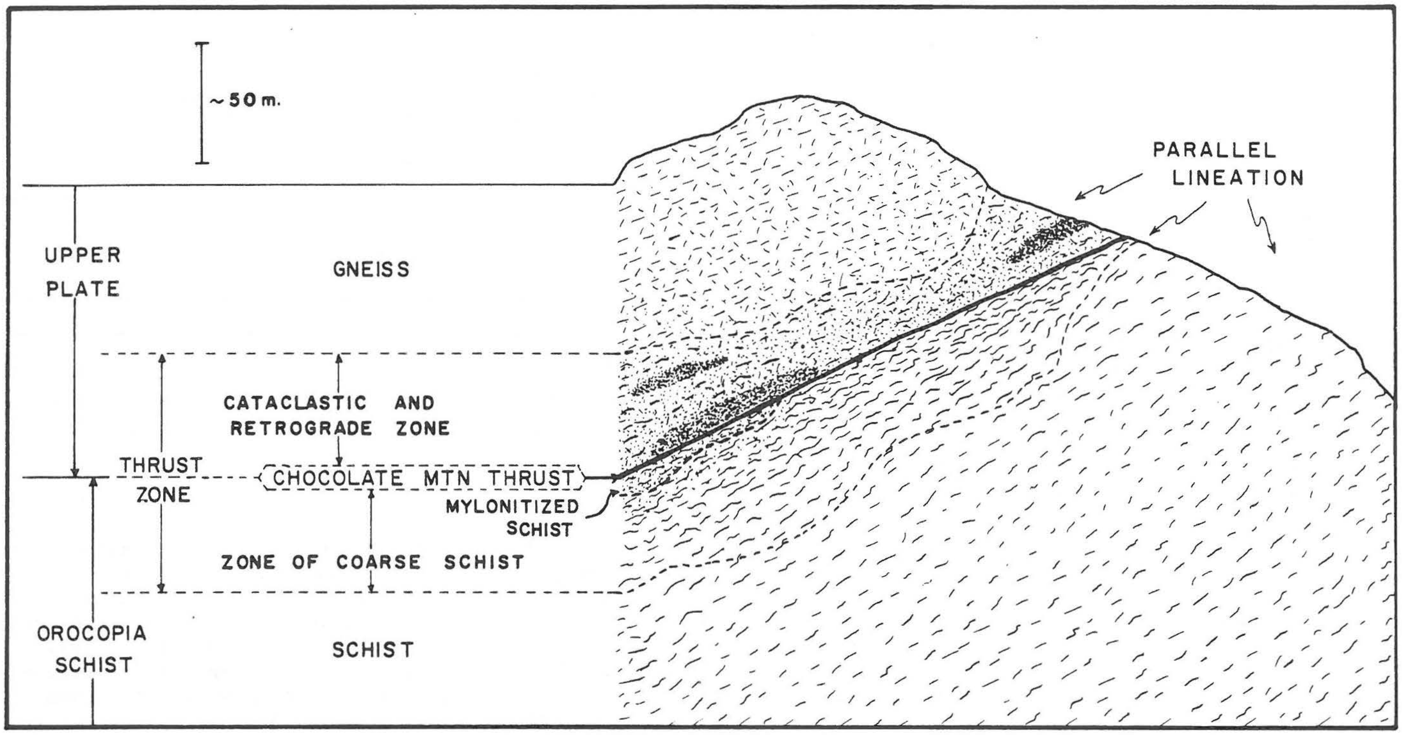

Figure 6. Generalized cross section of the Chocolate Mountain thrust zone. Stippling designates cataclastic rocks; dashed contacts are gradational.

Schist (Ehlig, 1958, 1968, 1975a, fig. 1). We will assume that the northeastward direction of overthrusting inferred for the Chocolate Mountain and Vincent thrusts is applicable to the thrust system as a whole.

Some segments of the Vincent-Chocolate Mountain thrust, for example the Orocopia thrust (Crowell, 1974), have been reactivated as late Cenozoic high-level faults marked by gouge and breccia.

Relation of the Thrust to the Schist

Ehlig (1958) first showed that the metamorphism of the Pelona Schist of the Mount Baldy area of the eastern San Gabriel Mountains was genetically related to the overlying Vincent thrust. Similar relations have subsequently been found in the Rand Mountains (Vargo, 1972), the Sierra Pelona (schist body 1; Graham, 1975; Graham and England, 1976), the southern Chocolate Mountains, and the Picacho-Peter Kane Mountain area. Evidence accumulated by these studies can be generalized as follows: (1) The synmetamorphic foliation and lineation of the schist are parallel, both locally and areally, to the foliation and lineation in the cataclastic and retrograde rocks at the base of the upper plate of the thrust. (2) Metamorphic grain size and metamorphic grade (Fig. 8) within the schist both increase upward toward the overlying thrust. (3) Along many segments of the thrust the cataclastic rocks at the base of the upper plate have been retrograded to the same metamorphic grade as the immediately underlying schist, so that there is a steep metamorphic gradient within the thrust zone but the thrust itself is not a metamorphic discontinuity. Water released from the

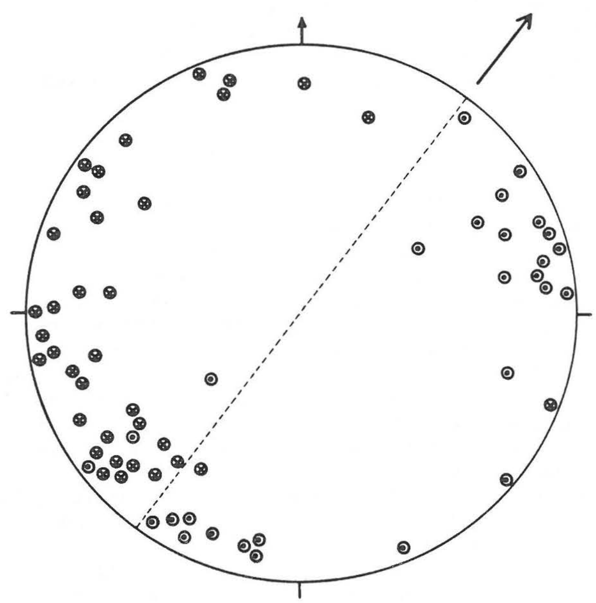

Figure 7. Lower-hemisphere equal-area projection of axes of drag folds in the Chocolate Mountain thrust zone. Symbols ⊙ and ⊗ represent the head and tail, respectively, of an arrow, and are related to fold vergence, as seen looking down the plunge of the fold axis, by the right-hand rule. That is, ⊙ = S fold, ⊗ = Z fold as seen looking down fold axis.

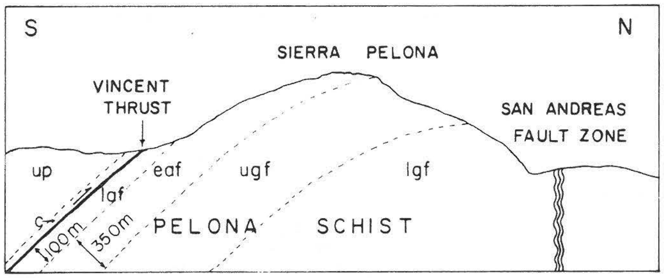

Figure 8. Schematic section showing inverted metamorphic zonation in the Pelona Schist of Sierra Pelona, after Graham and England (1976, fig. 2). Not to scale. Up, gneiss and granite of upper plate; c, cataclastic rocks; laf, lower amphibolite facies; eaf, epidote amphibolite facies; ugf, upper greenschist facies; lgf, lower greenschist facies. Dashed contacts are gradational.

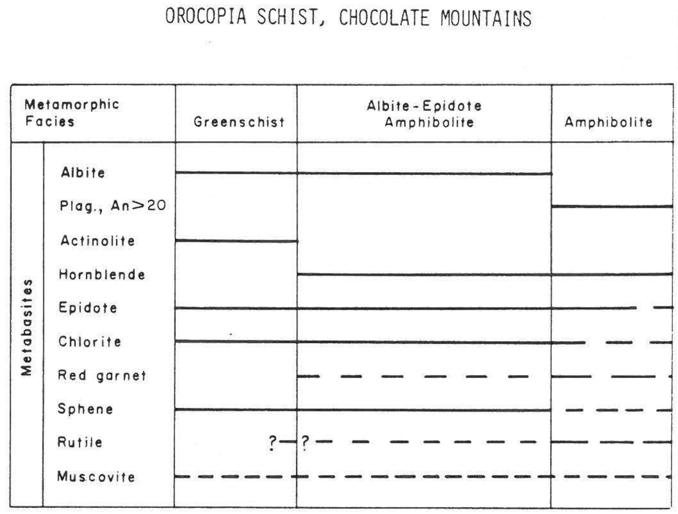

Figure 9. Mineral assemblages of metabasites in the Orocopia Schist of the southern Chocolate Mountains and Picacho-Peter Kane Mountain area. Details of the transitions between facies are poorly known because of the sporadic distribution of metabasite bodies. Length of dashes schematically represents frequency of occurrence of minerals. Not shown are the common accessory minerals quartz, calcite, biotite, magnetite, and apatite.

lower plate during prograde metamorphism of the Pelona-Orocopia schist apparently moved upward and was incorporated into hydrous minerals in the retrograde zone above the thrust (Ehlig, 1958; Conrad and Davis, 1977).

These relationships, which are comparable to those observed for a number of other crystalline overthrust sheets (Armstrong and Dick, 1974), have been interpreted in terms of metamorphism of the schist during thrusting (Ehlig, 1958, 1968), metamorphism of the schist as a consequence of tectonic burial beneath the upper plate of the thrust (Haxel, 1977; see also Bickle and others, 1975), and incipient subduction of the schist (Graham, 1975; Graham and England, 1976; Dillon, 1976). The inverted metamorphic zonation within the schist (Fig. 8) probably resulted from strain heating along the Vincent-Chocolate Mountain thrust (Graham and England, 1976).

Metamorphism

Metabasite mineral assemblages in the Pelona-Orocopia schist are those of the greenschist and albite-epidote amphibolite facies and, less commonly, the lower amphibolite facies or transitional greenschist-blueschist facies (Table 1, Fig. 9). Except for the Pelona Schist of Portal and Ritter Ridges, amphibolite-facies schist apparently occurs only in proximity to the Vincent-Chocolate Mountain thrust. The common major-mineral assemblages of the metagraywacke that makes up the bulk of the Pelona-Orocopia schist are albite + quartz + muscovite + clinozoisite + chlorite at lower metamorphic grades, and albite + quartz + muscovite ± microcline ± biotite + clinozoisite ± chlorite ± garnet at higher grades. Most of the gray schist contains at least a trace of graphite. Metachert assemblages are highly variable; the metacherts of the Orocopia Schist of the southern Chocolate Mountains and Picacho-Peter Kane Mountain area are typically spessartite-magnetite-riebeckite or spessartite-magnetite-hornblende quartzites. Piedmontite is a characteristic accessory mineral in greenschist-facies metachert (Ehlig, 1968). Metapelitic rocks are sparse and none of the three Al_2SiO_5 polymorphs are known to occur in the schist.

Metamorphism of the Orocopia Schist apparently took place at temperature-pressure conditions intermediate between those lying on the medium-pressure (Barrovian) and high-pressure-I facies series trajectories of Miyashiro (1973) (Haxel, 1977). On the basis of detailed electron-microprobe mineralogical studies, Graham and England (1976) estimate that metamorphic temperature and pressure in the epidote-amphibolite-facies Pelona Schist of Sierra Pelona were 420°C to 500°C and 6 to 7.5 kilobars (20 to 27 km depth). Glaucophane-bearing and crossite-bearing metachert, some of which also contains epidote, calcite, or acmite occurs in the Mount Baldy area (Ehlig, 1958; M. C. Blake, Jr., oral commun., 1977), and crossite(?)-bearing metabasite occurs very locally in the southern Chocolate Mountains, but no unequivocal blueschist-facies parageneses (Ernst, 1963) have been reported from the Pelona-Orocopia schist. Although metamorphic pressure within the schist was relatively high, temperatures were apparently too high, at the structural levels now exposed, to permit blueschist-facies metamorphism (see Graham and England, 1976). The high pressure is attributed simply to the thickness of the upper plate of the Vincent-Chocolate Mountain thrust, that is, to the depth to which the schist was subducted or tectonically buried.

Structure

The compositional layering visible throughout the gray schist of the Pelona-Orocopia schist (Fig. 3) is defined by variations in color which are caused mainly by variations in the content of graphite and graphitic albite. This layering clearly is derived from sedimentary bedding. The consistent positive correlation between the abundance of graphite and of micas and chlorite results from the concentration of organic material in the more pelitic layers of the protolith. Compositional graded bedding is locally preserved, and this grading reflects the original upward increase of pelitic and organic material within graded beds of graywacke.

Within the Orocopia Schist compositional layering and foliation (schistosity) are uniformly parallel except in the hinges of rare to locally abundant mesoscopic, strongly appressed, isoclinal intrafolial folds with axes consistently parallel to the mineral lineation of the schist. The foliation is axial-planar to the folds. The presence of these intrafolial folds suggests that bedding has been transposed into foliation on an outcrop scale (Haxel, 1977); this suggestion is consistent with several detailed structural studies (Raleigh, 1958; Evans, 1966; Harvill, 1969; Vargo, 1972) showing that the Pelona-Orocopia schist has undergone an episode of synmetamorphic isoclinal folding. Whether this transposition is local or general is unclear and controversial (P. L. Ehlig, written commun., 1976).

In most of the areas for which systematic structural data are available (Table 1), the lineation of the schist plunges gently to moderately to the northeast--southwest or north-northeast--south-southwest, and is thus subparallel to the inferred direction of overthrusting along the Vincent-Chocolate Mountain thrust.

The detailed structural studies cited above show that the Pelona-Orocopia schist has been subjected to several phases of postmetamorphic folding. For example, the Pelona Schist of Sierra Pelona (Harvill, 1969) contains a set of postmetamorphic parasitic folds formed during flexural-slip folding of the Sierra Pelona antiform (see below), and a later set of folds related to shear zones transecting the antiform.

On a regional scale the foliation of the Pelona-Orocopia schist has low to moderate dips, and in most of the larger schist bodies the foliation defines a postmetamorphic antiform or anticlinorium. The largest of these is the narrow, discontinuous, complexly faulted middle Tertiary Chocolate Mountain anticlinorium, which runs the length of the southern Chocolate Mountains and Picacho-Peter Kane Mountain area and extends eastward to the Middle Mountains (schist body 13) of southwesternmost Arizona. Broad, relatively simple antiforms are present in the Sierra Pelona (Dibblee, 1961a; Harvill, 1969), the Orocopia Mountains (Crowell, 1962, 1975c), and the Rand Mountains (Dibblee, 1967). The Vincent-Chocolate Mountain thrust crops out chiefly on the flanks of these antiformal structures (Fig. 2), although several small klippen occur along the crest of the Chocolate Mountain anticlinorium.

Age of Metamorphism

The Pelona-Orocopia schist was long regarded as probably (Muelberger and Hill, 1958) or certainly (Hershey, 1912; Hulin, 1925; Simpson, 1934; Miller, 1946) of Precambrian age, on the basis of this argument: Nearby Paleozoic rocks are unmetamorphosed or affected only by local contact metamorphism; therefore, there can have been no Phanerozoic regional metamorphism in southern California. This argument is invalid if the schist and the Paleozoic rocks were juxtaposed by overthrusting, with the schist undergoing metamorphism beneath the Vincent-Chocolate Mountain thrust and the unmetamorphosed Paleozoic rocks riding on the crystalline rocks of the upper plate of the thrust. (Also, some Paleozoic rocks in southern California are now known to be metamorphosed and intensely deformed; for example, see Hamilton, 1971). Rocks in southwesternmost Arizona now recognized as Orocopia Schist (Table 1) were mapped, along with several other rock types, as "Mesozoic schist" by Wilson (1933, 1960).

Ehlig (1958, 1968) showed that, because the metamorphism of the Pelona Schist was directly related to the Vincent thrust and the Vincent thrust cuts isotopically dated mid-Cretaceous plutonic rocks, the metamorphism of the schist must have occurred during Late Cretaceous or early Tertiary time (Table 2). The Orocopia Schist must be older than the unconformably overlying lower Oligocene Quechan Volcanic Formation (of Crowe, 1973, 1978).

The Pelona Schist and mylonitic rocks from the Vincent thrust zone have yielded six K-Ar and Rb-Sr dates ranging from 47 to 59 m.y. (Table 2). These dates come from areas within or adjacent to an incompletely delineated region of "reduced" K-Ar cooling ages in the eastern Transverse Ranges and adjacent Mojave Desert (Miller and Morton, 1975). This region includes a "zone of anamolous cooling ages" between approximately 55 and 80 m.y. in the San Bernardino and eastern San Gabriel Mountains (Miller and Morton, 1978). Pending clarification of the relation of these reduced cooling ages to the metamorphism of the Pelona Schist, a Late Cretaceous age for the schist can not be ruled out. However, the concentration of both K-Ar and Rb-Sr isotopic ages from the Pelona Schist and Vincent thrust zone in the interval from 50 to 60 m.y. (Table 2) strongly suggests that the metamorphism of the Pelona-Orocopia schist occurred in Paleocene time.

Relations to Granitic Plutons

One of the peculiar characteristics of the Pelona-Orocopia schist is that it is only very sparsely intruded by Mesozoic granitic rocks (Ehlig, 1968). The Rand Schist is intruded, just south of Randsburg, by a small ($\sim$2 km^2) body of metagranite of probable Mesozoic age (R. W. Kistler, oral commun., 1977; see Miller and Morton, 1977, p. 644). (The Mesozoic granitic rocks on the southwest and southeast sides of the Rand Mountains (Dibblee, 1967, pl. 1) are in the upper plate of the Rand thrust (Ehlig, 1968).) The Orocopia Schist of the southern Chocolate Mountains contains a single very small plug of epidote-garnet metagranite or metarhyolite (Dillon, 1976), and the Pelona Schist is known to contain two small metarhyolite dikes (P. L. Ehlig, oral commun., 1977). The oldest known postmetamorphic intrusion into the Pelona-Orocopia schist is the lower Tertiary(?) Marcus Wash Granite of the Picacho district (Haxel, 1977). In the eastern San Gabriel Mountains and the central and southern Chocolate Mountains the Pelona and Orocopia Schists are intruded by small, epizonal, granitic plutons, which were once assumed to be of Mesozoic age (Noble, 1954; Jennings, 1967). However, the plutons in the southern Chocolate Mountains are genetically related to the mid-Tertiary silicic volcanic rocks of the area (Dillon, 1976), and both sets of plutons have yielded concordant Miocene K-Ar dates (Miller and Morton, 1977).

Previous Distribution of the Schist

A schematic reconstruction of southern California prior to approximately 300 km of late-Cenozoic right slip on the San Andreas fault system (Crowell, 1973, 1975a; Dickinson, Cowan, and Schweickert, 1972; Nilsen and Clarke, 1975), including the San Gabriel fault (Crowell, 1975b), was produced by graphically reassembling the Orocopia-Soledad-Tejon terrane (Crowell, 1962; Silver, 1971), the northern

Table 2. Age data for the Pelona-Orocopia Schist

Rock	Locality	Relation to Pelona-Orocopia schist and Vincent-Chocolate Mountain thrust	Radiometric age (m.y.)	Method	References
Mount Lowe Granodiorite	San Gabriel Mountains	Cut by Vincent thrust	220±10	U-Pb	Silver, 1971; Ehlig, 1968, 1975a, b
Quartz diorite correlative with the quartz diorite of El Dorado Ridge and Ontario Peak	San Gabriel Mountains	Cut by Vincent thrust	105±10	Rb-Sr biotite age	Hsu, Edwards, and McLaughlin, 1963; Ehlig, 1968
Plutons correlative with the Mount Josephine Granodiorite	San Gabriel Mountains	Cut by Vincent thrust	80±10	U-Pb	Carter and Silver, 1972; P. L. Ehlig, oral commun., 1974
Quechan Volcanic Formation	Picacho district; Chocolate Mountains	Rests nonconformably on Orocopia Schist	~35 (several dates)	K-Ar	Daniel Krummenacher, written commun., 1976; Crowe, 1973, 1978; Dillon, 1976
Quartz monzonite; quartz monzonite of Mount Barrow	San Gabriel Mountains; Chocolate Mountains	Post-metamorphic intrusions into Pelona and Orocopia Schists	14-19; 20-23	K-Ar	Miller and Morton, 1977; Dillon, 1976; Haxel, 1977
Quartzo-feldspathic Pelona Schist	Sierra Pelona; San Gabriel Mountains	--	47±1 52±1	K-Ar whole rock	Ehlig, Davis, and Conrad, 1975
Quartzo-feldspathic Pelona Schist	Sierra Pelona	--	53±2	Rb-Sr mineral isochron	Ehlig, Davis, and Conrad, 1975
Metachert, Pelona Schist	San Gabriel Mountains	--	59±1	Rb-Sr mineral isochron	Gary Lass, written commun., 1978
Mylonite, Vincent thrust zone	San Gabriel Mountains	--	53±0.5	K-Ar whole rock	Ehlig, Davis, and Conrad, 1975
Blastomylonite, Vincent thrust zone	San Gabriel Mountains	--	58.5±4	Rb-Sr mineral isochron	Conrad and Davis, 1977

Chocolate Mountain-Mint Canyon Formation-Caliente Formation paleo-drainage system (Ehlig, Ehlert, and Crowe, 1975), and the Pinnacles-Neenach volcanic field (Huffman, Turner, and Jack, 1973; Matthews, 1976). Sixty kilometers of left slip along the Garlock fault (Smith, 1962; Davis and Burchfiel, 1973) was also restored. The resulting palinspastic map (Fig. 10) shows the probable approximate middle-Tertiary positions of the present day Pelona-Orocopia schist outcrops (Fig. 2) relative to one another and to several other tectonic elements of the California continental margin. Most of the schist bodies are alined in two subparallel, west- to west-northwest-trending anticlinoria in southeastern California and southwestern Arizona. Because the right-slip faults in the western Mojave Desert have displacements of, at most, a few tens of kilometers (Dibblee, 1961b; Garfunkel, 1974), the schist along the Garlock fault (schist bodies 4 and 5) probably always has been several hundred kilometers north of the schist of southeastern California and southwestern Arizona (Ehlig, 1968). The Pelona Schist of Portal and Ritter Ridges forms a sliver within the San Andreas fault system (Wallace, 1949), but the occurrence of similar schist at Quartz Hill several kilometers to the northeast in Antelope Valley

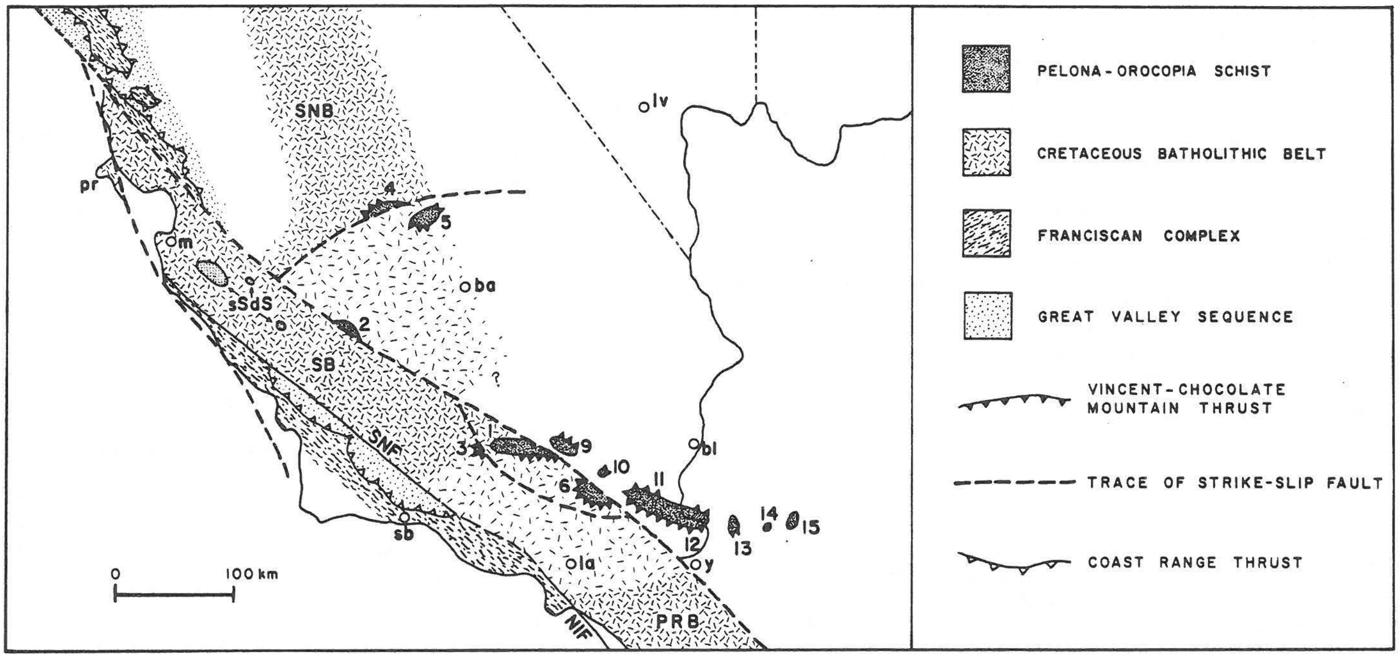

Figure 10. Palinspastic reconstruction showing present day outcrops of the Pelona-Orocopia schist and Vincent-Chocolate Mountain thrust restored to their approximate relative positions prior to late Cenozoic strike slip along the San Andreas fault system. Schist bodies numbered as in Figure 2 and Table 1, but bodies 7 and 8 are omitted. Distribution of Franciscan Complex, Great Valley Sequence, and Coast Range thrust simplified after Bailey, Blake, and Jones (1970), and Jones, Blake, and Rangin (1976). Restoration of San Gregorio-Hosgri fault after Graham and Dickinson (1978). Cretaceous batholithic belt after Kistler (1974). NIF, Newport-Inglewood fault; PRB, Peninsular Ranges batholith; SB, Salinian block; SNB, Sierra Nevada batholith; SNF, Sur-Nacimiento fault; sSdS, schist of Sierra de Salinas; ba, Barstow; bl, Blythe; la, Los Angeles; lv, Las Vegas; m, Monterey; pr, Point Reyes; sb, Santa Barbara.

suggests that schist body 2 may be more or less in place with respect to the Mojave Desert. Although correlation of the schist of Sierra de Salinas with the Pelona-Orocopia schist is equivocal, the probable restored position of the schist of Sierra de Salinas is shown (sSdS, Fig. 10) for reference.

The palinspastic map of the Pelona-Orocopia schist and Vincent-Chocolate Mountain thrust shows, more clearly than does the present day distribution of the schist, that the Pelona-Orocopia schist lies largely along and beneath the diffuse eastern margin of the Sierra Nevada-Salinia-Peninsular Ranges Cretaceous batholithic belt (Hamilton, 1969a, b; Kistler, 1974). The Pelona-Orocopia schist thus occupies a fundamentally different tectonic position than the lithologically similar Franciscan Complex, and the lithologically dissimilar Great Valley Sequence, which form separate and much more extensive belts on the west side of the batholithic belt in western California and Baja California (Bailey, Irwin, and Jones, 1964; Berkland and others, 1972; Ernst and others, 1970; Suppe, 1972; Jones, Blake, and Rangin, 1976). The Franciscan Complex includes the Catalina Schist of Santa Catalina Island (Platt, 1975, 1976). In spite of certain lithologic similarities between the Catalina Schist and the Pelona-Orocopia schist (Ehlig, 1968; Crowell, 1968) the above argument, and the fact that the metamorphic age of the Catalina Schist (Suppe and Armstrong, 1972) is appreciably older than that of the Pelona-Orocopia schist (Table 2), strongly suggests that the two schists are not directly related (Platt, 1976, p. 5). Consistent with these conclusions, the inferred direction of overthrusting along the Vincent-Chocolate Mountain thrust is roughly opposite to that along the Coast Range thrust overlying the Franciscan Complex (Bailey, Blake, and Jones, 1970; Ernst, 1970; Platt, 1975).

Subsurface Extent of the Schist

There are two possible interpretations of the subsurface extent of the Pelona-Orocopia schist. The schist of southeastern California (as palinspastically reconstructed in Fig. 10) and southwestern Arizona and the schist along the Garlock fault (schist bodies 4 and 5) may be disjunct; this would require that these unique and virtually identical rocks (Simpson, 1934; Ehlig, 1968; Vargo, 1972) originated independently in two areas at least 200 km apart (Ehlig, 1968). We prefer the tectonically simpler interpretation that all of the schist bodies were, prior to offset along the San Andreas and Garlock fault systems, connected at depth beneath a regional allochthon. This hypothesized allochthon extends from southwesternmost Arizona to the westernmost Mojave Desert and comprises the pre-Tertiary crystalline rocks (other than the schist) of the eastern Transverse Ranges, southwestern Mojave Desert, northwesternmost Sonoran Desert, northeasternmost Peninsular Ranges, and southern Salinian block (Figs. 2, 10).

We thus infer that the bulk of the Pelona-Orocopia schist is still deeply buried, chiefly beneath the southwestern Mojave Desert. The occurrence of most exposures of the schist along the San Andreas and Garlock fault systems (Fig. 2) is then due to strong uplift and deep erosion along these strike-slip faults, for example in the Transverse Ranges where the Pelona-Orocopia schist was first exposed to subaerial erosion in Miocene time (Ehlig, Davis, and Conrad, 1975). Inherent in this "single allochthon" interpretation is our treatment of the Vincent, Chocolate Mountain, Orocopia, and Rand thrusts as segments of a single thrust fault.

The allochthon is a fragment or flake (in the sense of Oxburgh, 1972) of continental crust with a complex and diverse Precambrian through Mesozoic geologic history (for example, Silver, 1971; Dibblee, 1967; Crowell, 1962; Ehlig, 1975a, b; Dillon, 1976; Allen, 1957), which contrasts with the distinctly simpler history of the tectonically underlying Pelona-Orocopia schist (Crowell, 1968). It is this striking contrast in variety of rock types and complexity of geologic history across the thrust that shows that the Vincent-Chocolate Mountain thrust is a major crustal discontinuity.

If the "single allochthon" interpretation is correct, then the allochthon must have a northeastern boundary somewhere in the southwestern Mojave Desert and northwesternmost Sonoran Desert. Future field studies in these areas may locate this suture zone; part of it may be represented by the thrust faults exposed in the Palen, McCoy, and Mule Mountains west of Blythe, California (Pelka, 1973a, b).

The Pelona-Orocopia Protolith

The metagraywacke of the Pelona-Orocopia schist is quartzo-feldspathic, rather than mafic, in composition (Ehlig, 1958; Haxel, 1977; Vargo, 1972), contains detrital zircon and allanite, and must have had a continental provenance. In most of the schist metagraywacke strongly predominates over metapelite, indicating that the Pelona-Orocopia protolith had a high sand-to-shale ratio. This suggests that the clastic sedimentary rocks that made up the bulk of the protolith were deposited, presumably by turbidity currents, in a proximal environment (Walker, 1967), but the virtual absence of metaconglomerate in the schist is puzzling.

The thick layers of metabasite in the Pelona-Orocopia schist were probably derived from submarine lava flows, and relict pillow structures have been found in the metabasite of Sierra Pelona at one locality (P. L. Ehlig, oral commun., 1977). Thin layers of metabasite within metagraywacke or metachert probably were derived from mafic tuff. A small body of metadiorite or metagabbro occurs in the Orocopia Schist of the southern Chocolate Mountains. Some isolated blocks of metabasite may originally have been olistoliths within the graywacke of the Pelona-Orocopia protolith.

The deposition of small amounts of limestone and ferromanganiferous chert in an environment of dominantly clastic deposition was probably related to the submarine volcanism now represented by the metabasites of the Pelona-Orocopia schist. The common spatial association of metachert and marble with metabasite suggests that the chert and limestone accumulated, above the reach of clastic sedimentation, on submarine volcanic topographic highs (Garrison, 1974), presumably as biogenic debris (Wise and Weaver, 1974).

No direct evidence, isotopic or palentologic, as to the age of the Pelona-Orocopia protolith is known to us.

The basement upon which the protolith of the Pelona-Orocopia schist accumulated has not been identified and apparently is not exposed. Metamorphosed ultramafic rocks, now serpentinite and actinolite-rock, are widespread and locally abundant (for example, near Wrightwood, California) in the schist. The presence of these ultramafic rocks, and the association of graywacke, shale, basalt, ferromanganiferous chert, and ultramafic rock, indicate that the protolith accumulated on oceanic or semi-oceanic crust.

Regional Uniqueness of the Schist

None of the Precambrian rock units of southeastern California and adjacent areas (see, for example, the descriptions given by Hunt and Mabey, 1966; Silver, 1971; Silver and others, 1977; Anderson and Silver, 1976; Babcock, Brown, and Clark, 1976; Ford and Breed, 1976; Shride, 1967; Anderson and Silver, 1971; Cooper and Silver, 1964) appears to warrant consideration as the Pelona-Orocopia protolith, because none consists of graywacke or metagraywacke in combination with the minor rock types characteristic of the protolith. The Pelona-Orocopia schist obviously was not derived from the limestone, dolomite, shale, and orthoquartzite of the Paleozoic and uppermost Precambrian miogeocline and craton (Stewart and Poole, 1974, 1975; Burchfiel and Davis, 1972, 1975); and the Antler flysch belt (Poole, 1974) is likewise lithologically dissimilar to the protolith (Ross, 1976). Furthermore, the northwest-trending Pelona-Orocopia schist belt (Figs. 2, 10) lies athwart the southwesterly trend of these Paleozoic belts.

Most of the Mesozoic supracrustal rock units of southeastern California and adjacent areas (Jones, Blake, and Rangin, 1976; Burchfiel and Davis, 1972, 1975; Abbott, 1971; Grose, 1959; Dibblee, 1967; Gastil, Phillips, and Allison, 1975) differ from the Pelona-Orocopia protolith and schist in that they include appreciable proportions of silicic or intermediate volcanic rocks and (or) shallow marine or nonmarine sedimentary rocks. Some of the lower Mesozoic country rocks of the Peninsular Ranges batholith (Gastil, Phillips, and Allison, 1975), specifically the Bedford Canyon Formation (Schwarcz, 1969; Larsen, 1948) and the Julian Schist (Merriam, 1958; Donnelly, 1934), have a limited degree of similarity to the Pelona-Orocopia protolith but, again, apparently lack the distinctive minor rock types characteristic of the protolith. Facies changes might be invoked to allow correlation of these rocks with the Pelona-Orocopia protolith, but such a correlation seems rather unlikely. Finally, there are the Mesozoic supracrustal rocks, other than the schist itself, of the northwestern Sonoran Desert (Hayes, 1970; Miller and McKee, 1971; Hamilton, 1964; Pelka, 1973a, b; Wilson, 1933). Of these, the Palen Formation (Pelka, 1973a) is somewhat similar to the Pelona-Orocopia protolith, and the McCoy Mountains Formation is comparable to the Pelona-Orocopia schist in that it is overlain by a crystalline thrust sheet (Pelka, 1973a, b). Either or both of these units may be related to the Pelona-Orocopia schist or to the Vincent-Chocolate Mountain thrust (Haxel, 1977; Dillon, 1976), but neither is obviously a facies of the protolith.

These comparisons suggest that the Pelona-Orocopia schist--plus, possibly, the schist of Sierra de Salinas--is regionally unique, in the sense that it was not derived from any of the other widespread tectonic-lithologic units of southern California and vicinity. The Pelona-Orocopia schist belt has no counterpart to the north on the east side of the Sierra Nevada batholith in east-central California and southern Nevada. The schist belt extends eastward an unknown, but probably not great, distance into southwestern Arizona, and apparently has no counterpart to the south in northwestern Mexico (see: Salas, 1968; Merriam, 1972; Gastil, Philips, and Allison, 1975; Cooper and Arellano, 1946; Anderson, Silver, and Cordoba M., 1969; Anderson and Silver, 1971; Cserna, 1970; Salas, Cordoba, M., and Avila, 1974; Clark, 1975; Gastil and Krummenacher, 1977; Gastil, Krummenacher, and students, 1974). The Pelona-Orocopia schist thus appears to be endemic to the region of southern California and southwesternmost Arizona.

PALEOGEOGRAPHIC SIGNIFICANCE OF THE PELONA-OROCOPIA SCHIST: A STATEMENT OF THE PROBLEM

The presence of the oceanic rocks of the Pelona-Orocopia schist in their present tectonic position along the eastern margin of the Cretaceous batholithic belt, where they are surrounded and tectonically overlain by Precambrian through Mesozoic gneisses and granites of typically continental aspect, seems anomolous, especially since the Orocopia Schist extends as far inland as the southwestern corner of Arizona. The Pelona-Orocopia schist, as such, is the product of a Paleocene (or Late Cretaceous) orogenic event in which the protolith of the schist was overridden, along the Vincent-Chocolate Mountain thrust, by a northeast-directed flake of continental crust. However, the origin of the Pelona-Orocopia protolith and the paleogeographic significance of the orogenic event that converted it into the schist are unclear because of uncertainty as to the place of origin of the Salinian block (Compton, 1966; Ross, 1972a) and of the slab of continental crust that now constitutes the allochthon overlying the Pelona-Orocopia schist.

The conventional hypothesis is that Salinia and the crystalline rocks of northwestern and southeastern southern California were originally alined between the Sierra Nevada and Peninsular Ranges batholiths (Hamilton, 1969a, b). The present configuration of crystalline rocks in southern and western California is then explained by a possible 150 or more km of Late Cretaceous and (or) early Paleocene right-slip along the proto-San Andreas fault system and 300 km of unequivocal right slip along the late Cenozoic San Andreas fault system (Crowell, 1973, 1975a; Nilsen and Clarke, 1975; Graham and Dickinson, 1978). However, some of the distinctive rocks of the allochthon may not have counterparts elsewhere in southwestern North America (Silver, 1971; Silver and others, 1977) and the pre-intrusive and intrusive rocks of Salinia may not have counterparts in the expected areas east of the San Andreas fault in the western Mojave Desert and southern Sierra Nevada (Ross, 1977, 1978). This raises the possibility that Salinia and the allochthon comprise an exotic microcontinent, or two separate exotic microcontinents, that collided with southern California (for example, Hsu, 1971; Nur and Ben-Avraham, 1978) or reached southern California by large-scale Mesozoic strike-slip faulting (for example, Silver and Anderson, 1974; Kistler and Peterman, 1978).

This in turn raises the possibility that the Pelona-Orocopia protolith may itself be exotic, having accumulated elsewhere and been tectonically introduced into southern California sometime after the truncation of the continental margin there in Late Permian or Early Triassic time (Hamilton and Myers, 1966; Hamilton, 1969a; Burchfiel and Davis, 1972, 1975). There appear to be two broad alternatives for the origin of the Pelona-Orocopia protolith: (1) The oceanic rocks of the protolith accumulated outboard of a continental margin, in southern California or elsewhere, and were subsequently tectonically trapped in their present position inboard of the granitic and gneissic continental rocks that now lie to the west of the Pelona-Orocopia schist. (2) The protolith accumulated inboard of the continental margin, in an intracontinental ensimatic basin within southern California. The presently available geologic, geochronologic, and isotopic data do not allow a clear-cut choice between these alternatives, and only partially constrain the several protracted tectonic scenarios possible under the first alternative.

The second alternative leads to tectonic models of the sort we have presented previously. We have suggested that the Pelona-Orocopia protolith accumulated in a Late Cretaceous ensimatic intracontinental back-arc basin formed by crustal dilation above a mantle diapir (Dillon and Haxel, 1975) or by oblique rifting associated with right-lateral transform faulting along the proto-San Andreas fault system (Haxel and Dillon, 1977). In either model overthrusting (or incipient subduction) along the Vincent-Chocolate Mountain thrust resulted from closing of the back-arc basin in response to the initiation of subduction of the Farallon plate beneath southern California (Atwater, 1970). Although these back-arc basin models provide a straightforward explanation for the existence of the Pelona-Orocopia schist in southern California, they are, in view of the uncertainties outlined above, obviously speculative at this time.

In conclusion, we offer the following suggestions for future study of the tectonic aspects of the Pelona-Orocopia schist. (1) The northeastward direction of overthrusting inferred for the Chocolate Mountain thrust and the Vincent thrust of the eastern San Gabriel Mountains should be verified in other areas. (2) The hypothesis that the upper plates of the Vincent, Chocolate Mountain, Orocopia, and Rand thrusts constitute a single large allochthon should be critically evaluated. (3) The geometric relation of the hypothesized allochthon to the distribution of Paleozoic sedimentary facies in southern California and southwestern Arizona (Stewart and Poole, 1975) should be investigated. (4) The lithologic correlation of the Rand Schist with the Pelona and Orocopia Schists should be tested by isotopic dating of the Rand Schist. (5) The relationship, if any, of the Vincent-Chocolate Mountain thrust to the thrust faults west of Blythe (Pelka, 1973a), the Alamo Mountain movement zone (Crowell, 1968), the Mill Canyon mylonite zone and window (Carter and Silver, 1972; Ehlig, 1975a), the cataclastic rocks about Cucamonga Canyon (Hsu, 1955; Ehlig, 1975a), and the Santa Rosa mylonite belt (Theodore, 1970) needs to be clarified. (6) The relation of the schist of Sierra de Salinas (Ross, 1976) to the Pelona-Orocopia protolith and schist should be given further study. (7) It is very important to determine the age of the Pelona-Orocopia protolith. (8) The origin and paleogeographic significance of the Pelona-Orocopia schist cannot be understood until it is known whether the Salinian block and the allochthon atop the schist are indigenous or exotic to southern California.

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REFERENCES CITED

Abbott, E. W., 1971, Stratigraphy and petrology of the Mesozoic volcanic rocks of southeastern California [abs.]: Geol. Soc. America Abs. with Programs, v. 3, no. 2, p. 69.

Allen, C. R., 1957, San Andreas fault zone in San Gorgonio Pass, southern California: Geol. Soc. America Bull., v. 68, p. 315-349.

Anderson, C. A., and Silver, L. T., 1976, Yavapai series--A greenstone belt: Arizona Geol. Soc. Digest, v. 10, p. 13-26.

Anderson, T. H., and Silver, L. T., 1971, Preliminary history for Precambrian rocks, Bamori region, Sonora, Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 3, no. 2, p. 72-73.

Anderson, T. H., Silver, L. T., and Cordova, M., Diego A., 1969, Mesozoic magmatic events of the northern Sonora coastal region, Mexico [abs.]: Geol. Soc. America Abs. with Programs 1969, pt. 7, p. 3-4.

Armstrong, R. L., and Dick, H. J. B., 1974, A model for the development of thin overthrust sheets of crystalline rock: Geology, v. 2, p. 35-40.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. America Bull., v. 81, p. 3513-3536.

Babcock, R. S., Brown, E. H., and Clark, M. D., 1976, Geology of the older Precambrian rocks of the upper granite gorge of the Grand Canyon, in Breed, W. J., and Roat, Evelyn, eds., Geology of the Grand Canyon: Mus. Northern Arizona/Flagstaff and Grand Canyon Nat. History Assoc., p. 2-19.

Bailey, E. H., Black, M. C., Jr., and Jones, D. L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges, in Geological Survey research 1970: U.S. Geol. Survey Prof. Paper 700-C, p. C70-C81.

Bailey, E. H., Irwin, W. P., and Jones, D. L., 1964, Franciscan and related rocks, and their significance in the geology of western California: California Div. Mines and Geology Bull. 183, 177 p.

Berkland, J. O., Raymond, L. A., Kramer, J. C., Moores, F. M., and O'Day, M., 1972, What is Franciscan?: Am. Assoc. Petroleum Geologists Bull., v. 56, no. 12, p. 2295-2302.

Bickle, M. J., Hawkesworth, C. H., England, P. C., and Athey, D. R., 1975, A preliminary thermal model for regional metamorphism in the Eastern Alps: Earth and Planetary Sci. Letters, v. 26, no. 1, p. 13-28.

Burchfiel, B. C., and Davis, G. A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: Am. Jour. Sci., v. 272, p. 97-118.

_____1975, Nature and controls of Cordilleran orogenesis, western United States--Extension of an earlier synthesis: Am. Jour. Sci., v. 275-A, p. 363-396.

Carter, B., and Silver, L. T., 1972, Structure and petrology of the San Gabriel anorthosite-syenite body, California: Internat. Geol. Cong., 24th, Montreal, Canada, 1972, sec. 2, p. 303-311.

Clark, K. F., 1975, Geologic section across central Sonora, Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 7, no. 5, p. 596.

Compton, R. R., 1966, Granitic and metamorphic rocks of the Salinian block, California Coast Ranges: California Div. Mines and Geology Bull. 190, p. 277-287.

Conrad, R. L., and Davis, T. E., 1977, Rb/Sr geochronology of cataclastic rocks of the Vincent thrust, San Gabriel Mountains, southern California [abs.]: Geol. Soc. America Abs. with Programs, v. 9, no. 4, p. 403-404.

Cooper, G. A., and Arellano, A. R. V., 1946, Stratigraphy near Caborca, northwest Sonora, Mexico: Am. Assoc. Petroleum Geologists Bull., v. 30, no. 4, p. 606-611.

Cooper, J. R., and Silver, L. T., 1964, Geology and ore deposits of the Dragoon quadrangle, Cochise County, Arizona: U.S. Geol. Survey Prof. Paper 416, 196 p.

Crowe, B. M., 1973, Cenozoic volcanic geology of the southeastern Chocolate Mountains, California: California Univ., Santa Barbara, Ph. D. thesis, 117 p.

_____1978, Cenozoic volcanic geology and age of inception of basin-range faulting in the southeasternmost Chocolate Mountains, California: Geol. Soc. America Bull. (In press)

Crowell, J. C., 1962, Displacement along the San Andreas fault, California: Geol. Soc. America Spec. Paper 71, 61 p.

_____1968, Movement histories of faults in the Transverse Ranges, and speculations on the tectonic history of California: Stanford Univ. Pubs. Geol. Sci., v. 11, p. 323-341.

_____1973, Problems concerning the San Andreas fault system in southern California: Stanford Univ. Pubs. Geol. Sci., v. 13, p. 125-135.

_____1974, The Orocopia thrust, southeastern California [abs.]: Geol. Soc. America Abs. with Programs, v. 6, no. 3, p. 159.

_____1975a, The San Andreas fault in southern California: California Div. Mines and Geology Spec. Rept. 118, p. 7-27.

_____1975b, The San Gabriel fault and Ridge Basin, southern California: California Div. Mines and Geology Spec. Rept. 118, p. 208-219.

_____1975c, Geologic sketch of the Orocopia Mountains, southeastern California: California Div. Mines and Geology Spec. Rept. 118, p. 99-110.

Cserna, Zoltan de, 1970, Mesozoic sedimentation, magmatic activity and deformation in northern Mexico, in Seewald, K., and Sundeen, D., eds., The geologic framework of the Chihuahua tectonic belt: Midland, Tex., Texas Geol. Soc., p. 99-117.

Davis, G. A., and Burchfiel, B. C., 1973, Garlock fault of southern California--An intracontinental transform structure: Geol. Soc. America Bull., v. 84, p. 1407-1422.

Dibblee, T. W., Jr., 1961a, Geologic map of the Bouquet Reservoir quadrangle, Los Angeles County, California: U.S. Geol. Survey Misc. Inv. Field Studies Map MF-79, scale 1:62,500.

_____1961b, Evidence of strike-slip movement on northwest-trending faults in Mojave Desert, California, in Geological Survey research 1961: U.S. Geol. Survey Prof. Paper 424-B, p. B197-B199.

_____1964, Geologic map of the San Gorgonio Mountain quadrangle, San Bernardino and Riverside Counties, California: U.S. Geol. Survey Misc. Geol. Inv. Map I-431, scale 1:62,500.

_____1967, Areal geology of the western Mojave Desert, California: U.S. Geol. Survey Prof. Paper 522, 153 p.

Dickinson, W. R., Cowan, D. S., and Schweickert, R. A., 1972, Test of new global tectonics--Discussion: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 375-384.

Dillon, J. T., 1976, Geology of the Chocolate and Cargo Muchacho Mountains, southeasternmost California: California Univ., Santa Barbara, Ph. D. thesis, 575 p.

Dillon, John, and Haxel, Gordon, 1975, The Chocolate Mountain-Orocopia-Vincent thrust system as a tectonic element of late Mesozoic California [abs.]: Geol. Soc. America Abs. with Programs, v. 7, no. 3, p. 311-312.

Donnelly, M., 1934, Geology and mineral deposits of the Julian district, San Diego County, California: California Jour. Mines Geology, v. 30, no. 4, p. 331-370.

Ehlig, P. L., 1958, The geology of the Mount Baldy region of the San Gabriel Mountains, California: California Univ., Los Angeles, Ph. D. thesis, 195 p.

_____1968, Causes of distribution of Pelona, Rand, and Orocopia schists along the San Andreas and Garlock faults: Stanford Univ. Pubs. Geol. Sci., v. 11, p. 294-306.

_____1975a, Geologic framework of the San Gabriel Mountains, California: California Div. Mines and Geology Bull. 196, p. 7-18.

_____1975b, Basement rocks of the San Gabriel Mountains, south of the San Andreas fault, southern California: California Div. Mines and Geology Spec. Rept. 118, p. 177-186.

Ehlig, P. L., Davis, T. E., and Conrad, R. L., 1975, Tectonic implications of the cooling ages of the Pelona Schist [abs.]: Geol. Soc. America Abs. with Programs, v. 7, no. 3, p. 314-315.

Ehlig, P. L., Ehlert, K. W., and Crowe, B. M., 1975, Offset of the upper Miocene Caliente and Mint Canyon Formations along the San Gabriel and San Andreas faults: California Div. Mines and Geology Spec. Rept. 118, p. 83-92.

Ernst, W. G., 1963, Petrogenesis of glaucophane schists: Jour. Petrology, v. 4, no. 1, p. 1-30.

_____1970, Tectonic contact between the Franciscan melange and the Great Valley sequence, crustal expression of a Late Mesozoic Benioff Zone: Jour. Geophys. Research, v. 75, p. 886-902.

Ernst, W. G., Seiki, Y., Onuki, H., and Gilbert, M. C., 1970, Comparative study of low-grade metamorphism in the California Coast Ranges and the Outer Metamorphic Belt of Japan: Geol. Soc. America Mem. 124, 276 p.

Evans, J. G., 1966, Structural analysis and movements of the San Andreas fault zone near Palmdale, southern California: California Univ., Los Angeles, Ph. D. thesis, 186 p.

_____1978, Postcrystalline deformation of the Pelona Schist bordering Leona Valley, southern California: U.S. Geol. Survey Prof. Paper. (In press)

Ford, T. D., and Breed, W. J., 1976, The younger Precambrian rocks of the Grand Canyon, _in_ Breed, W. J., and Roat, Evelyn, eds., Geology of the Grand Canyon: Mus. Northern Arizona/Flagstaff and Grand Canyon Nat. History Assoc., p. 21-33.

Garfunkel, Z., 1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent regions: Geol. Soc. America Bull., v. 85, p. 1931-1944.

Garrison, R. E., 1974, Radiolarian cherts, pelagic limestones, and igneous rocks in eugeosynclinal assemblages: Internat. Assoc. Sedimentologists Spec. Pub., v. 1, p. 367-399.

Gastil, R. G., and Krummenacher, D., 1977, Reconnaissance geology of coastal Sonora between Puerto Lobos and Bathia Kino: Geol. Soc. America Bull., v. 88, p. 189-198.

Gastil, R. G., Krummenacher, D., and students, 1974, Reconnaissance geologic map of coastal Sonora between Puerto Lobos and Bahia Kino: Geol. Soc. America, Map and Chart Ser., MC-16.

Gastil, R. G., Phillips, R. P., and Allison, E. C., 1975, Reconnaissance geology of the State of Baja California: Geol. Soc. America Mem. 140, 170 p.

Graham, C. M., 1975, Inverted metamorphic zonation and mineralogy of the Pelona Schist, Sierra Pelona, Transverse Ranges [abs.]: Geol. Soc. America Abs. with Programs, v. 7, no. 3, p. 321-322.

Graham, C. M., and England, P. C., 1976, Thermal regimes and regional metamorphism in the vicinity of overthrust faults--An example of shear heating and inverted metamorphic zonation from southern California: Earth and Planetary Sci. Letters, v. 31, p. 142-152.

Graham, S. A., and Dickinson, W. R., 1978, Evidence for 115 kilometers of right slip on the San Gregorio-Hosgri fault trend: Science, v. 199, p. 179-181.

Grose, L. T., 1959, Structure and petrology of the northeast part of the Soda Mountains, San Bernardino County, California: Geol. Soc. America Bull., v. 70, p. 1509-1547.

Hamilton, Warren, 1964, Geologic map of the Big Maria Mountains NE quadrangle, Riverside County, California, and Yuma County, Arizona: U.S. Geol. Survey Geol. Quad. Map GQ-350.

_____1969a, Mesozoic California and the underflow of the Pacific mantle: Geol. Soc. America Bull., v. 80, p. 2409-2430.

_____1969b, The volcanic central Andes--A modern model for the Cretaceous batholiths and tectonics of western North America: Oregon Dept. Geology and Mineral Industries Bull. 65, p. 175-184.

_____1971, Tectonic framework of southeastern California [abs.]: Geol. Soc. America Abs. with Programs, v. 3, no. 2, p. 130-131.

Hamilton, Warren, and Myers, W. B., 1966, Cenozoic tectonics of the western United States: Rev. Geophysics, v. 4, no. 4, p. 509-549.

Hansen, Edward, 1967, Methods of deducing slip-line orientations from the geometry of folds: Carnegie Inst. Washington Yearbook 65, p. 387-405.

Harvill, L. L., 1969, Deformational history of the Pelona Schist, northwestern Los Angeles County, California: California Univ., Los Angeles, Ph. D. thesis, 117 p.

Haxel, G. B., 1977, The Orocopia Schist and the Chocolate Mountain thrust, Picacho-Peter Kane Mountain area, southeasternmost California: California Univ., Santa Barbara, Ph. D. thesis, 277 p.

Haxel, Gordon, and Dillon, John, 1977, The Pelona and Orocopia Schists and the Proto-San Andreas fault of southern California [abs.]: Geol. Soc. America Abs. with Programs, v. 9, no. 4, p. 423-433.

Hayes, P. T., 1970, Cretaceous paleogeography of southeastern Arizona and adjacent areas: U.S. Geol. Survey Prof. Paper 658-B, 42 p.

Hershey, O. H., 1912, The Belt and Pelona series: Am. Jour. Sci., ser. 4, v. 34, p. 263-273.

Higgins, M. W., 1971, Cataclastic rocks: U.S. Geol. Survey Prof. Paper 687, 97 p.

Hsu, K. J., 1955, Granulites and mylonites of the region about Cucamonga and San Antonio Canyons, San Gabriel Mountains, California: California Univ. Pubs. Geol. Sci., v. 30, p. 223-324.

_____1971, Franciscan melanges as a model for eugeosynclinal sedimentation and underthrusting tectonics: Jour. Geophys. Research, v. 76, p. 1162-1170.

Hsu, K. J., Edwards, G., and McLaughlin, W. A., 1963, Age of the intrusive rocks of the southeastern San Gabriel Mountains, California: Geol. Soc. America Bull., v. 74, p. 507-512.

Huffman, O. F., Turner, D. L., and Jack, R. N., 1973, Offset of late Oligocene-early Miocene volcanic rocks along the San Andreas fault in central California: Stanford Univ. Pubs. Geol. Sci., v. 13, p. 368-371.

Hulin, C. D., 1925, Geology and ore deposits of the Randsburg quadrangle, California: California Mining Bur. Bull 95, 152 p.

Hunt, C. B., and Mabey, D R., 1966, Stratigraphy and structure of Death Valley, California: U.S. Geol. Survey Prof. Paper 494-A, 162 p.

Jennings, C. W., 1967, Geologic map of California, Olaf P. Jenkins edition--Salton Sea sheet: California Div. Mines and Geology, scale 1:250,000.

Jennings, C. W., 1973, Preliminary fault and geologic map of southern California: California Div. Mines and Geology Prelim. Rept. 13, map, scale 1:750,000.

Jennings, C. W., and Strand, R. G., 1969, Geologic map of California, Olaf P. Jenkins edition--Los Angeles sheet: California Div. Mines and Geology, scale 1:250,000.

Jones, D. L., Rangin, Claude, and Blake, M. C., Jr., 1976, The four Jurassic belts of northern California and their significance to the geology of the southern California Borderland, in Howell, D. G., ed., Aspects of the geologic history of the California continental borderland: Am. Assoc. Petroleum Geologists, Pacific Sec., Misc. Pub. 24, p. 343-362.

Kistler, R. W., 1974, Phanerozoic batholiths in western North America: Ann. Rev. Earth and Planetary Sci., v. 2, p. 403-418.

Kistler, R. W., and Peterman, Z. E., 1978, Reconsruction of crustal blocks of California on the basis of initial strontium isotopic compositions of Mesozoic granitic rocks: U.S. Geol. Survey Prof. Paper. (In press)

Larsen, E. S., Jr., 1948, Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: Geol. Soc. America Mem. 29, 182 p.

Matthews, Vincent, 3d, 1976, Correlation of Pinnacles and Neenach volcanic formations and their bearing on San Andreas fault problem: Am. Assoc. Petroleum Geologists Bull., v. 60, no. 12, p. 2128-2141.

Merriam, R. H., 1958, Geology of Santa Ysabel quadrangle, San Diego County, California, in Geology and mineral resources of Santa Ysabel quadrangle, San Diego County, California: California Div. Mines Bull. 177, p. 7-20.

_____1972a, Reconnaissance geologic map of the Sonoyta quadrangle, northwest Sonora, Mexico: Geol. Soc. America Bull., v. 83, p. 3533-3536.

_____1972b, Evidence for 200 miles of right-lateral displacement on faults of the San Andreas zone in southwest Sonora, Mexico [abs.]: Geol. Soc. America Abs. with Programs, v. 4, no. 3, p. 198.

Miller, F. K., and McKee, E. H., 1971, Thrust and strike-slip faulting in the Plomosa Mountains, southwestern Arizona: Geol. Soc. America Bull., v. 82, p. 717-722.

Miller, F. K., and Morton, D. M., 1975, K-Ar geochronology of the eastern Transverse Ranges [abs.]: Geol. Soc. America Abs. with Programs, v. 7, no. 3, p. 348.

_____1977, Comparison of granitic intrusions in the Pelona and Orocopia Schists, southern California: U.S. Geol. Survey Jour. Research, v. 5, no. 5, p. 643-649.

_____1978, K-Ar geochronology of the eastern Transverse Ranges and southern Mojave Desert, southern California: U.S. Geol. Survey Jour. Research. (In press)

Miller, W. J., 1946, Crystalline rocks of southern California: Geol. Soc. America Bull., v. 57, p. 457-540.

Miyashiro, A., 1973, Metamorphism and metamorphic belts: New York, John Wiley & Sons, A Halsted Press Book, 492 p.

Muehlberger, W. R., and Hill, H. S., 1958, Geology of the central Sierra Pelona, Los Angeles County, California: Am. Jour. Sci., v. 256, p. 630-643.

Murray, K. S., and Crowe, B. M., 1976, Geology of the northern and central Chocolate Mountains, southeastern California [abs.]: Geol. Soc. America Abs. with Programs, v. 8, no. 6, p. 1023-1024.

Nilsen, T. H., and Clarke, S. H. Jr., 1975, Sedimentation and tectonics in the early Tertiary continental borderland of central California: U.S. Geol. Survey Prof. Paper 925, p. 1-64.

Noble, L. F., 1954, The San Andreas fault zone from Soledad Pass to Cajon Pass, California, in Chap. 4 of Jahns, R. H., ed., Geology of southern California: California Div. Mines Bull. 170, p. 37-48.

Nur, A., and Ben-Avraham, Z., 1978, Lost Pacifica continent: Nature, v. 270, p. 41-43.

Oxburgh, E. R., 1972, Flake tectonics and continental collision: Nature, v. 239, p. 202-204.

Pelka, G. J., 1973a, Geology of the McCoy and Palen Mountains, southeastern California: California Univ., Santa Barbara, Ph. D. thesis, 162 p.

_____1973b, Geology of the McCoy and Palen Mountains, southeastern California [abs.]: Geol. Soc. America Abs. with Programs, v. 5, no. 1, p. 89-90.

Platt, J. P., 1975, Metamorphic and deformational processes in the Franciscan complex, California--Some insights from the Catalina Schist terrane: Geol. Soc. America Bull., v. 86, p. 1337-1347.

_____1976, The petrology, structure, and geologic history of the Catalina Schist terrain, southern California: California Univ. Pub. Geol. Sci., v. 112, 111 p.

Poole, F. G., 1974, Flysch deposits of Antler foredeep, western United States, in Dickinson, W R., ed., Tectonics and sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 22, p. 58-82.

Raleigh, C. B., 1958, Structure and petrology of a part of the Orocopia Schists: Claremont Graduate School, Claremont, Calif., M.A. thesis, 64 p.

Rogers, T. H., 1967, Geologic map of California, Olaf P. Jenkins edition--San Bernardino sheet: California Div. Mines and Geology, scale 1:250,000.

Ross, D. C., 1972a, Petrographic and chemical reconnaissance of some granitic and gneissic rocks near the San Andreas fault from Bodega Head to Cajon Pass, California: U.S. Geol. Survey Prof. Paper 698, 92 p.

_____1972b, Geologic map of the pre-Cenozoic basement rocks, Gabilan Range, Monterey and San Benito Counties, California: U.S. Geol. Survey Misc. Field Studies Map MF-357, scale 1:125,000.

_____1976, Metagraywacke in the Salinian block, central Coast Ranges, California--And a possible correlative across the San Andreas fault: U.S. Geol. Survey Jour. Research, v. 4, p. 683-696.

_____1977, Pre-intrusive metasedimentary rocks of the Salinian block, California--A paleotectonic dilemma, in Stewart, J. H., and Stevens, C. H., and Fritsche, A. E., eds., Paleozoic paleogeography of the western United States, Pacific Paleogeography Symposium 1: Los Angeles, Calif., Soc. Econ. Paleontologists and Mineralogists, Pacific Sec., p. 371-380.

_____1978, The Salinian block--A Mesozoic granitic orphan: This volume.

Salas, G. A., 1968, Areal geology and petrology of the igneous rocks of the Santa Ana region, northwest Sonora: Bol. Soc. Geologic Mexicana, v. 31, p. 11-64.

Salas, G. P., Cordoba, M. D. A., and Avila, J. L., 1974, General aspects of batholiths and intrusive rocks of western Mexico: Pacific Geology, v. 8, p. 67-72.

Schwarcz, H. P., 1969, Pre-Cretaceous sedimentation in the Winchester area, northern Peninsular Ranges, California: Geol. Soc. America Spec. Paper 100, 63 p.

Shride, A. F., 1967, Younger Precambrian geology in southern Arizona: U.S. Geol. Survey Prof. Paper 566, 89 p.

Silver, L. T., 1971, Problems of crystalline rocks of the Transverse Ranges [abs.]: Geol. Soc. America Abs. with Programs, v. 3, no. 2, p. 193-194.

Silver, L. T., and Anderson, T. H., 1974, Possible left-lateral early to middle Mesozoic disruption of the southwestern North American craton margin [abs.]: Geol. Soc. America Abs. with Programs, v. 6, no. 7, p. 955-956.

Silver, L. T., Anderson, C. A., Crittenden, M., and Robertson, J. M., 1977, Chronostratigraphic elements of the Precambrian rocks of the southwestern and far western United States [abs.]: Geol. Soc. America Abs. with Programs, v. 9, no. 7, p. 1176-1177.

Simpson, E. C., 1934, Geology and mineral resources of the Elizabeth Lake quadrangle, California: California Jour. Mines and Geology, v. 30, no. 4, p. 371-415.

Smith, G. I., 1962, Large lateral displacement on the Garlock fault, California, as measured from offset dike swarm: Am. Assoc. Petroleum Geologists Bull., v. 46, p. 85-104.

Stewart, J. H., and Poole, F. G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran miogeocline, Great Basin, western United States: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 22, p. 28-57.

_____1975, Extension of the Cordilleran miogeosynclinal belt to the San Andreas fault, southern California: Geol. Soc. America Bull., v. 86, p. 205-212.

Suppe, John, 1972, Interrelationships of high-pressure metamorphism, deformation and sedimentation in Franciscan tectonics, U.S.A.: Internat. Geol. Cong., 24th, Montreal, Canada, 1972, sec. 3, p 552-559.

Suppe, John, and Armstrong, R. L., 1972, Potassium-argon dating of Franciscan metamorphic rocks: Am. Jour. Sci., v. 272, p. 217-233.

Theodore, T. G., 1970, Petrogenesis of mylonites of high metamorphic grade in the Peninsular Ranges of southern California: Geol. Soc. America Bull., v. 81, p. 435-450.

Vargo, J. M., 1972, Structural geology of a portion of the eastern Rand Mountains, Kern and San Bernardino Counties: Univ. Southern California, Los Angeles, Calif., M.A. thesis, 117 p.

Walker, R. G., 1967, Turbidite sedimentary structures and their relationship to proximal and distal depositional environments: Jour. Sed. Petrology v. 37, p. 25-43.

Wallace, R. E., 1949, Structure of a portion of the San Andreas rift in southern California: Geol. Soc. America Bull, v. 60, p. 781-806.

Wiese, J. H., 1950, Geology and mineral resources of the Neenach quadrangle, California: California Div. Mines Bull. 153, 53 p.

Wilson, E. D., 1933, Geology and mineral deposits of southern Yuma County, Arizona: Arizona Bur. Mines Bull., v. 134, 234 p.

_____1960, Geologic map of Yuma County, Arizona: Arizona Bu. Mines, Arizona Univ., map, scale 1:375,000.

Wise, S. W., Jr., and Weaver, F. M., 1974, Chertification of oceanic sediments: Internat. Assoc. Sedimentologists Spec. Pub., v. 1, p. 301-326.

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ABSTRACT

The Geology of the Cargo Muchacho and Southern Chocolate Mountains, Southeasternmost California

by

John Thomas Dillon

Mapping in the Cargo Muchacho and southern Chocolate Mountains, ranges just east of the San Andreas fault in southeasternmost California, was directed principally at unraveling the histories of the late Mesozoic Chocolate Mountain thrust and Orocopia Schist, mid-Tertiary magmatism, and the late Cenozoic San Andreas fault system. Geologic mapping, structural, stratigraphic, petrographic, geochemical, and geochronologic techniques were used in deciphering the geologic events and features described, starting with the oldest, below.

Rocks in the upper plate of the Chocolate Mountain thrust consist of pre-Phanerozoic(?) mafic meta-igneous gneiss and banded and laminated paragneisses,which locally are intruded by pre-Phanerozoic porphyritic granite, now augen gneiss. These gneisses appear to be an extension of a pre-Phanerozoic complex from southwestern Arizona into southeasternmost California, where at least

five types of Mesozoic granitic rocks were intruded into the complex prior to thrusting. The oldest granitic intrusion, early Triassic garnet-bearing granodiorite, is correlated with the Lowe Granodiorite of the San Gabriel Mountains. Jurassic quartz monzonite and granite, and undated granodiorite, were subsequently emplaced, metamorphosed at the amphibolite facies, and intruded by leucogranite and quartz diorite. During emplacement, the Jurassic granite of the Cargo Muchacho Mountains leached its quartzofeldspathic wall rocks to produce a quartz-kyanite assemblage.

These Mesozoic granitic gneisses may represent the Cordilleran Mesozoic batholithic belt in southeasternmost California.

All the upper plate gneisses have a strong metamorphic fabric imparted during late Mesozoic amphibolite-facies metamorphism. This fabric is parallel to the Chocolate Mountain thrust and the metamorphic fabric of the Orocopia Schist of the lower plate. This geometry is interpreted as indicating a relation between movement on the thrust and metamorphism of the plates. This interpretation is supported by the inverted metamorphic convergence near the thrust between the greenschist-facies Orocopia Schist and the amphibolite-facies upper-plate gneisses.

The Chocolate Mountain thrust is a folded, gently to moderately dipping surface with cataclastic gneiss immediately above and neomineralized schist below. Drag folds in the cataclastic rocks are interpreted as indicating north-northeast movement of the upper plate.

It is hypothesized that the protoliths of the Orocopia Schist (graywacke, chert, greenstone, and serpentinite) were deposited in an ensimatic basin to the east of an ensialic ridge (upper-plate gneisses) which moved northeasterly over the protolith during latest Mesozoic thrusting.

Mid-Tertiary calc-alkaline volcanic and epizonal plutonic rocks in the southern Chocolate Mountains crop out in a pattern suggesting that they may form part of a ring dike fault system 18 miles (30 kms) in diameter. Fine-grained phases of the plutons feed chemically and petrographically analogous volcanic rocks. Similar magmatic rocks extend northwestward from southwestern Arizona to the Orocopia Mountains. The genesis of this magmatic belt may be related to the subduction of the Farallon plate.

Late Cenozoic deposits of the Cargo Muchacho and southern Chocolate Mountains overlie older rocks with angular unconformity. They consist of middle to late

Miocene fanglomerates and interbedded olivine basalts, unconformably overlain locally by the early Pliocene estuarine Bouse Formation, which in turn is unconformably overlain by late Pliocene to Quaternary alluvial deposits. The Miocene fanglomerates, interbedded basalts, and Bouse shoreline are probably the displaced continuations of the Coachella Fanglomerate and Basalt, and shoreline of the marine Imperial Formation as judged from the chemistry and petrography of clasts in the fanglomerates and of the basalts, and from the shoreline age and the source of the marine sediments. The correlation requires 110 ± 10 miles (180 ± 20 km) of right slip on the North Branch of the San Andreas fault alone since deposition of the marine and estuarine units in the proto-Gulf of California. Late Pliocene and Quarternary alluviation from the youthful Colorado River and by local drainages filled the proto-Gulf.

Tectonic Setting and Lithology of the Winterhaven Formation: A New Mesozoic Stratigraphic Unit in Southeasternmost California and Southwestern Arizona

By GORDON B. HAXEL, RICHARD M. TOSDAL, and JOHN T. DILLON

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By Gordon B. Haxel, Richard M. Tosdal, *and* John T. Dillon[1]

Abstract

A 450-m-thick sequence of distinctive, variably metamorphosed Jurassic(?) supracrustal rocks in southeasternmost California and southwesternmost Arizona is herein named the Winterhaven Formation. The formation consists of a basal dacite member, which evidently rests depositionally on and interfingers with Jurassic rhyodacitic metavolcanic rocks, a medial quartz arenite member, and an upper argillitic siltstone member. The formation is unconformably overlain by Tertiary rocks. Complex relations of the Winterhaven Formation to the late Mesozoic Orocopia Schist and overlying Chocolate Mountains thrust represent the superimposed effects of several late Mesozoic to late Tertiary deformational episodes. Significant lithologic contrasts indicate that the Winterhaven Formation is not related to the protolith of the Orocopia Schist. The Winterhaven Formation evidently was originally part of the upper plate of the Chocolate Mountains thrust and was subsequently placed directly over the Orocopia Schist along the Sortan fault, a newly recognized late Mesozoic low-angle normal fault. Because this juxtaposition and later metamorphism and intrusion by granite occurred before about 60 m.y. ago, the metamorphic age of the Orocopia Schist must be no younger than Late Cretaceous, rather than early Tertiary. The Winterhaven Formation has several similarities to, and may correlate with, the lower part of the Jurassic and (or) Cretaceous McCoy Mountains Formation.

INTRODUCTION

Geologic mapping and reconnaissance in southeastern California and southwestern Arizona from 1972 to 1985 have revealed a distinctive and widespread but previously unrecognized Mesozoic, probably Jurassic, lithostratigraphic unit (fig. 1). This sequence of siliciclastic sedimentary rocks, with a basal volcanic unit, is here named the Winterhaven Formation. The formation is important as part of the Mesozoic supracrustal record and because of its relations to the enigmatic Orocopia Schist.

Elucidating the Mesozoic tectonic history of the region in the southeast corner of California and southwest corner of Arizona is substantially a matter of determining the temporal and tectonic relations among several major Mesozoic supracrustal lithostratigraphic units (Crowell, 1981). These units are: (1) The late Mesozoic Orocopia Schist, composed of thoroughly metamorphosed graywacke and minor basalt, mudstone, chert, and peridotite (Haxel and Dillon, 1978); (2) the Jurassic and (or) Cretaceous McCoy Mountains Formation of Harding and Coney (1985), a 7-km-thick continental clastic sedimentary sequence; (3) Jurassic and Jurassic(?) silicic and subordinate intermediate volcanic and hypabyssal rocks (Tosdal, 1982); and (4) the Jurassic(?) Winterhaven Formation and similar strata.

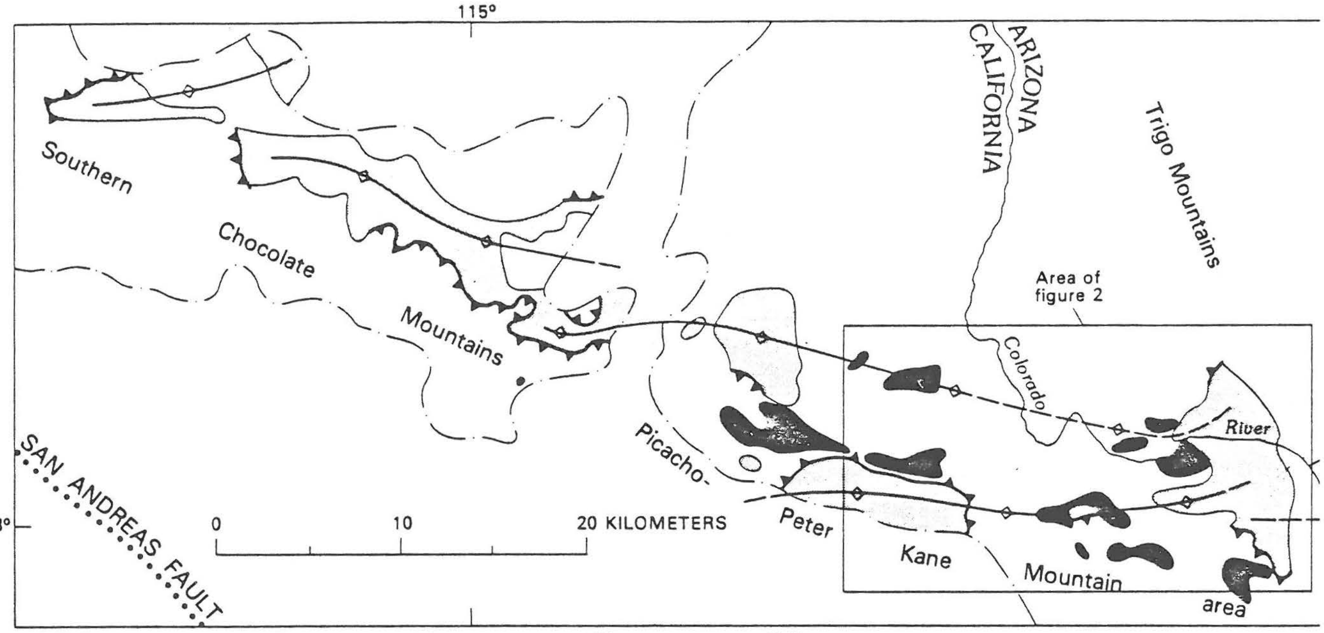
The purpose of this report is to summarize the extent and lithology of the Winterhaven Formation and to describe and discuss its relations to other Mesozoic lithotectonic units, particularly the Orocopia Schist. Most of the information presented here was gathered during mapping of the Picacho-Peter Kane Mountain area of southeasternmost California (fig. 2) as part of a study of the Orocopia Schist and related Chocolate Mountains thrust fault (Haxel, 1977), and during later mapping of the adjoining area to the north by R.M. Tosdal and D.R. Sherrod (unpub. data, 1982-85). The stratigraphy and sedimentary petrology of the Winterhaven Formation have yet to be studied in detail. The formation is named after a small California town just north of Yuma, Ariz.

Previous mention of some of the rocks here assigned to the Winterhaven Formation is restricted to brief descriptions by Olmsted and others (1973, p. 32) and Morton (1977, p. 16); in both of these reports, the rocks are tentatively correlated with the McCoy Mountains Formation. The name Winterhaven Formation was first used informally by Haxel (1977, app. 2).

ACKNOWLEDGMENTS

The presence in the Picacho area of supracrustal rocks intermediate in metamorphic grade between the Orocopia Schist and the middle Tertiary volcanic and sedimentary rocks was first pointed out to us by John Crowell and Perry Ehlig, both of whom have been of considerable help in our efforts to understand the Winterhaven Formation. We have also benefited from discussions with Bill Bagby, Peter Coney, Bruce

[1]Alaska Division of Geological and Geophysical Surveys.



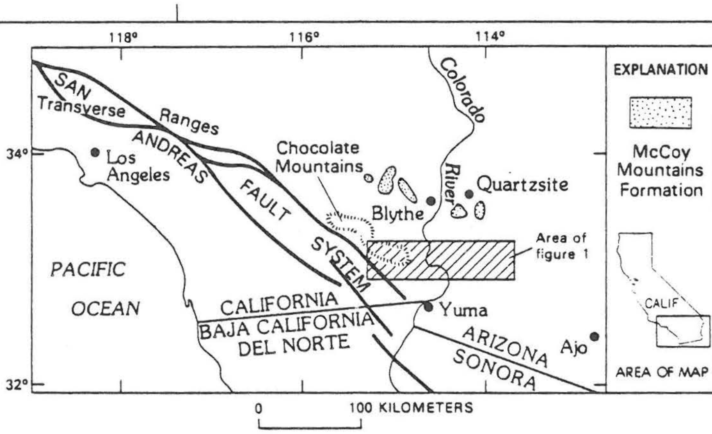
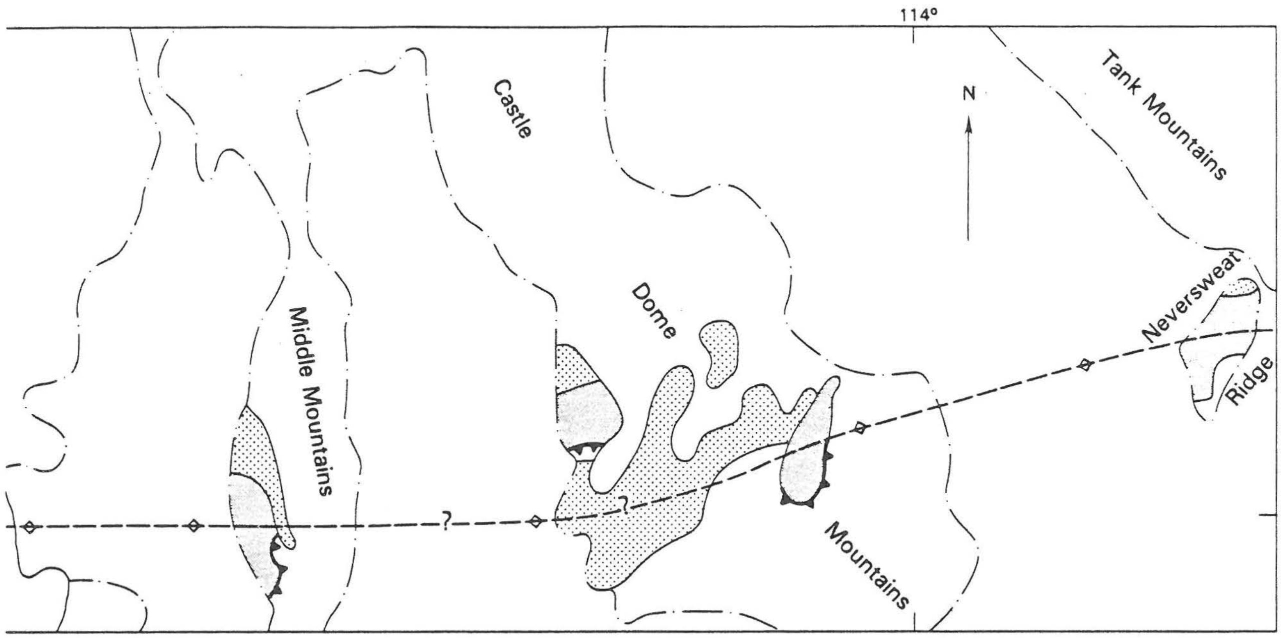


Figure 1. Distribution of the Winterhaven Formation, the Orocopia Schist, and the Chocolate Mountains thrust along the Chocolate Mountains anticlinorium in southeastern California and southwestern Arizona. Strata similar to the Winterhaven Formation in southwestern Arizona east of the Trigo Mountains are informally designated as the sedimentary and volcanic rocks of Slumgullion. Complex map relations among the Orocopia



EXPLANATION

Winterhaven Formation (Jurassic?)

Sedimentary and volcanic rocks of Slumgullion (Jurassic?)

Orocopia Schist (late Mesozoic)

Contact

Fault—Dotted where concealed

Chocolate Mountains thrust—Sawteeth on upper plate

Antiform of Chocolate Mountains anticlinorium—Dashed where approximately located; queried where uncertain

Outline of mountainous area

Dillon, 1976

Parker, 1966; R.M. Tosdal and D.R. Sherrod [1982-85]

G.B. Haxel, M.J. Grubensky, J.T. Dillon, and R.D. Koch [1973-85]; Wilson and others, 1969

Haxel, 1977

Crowe, 1973; Haxel, 1977

SOURCES OF GEOLOGIC DATA

Schist, Chocolate Mountains thrust, and Winterhaven Formation cannot be portrayed at this scale (see figs. 2, 3, 7, 8). Inset map shows location of map area and of outcrop area of the McCoy Mountains Formation of Harding and Coney (1985). In "Sources of Geologic Data," dates in brackets refer to unpublished mapping and (or) reconnaissance.

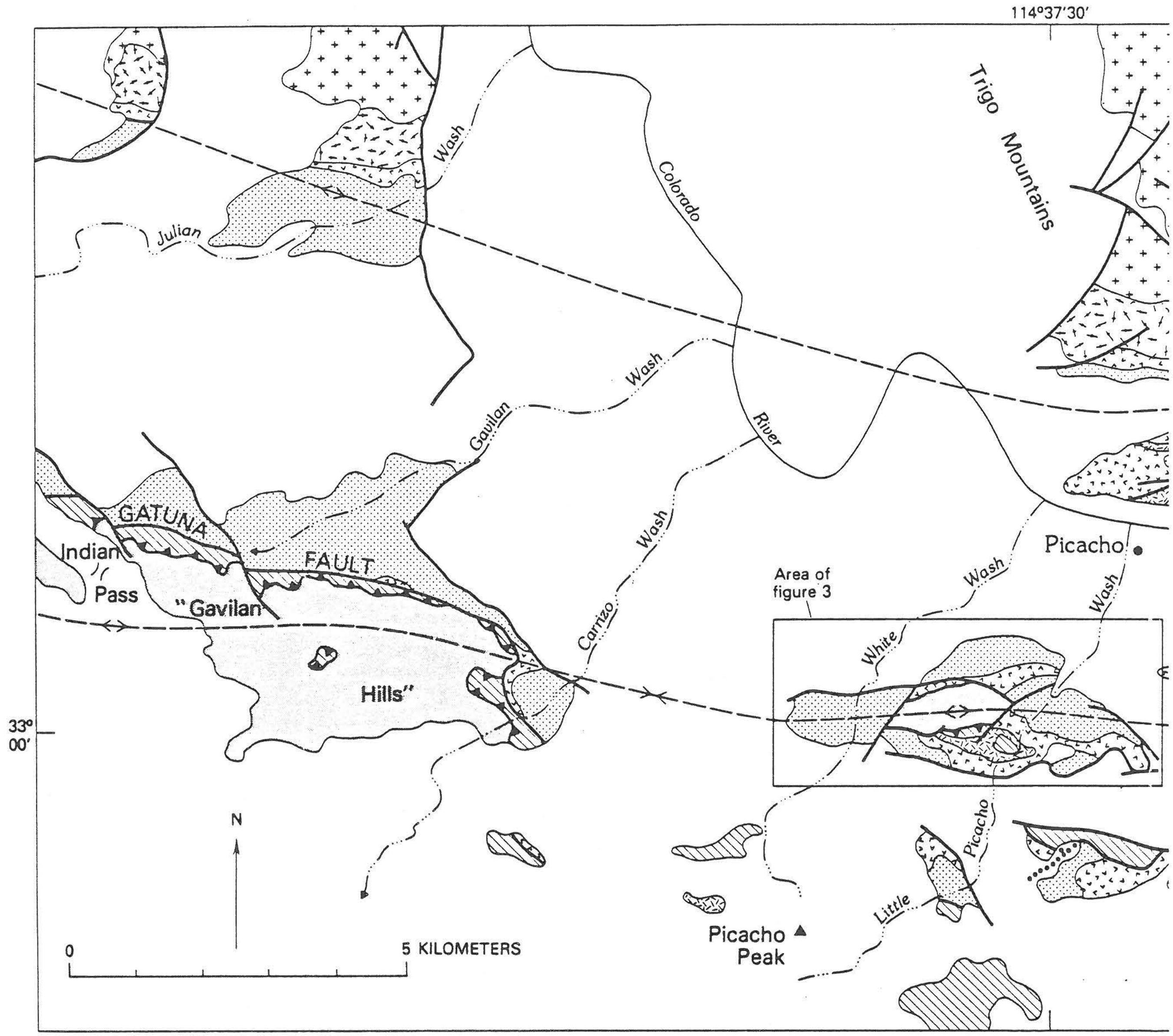
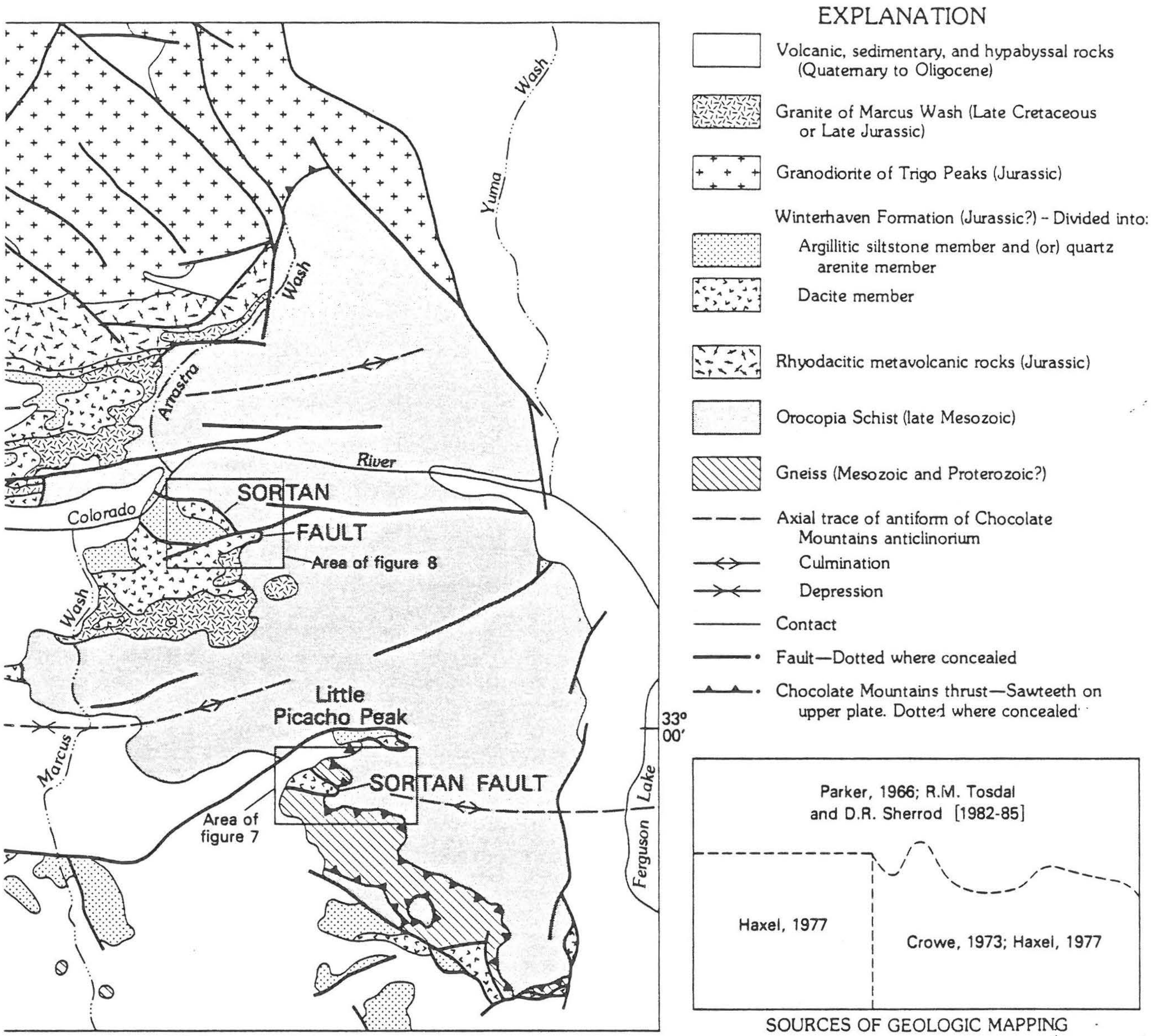


Figure 2. Pre-middle Tertiary rocks in the area between Indian Pass and Ferguson Lake, and Julian Wash and Arrastra Wash areas, southeastern California and southwestern Arizona (see fig. 1 for location). The granite of Marcus Wash may locally include some unmapped bodies of rhyodacitic metavolcanic rocks. "Gavilan Hills" is an



informal name used to designate the hills south of the Gatuna fault between Carrizo Wash and Indian Pass. Picacho is headquarters of the Picacho State Recreation Area. In "Sources of Geologic Mapping," dates in brackets refer to unpublished mapping.

Crowe, Bill Dickinson, Eric Frost, Mike Grubensky, Lucy Harding, Keith Howard, Carl Jacobson, Richard Koch, Donna Martin, Dan May, Frank Olmsted, Gary Pelka, Bob Powell, Lee Silver, and Paul Stone; and from the cooperation of the personnel of Picacho State Recreation Area. Much of this work was supported by U.S. National Science Foundation Grants EAR 71-00498 (Crowell) and EAR 81-15730 (Crowell).

GEOLOGIC SETTING

The dominant late Mesozoic tectonic feature of the Picacho-Peter Kane Mountain area and adjacent southern Chocolate Mountains (Dillon, 1976) is the Chocolate Mountains thrust, along which Mesozoic (and Proterozoic?) gneissic and granitoid rocks overlie the late Mesozoic Orocopia Schist. This regional thrust fault is exposed on the flanks, and the Orocopia Schist in the core, of the Tertiary Chocolate Mountains anticlinorium, which extends some 110 km from the central Chocolate Mountains east to Neversweat Ridge (fig. 1). This narrow, complexly faulted anticlinorium consists of several aligned, subparallel, or echelon antiformal segments.

Two subparallel east-trending antiforms control the distribution of exposures of the Winterhaven Formation and the Orocopia Schist within the Picacho-Peter Kane Mountain area and adjoining areas. The southern antiform extends from the area west of Indian Pass eastward toward Ferguson Lake; three separate exposures of the Orocopia Schist, overlain by segments of the Chocolate Mountains thrust, mark three culminations along the antiformal trace (fig. 2). The Winterhaven Formation is exposed along the flanks of the antiform and on the noses of the culminations. The northern antiform, likewise marked by culminations exposing the Orocopia Schist and (or) the Winterhaven Formation, extends from the easternmost southern Chocolate Mountains eastward through Peter Kane Mountain and the Julian Wash area to the southern Trigo Mountains. This antiform is disrupted by numerous high- to low-angle Tertiary faults and is less clearly defined than the southern antiform. In several areas along these antiforms, the Winterhaven Formation is folded into smaller, open to tight anticlines and synclines with wavelengths of about 0.5 to 1 km; both late Mesozoic and middle Tertiary folds are present.

In most areas, the basal contact of the Winterhaven Formation is, or evidently was, a newly recognized late Mesozoic low-angle normal fault along which the Winterhaven Formation overlies both plates of the Chocolate Mountains thrust. Field relations in a few areas indicate that at its base the Winterhaven Formation originally stratigraphically overlaid Jurassic(?) rhyodacitic volcanic rocks that form part of the upper plate of the Chocolate Mountains thrust. In most places, these two types of Mesozoic basal contacts of the Winterhaven Formation have been modified or excised by Tertiary faults. The Winterhaven Formation is intruded by the epizonal granite of Marcus Wash (fig. 2). This granite is younger than the 163-m.y. (Middle or Late Jurassic) minimum protolith age and maximum metamorphic age of the Orocopia Schist (Mukasa and others, 1984), which it also intrudes, and older than earliest Tertiary K-Ar minimum ages of about 60 m.y. (Frost and Martin, 1983). The granite of Marcus Wash is considered to be either Late Jurassic or Late Cretaceous because igneous rocks of both these ages are common in the southeastern California-southwestern Arizona region. The Winterhaven Formation is overlain with angular unconformity by Oligocene to Holocene volcanic and sedimentary rocks (Crowe, 1973; Dillon, 1976; Crowe and others, 1979).

STRATIGRAPHY AND LITHOLOGY

The thickest section of known stratigraphic position is designated as the type section of the Winterhaven Formation (fig. 3). This section, which forms the northern limb of an anticline just west of Little Picacho Wash (in the southeast corner of the Picacho SW 7-1/2-minute quadrangle), consists of three members, with a total exposed thickness of about 450 m (fig. 4). Except where strongly metamorphosed, most of the Winterhaven Formation is typically dull purplish gray in outcrop.

The basal unit of the Winterhaven Formation is a dacite member, somewhat more than 80 m thick as presently exposed, composed of massive, purple and dark-brown, strongly altered, aphanitic to sparsely porphyritic rocks of intermediate composition, probably dacite and possibly including some andesite. Phenocrysts of plagioclase, biotite, and (or) another mafic mineral were originally present; the plagioclase and biotite are now completely altered to chlorite, sericite (that is, fine-grained white mica), and opaque minerals. These rather nondescript rocks presumably are largely volcanic flows. Rare beds of coarse-grained volcaniclastic graywacke are interlayered with the volcanic rocks. Near the top of the dacite member, some rocks contain amygdules of quartz or calcite, and there are some layers of dark-gray, very poorly bedded breccia composed of angular fragments (typically approx. 1-3 cm across) of strongly altered, sparsely porphyritic volcanic rock in a matrix of fine-grained sericitic sandstone. Locally this breccia forms a distinct layer, as much as 10 m thick, at the top of the dacite member. The dacite member also includes a few dikes and small, irregular, probably intrusive bodies of grayish-purple porphyry containing epidotized plagioclase laths, as much as 1 cm long, in a groundmass similar to that of the dacitic flows.

The middle unit of the Winterhaven Formation is a quartz arenite member (fig. 5), approximately 60 m thick, consisting chiefly of brown, tan, or white quartz arenite and feldspathic quartz arenite, some of which is slightly sericitic and (or) calcareous. The sandstone is very well indurated, fine to coarse grained (mostly medium grained), and laminated through medium bedded to locally massive. Subordinate rock types interbedded with the quartz arenite are brown sandy limestone, purplish-gray to brown argillitic siltstone, and brown to light-gray, thinly laminated, silty calcareous argillite, which in some places is converted to flaggy phyllite or semischist. At the base of the quartz arenite member, as much as a few meters of

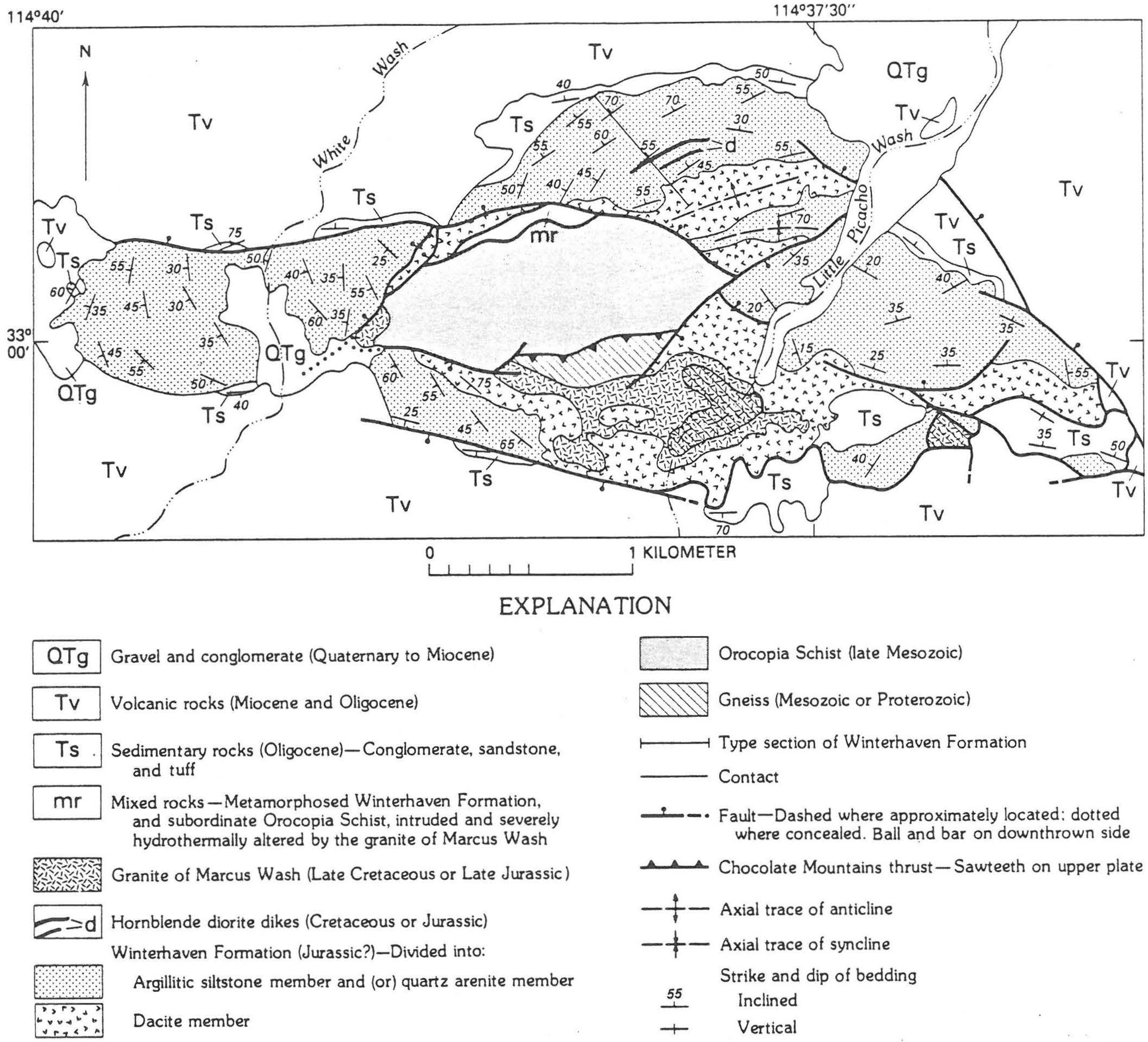


Figure 3. Relations between the Winterhaven Formation and the Orocopia Schist and Chocolate Mountains thrust in the area between Little Picacho Wash and White Wash (from Haxel, 1977, app. 2). See figure 2 for location. Fault-bounded sliver labeled "mr" (mixed rocks) northwest of center of map consists of metasedimentary and metavolcanic rocks of the Winterhaven Formation and subordinate Orocopia Schist, all intruded and severely hydrothermally altered by the granite of Marcus Wash; several faults within this sliver are not shown. Area southeast of map center that consists of gneiss strongly intruded by the granite of Marcus Wash is shown by superposition of patterns for these two units. Some pre-Tertiary contacts between the gneiss, the Winterhaven Formation, and the granite of Marcus Wash in the southeastern part of the map area have been modified or overprinted by Tertiary low-angle normal faults. Distribution of map units Ts and Tv is largely from Crowe (1973).

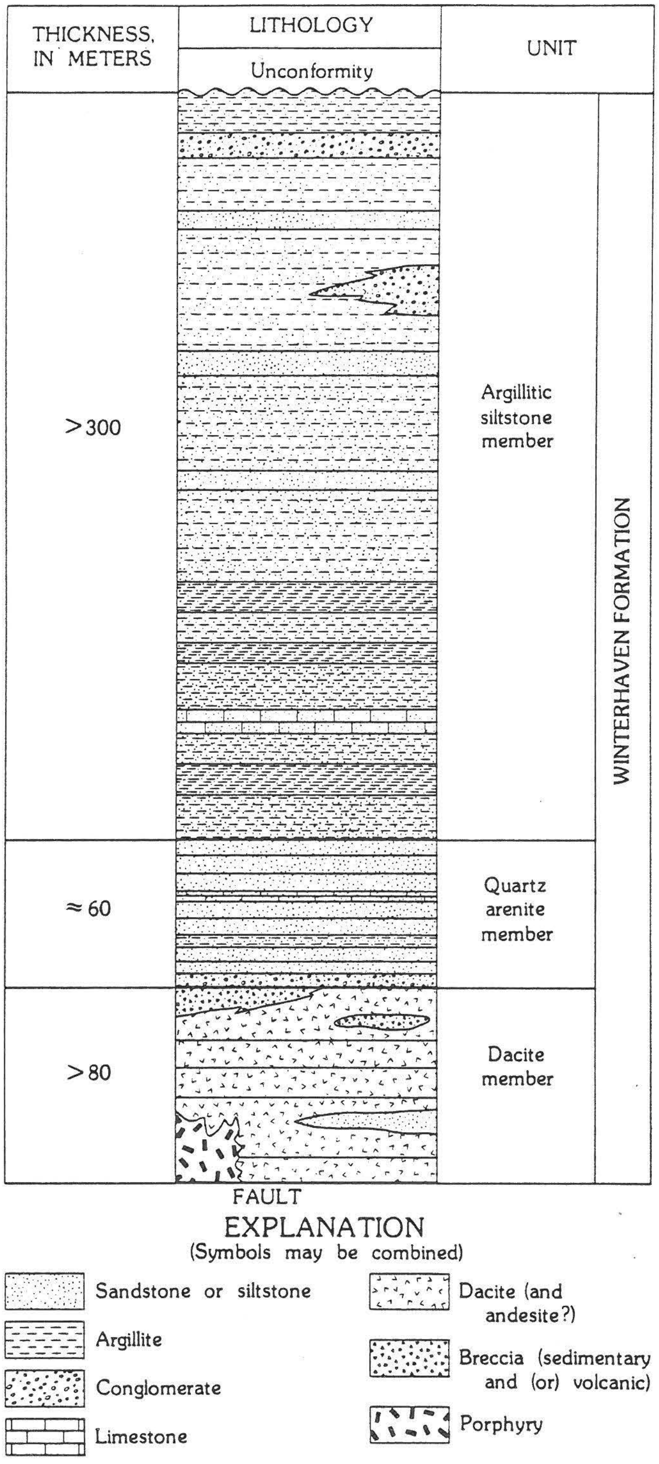


Figure 4. Generalized stratigraphic column for type section of the Winterhaven Formation (see fig. 3 for location). Position and thickness of individual lithologic layers within each of the three major units is schematic only. See text for lithologic descriptions.

brown and purple pebble conglomerate and conglomeratic sandstone are present; in some places these beds are absent, owing to minor faulting localized along the top of the dacite member.

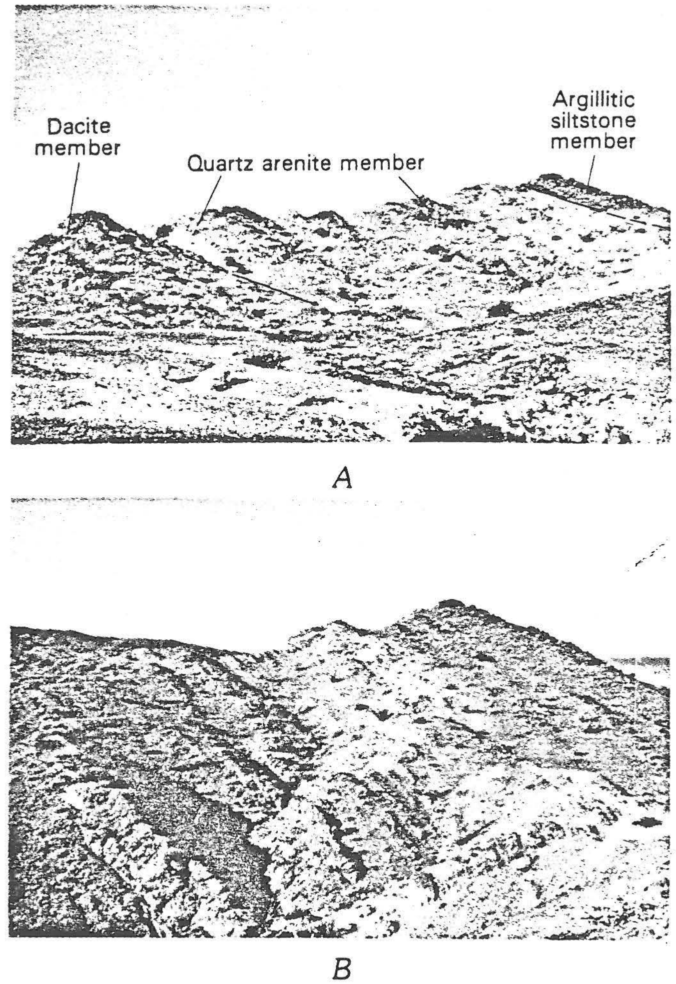


Figure 5. Strata of the Winterhaven Formation, on a ridge about 250 m north-northeast of south end of type section (fig. 3). Both views are approximately westward. A, Upper part of dacite member overlain by quartz arenite member, in turn overlain by base of argillitic siltstone member. Width of view, about 120 m. B, Upper part of quartz arenite member (right side of A); resistant beds of quartz arenite are interbedded with less resistant siltstone, argillite, and limestone. Dark unit capping sequence is base of the argillitic siltstone member, intruded by a hornblende diorite dike (fig. 3).

The quartz arenite member is overlain by an argillitic siltstone member, which in the type section has a maximum exposed thickness of about 300 m. The most common rock type is massive, dark-purple to dark-brown, slightly calcareous argillitic siltstone (micrograywacke), some of which is slightly sandy and some of which contains brown, decimeter-size, discoid calcareous concretions(?). Other abundant rock types are dark-purple and dark-brown silty argillite and brown to gray, medium-grained to very coarse grained, locally pebbly, slightly calcareous graywacke. Relatively minor rock types are dark-purple argillite, dark-brown sandy limestone, tan, slightly argillitic sandstone, and granule to pebble conglomerate with a graywacke matrix. The member as a whole coarsens upward; several rock types coarsen toward the top of the exposed section; and the coarser grained rock types, notably conglomerate, are more common toward the top.

The most common clasts in the conglomerates of the Winterhaven Formation are well-rounded to very well rounded pebbles, typically about 0.5 to 3 cm in diameter, of black, white, brown, and dark-bluish-gray chert or very fine grained quartzite; a few of these pebbles are faintly laminated. Also common are well-rounded clasts, typically 2 to 5 cm in diameter but locally as much as 10 cm in diameter, of fine-grained, vitreous, white or light-gray quartzite. A few conglomerate beds also contain intraformational clasts of purple and brown graywacke, argillite, and siltstone; these large pebbles and small cobbles are typically subrounded to rounded. Small, pebble-size "shale chips" are locally present along bedding planes. Pebbles of dull-red-brown or light-gray, finely porphyritic volcanic rocks and fine-grained, nondescript granitic rocks are rare. No clasts of Orocopia Schist or of gneissic rocks were found, and these are believed to be absent.

All exposures of the Winterhaven Formation within the Picacho-Peter Kane Mountain area and the adjoining area to the north (fig. 2) are lithologically similar to some part of the type section. A 500- or 600-m-thick homoclinal section along Marcus Wash about 4 km southwest of Little Picacho Peak is lithologically similar to the argillitic siltstone member of the type section but has not been correlated with it in detail because of the absence of distinctive marker units in either section. In the area between Carrizo Wash and Gavilan Wash, the quartz arenite member is less than 10 m thick and in most places absent, so that the argillitic siltstone member rests directly on the dacite member.

DISTRIBUTION IN OUTLYING AREAS OF CALIFORNIA; SIMILAR STRATA IN SOUTHWESTERN ARIZONA

Northwest of Indian Pass, the Winterhaven Formation is in part poorly exposed beneath a cover of basalt-boulder talus and has been examined in less detail than farther east. In the southern Chocolate Mountains (fig. 1), rocks similar to the Winterhaven Formation are restricted to a few localized outcrops at the southeast end of the range (Dillon, 1976, p. 203). Strata equivalent to the Winterhaven Formation have not been recognized in the main part of the Chocolate Mountains (fig. 1) nor west of the San Andreas fault. The only other strata similar to the Winterhaven Formation known in California occur within a fault-bounded block in low hills west of the Imperial Dam, 9 km south of Ferguson Lake (fig. 2).

Strata lithologically similar to the Winterhaven Formation are exposed in a large area of the southern Castle Dome Mountains, and in smaller areas in the Middle Mountains and at the north end of Neversweat Ridge (fig. 1). These strata are here referred to as the sedimentary and volcanic rocks of Slumgullion (after Slumgullion Pass in the Castle Dome Mountains). In the southern Castle Dome Mountains, the Slumgullion unit is considerably thicker and more diverse than the Winterhaven Formation (fig. 6). In particular, the Slumgullion unit contains large amounts of rhyodacitic volcanic rocks and coarse conglomerate and sedimentary breccia, rock types that are absent from the Winterhaven Formation. Nonetheless, the Slumgullion section includes lithologic units that are similar to, and occur in the same stratigraphic order as, the three members of the Winterhaven Formation. Provisional lithologic correlations between the Winterhaven Formation and the Slumgullion unit are shown in figure 6; confirmation of these correlations awaits completion of studies in progress of the Slumgullion unit.

METAMORPHISM AND DEFORMATION

The Winterhaven Formation is incipiently to strongly recrystallized, but over much of its outcrop area, mainly along the southern (Indian Pass to Ferguson Lake) antiform, it is not penetratively deformed. Sedimentary rocks in these areas are typically quartzitic or argillitic and show well-preserved sand and silt grains in thin section. The volcanic rocks recrystallized more readily and in some places have been converted to massive, very fine grained granofels composed of relict plagioclase laths (partially to completely altered to epidote and (or) sericite), epidote, chlorite, biotite, opaque minerals, calcite, and sericite, with or without sparse quartz or actinolite.

In the area of Arrastra Wash and lower Marcus Wash (fig. 2), where the Winterhaven Formation is intruded by the granite of Marcus Wash, deformation and metamorphism are more intense. The dacite member has been converted to greenschist-facies schist or hornfelsic granofels, both composed of chlorite and (or) biotite, actinolite, epidote, albite, and quartz; relict plagioclase laths are uncommon. The metasedimentary rocks overlying the dacite member have been converted to quartzofeldspathic phyllite, semischist, and schist containing metamorphic muscovite, biotite, epidote, chlorite, and calcite. The Winterhaven Formation in the Julian Wash area is intermediate in textural and mineralogic metamorphic grade between the generally undeformed rocks along the southern antiform and the more or less schistose rocks of the Arrastra Wash-Marcus Wash area.

In both the Arrastra Wash and Julian Wash areas, the Winterhaven Formation is folded into a south-facing, shallowly plunging, asymmetric syncline with a steep to slightly overturned northern limb and subhorizontal, stratigraphically upright lower limb. Deformation increases in intensity toward the hinge area of the fold, where primary sedimentary and volcanic fabrics are strongly overprinted by cleavage axial-planar with respect to upright to recumbent mesoscopic folds.

In the Arrastra Wash and lower Marcus Wash areas, metamorphism of the Winterhaven Formation is accompanied by remetamorphism of the Orocopia Schist, including reorientation of the regional fabric elements of the schist and development of a new metamorphic fabric with elements parallel to that in the Winterhaven Formation. This second fabric also is widespread in the granite of Marcus Wash. It is

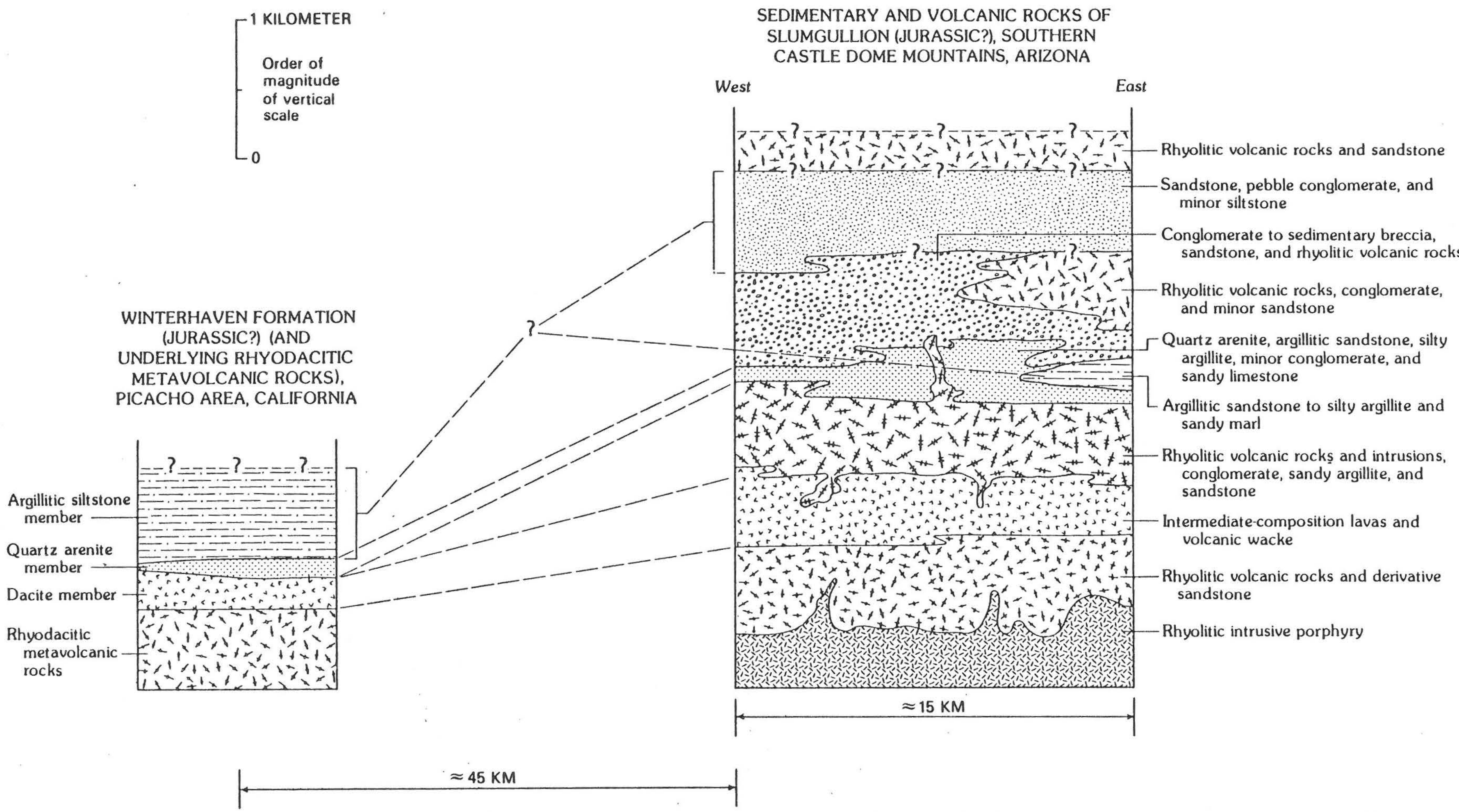


Figure 6. Generalized lithostratigraphic column for the sedimentary and volcanic rocks of Slumgullion and provisional correlations of the Slumgullion unit with the Winterhaven Formation. Arrangement of lithologic subunits within the column schematically represents observed and inferred facies relations within the Slumgullion unit across the 15-km width of the southern Castle Dome Mountains (fig. 1). Details of stratigraphic relations and thicknesses within these incipiently to moderately metamorphosed rocks are considerably more complex and uncertain than portrayed here, and stratigraphy of the upper part of the Slumgullion unit is highly uncertain, owing to intrusion by Jurassic granitoids, faulting, and Neogene volcanic cover. The dacite and quartz arenite members of the Winterhaven Formation and their counterparts within the Slumgullion unit are sufficiently distinctive, in lithology and sequence, that their correlation is straightforward. Correlation of the argillitic siltstone member of the Winterhaven Formation is less clear; it could correspond to either of two Slumgullion subunits.

unclear how much of the low-grade recrystallization of the Winterhaven Formation in the area from upper Marcus Wash westward to Indian Pass (fig. 2) and farther west (fig. 1) occurred during this metamorphic episode and how much occurred earlier, during intrusion of the Jurassic granodiorite (see next section) and (or) during movement on the Chocolate Mountains thrust.

BASAL CONTACT

In the Julian Wash and Arrastra Wash areas (fig. 2), the base of the Winterhaven Formation is a structurally concordant contact along which schistose rocks of the basal dacite member overlie schistose, rhyodacitic, quartz-phenocrystic metavolcanic rocks of presumed Jurassic age. This contact is neither obviously tectonic nor obviously depositional, but several lines of evidence favor the latter interpretation. In the Julian Wash area, rare sandstone interbeds within the dacite member of the Winterhaven Formation appear to have been derived from the underlying rhyodacitic volcanic rocks. In the Arrastra Wash area, the dacite member and the subjacent rhyodacitic metavolcanic rocks locally are interlayered and appear to be interbedded. Finally, in the Slumgullion unit of the southern Castle Dome Mountains, a lithologic unit that includes intermediate volcanic rocks similar to those of the basal member of the Winterhaven Formation clearly is interbedded with rhyodacitic volcanic to metavolcanic rocks (fig. 6). These relations, taken together, strongly suggest that the Winterhaven Formation stratigraphically overlies and interfingers with the rhyodacitic metavolcanic rocks.

These rhyodacitic metavolcanic rocks are intruded by the sphene-bearing hornblende-biotite granodiorite of Trigo Peaks in the southern Trigo Mountains (fig. 2). Both the rhyodacitic volcanic rocks and the granodiorite are considered Jurassic because of similarities in lithology and stratigraphic position to isotopically dated units elsewhere in the region of southern Arizona, southeastern California, and northern Sonora, Mexico (Dillon, 1976; Anderson and Silver, 1978; Crowl, 1979; Haxel and others, 1980, Powell, 1981; Hamilton, 1982; Wright and others, 1981; Tosdal, 1982; L.T. Silver, oral commun., 1983).

AGE

The Winterhaven Formation is older than earliest Tertiary K-Ar dates (Frost and Martin, 1983) and is lithologically dissimilar to any of the major Precambrian or Paleozoic tectonostratigraphic units of the southern Cordillera. Therefore, it is almost certainly of Mesozoic age. The field relations and regional lithologic correlations just described imply a Jurassic age. In the absence of direct paleontologic or isotopic age determinations, the age of the Winterhaven Formation is designated as Jurassic(?).

RELATIONS OF THE WINTERHAVEN FORMATION TO THE OROCOPIA SCHIST AND THE CHOCOLATE MOUNTAINS THRUST

The Orocopia Schist is the structurally lowest lithotectonic unit exposed in the region of the southeast corner of California and the southwest corner of Arizona (Haxel and Dillon, 1978). This schist forms the lower plate of the regionally extensive Chocolate Mountains thrust, the upper plate of which comprises almost all of the Mesozoic (and Proterozoic?) gneissic and granitoid rock units of the region. Elucidating the tectonic significance of the Winterhaven Formation with respect to the Orocopia Schist and the Chocolate Mountains thrust (Haxel, 1977; Crowell, 1981) involves choosing among four possibilities: (1) The Winterhaven Formation was originally a facies of the protolith of the Orocopia Schist, (2) the Winterhaven Formation was deposited nonconformably on the schist and upper-plate rocks, (3) the Winterhaven Formation and Orocopia Schist were originally juxtaposed along a fault younger than the Chocolate Mountains thrust, or (4) the Winterhaven Formation was originally part of the upper plate of the thrust. Evidence presented below indicates that the fourth possibility is the correct one.

Fault Contacts Between the Winterhaven Formation and the Orocopia Schist

Most present contacts between the Winterhaven Formation and the Orocopia Schist or gneiss of the upper plate of the Chocolate Mountains thrust are low- to high-angle faults. Most of these faults are largely or entirely of middle and (or) late Tertiary age because they cut the Oligocene and Miocene volcanic and sedimentary sequence or form part of some larger fault system that cuts that sequence. Evidence as to pre-middle Tertiary relations between the Winterhaven Formation and the Orocopia Schist and Chocolate Mountains thrust is preserved in only a few places. This evidence indicates that the Winterhaven Formation is, or was, separated from the Orocopia Schist by two different late Mesozoic low-angle faults—the Chocolate Mountains thrust and a younger, low-angle normal fault.

In the Arrastra Wash area, the upper plate of the Chocolate Mountains thrust is the Jurassic granodiorite that intrudes the rhyolitic metavolcanic rocks which are inferred to stratigraphically underlie the Winterhaven Formation. Essentially continuous exposures of crystalline rocks, extending structurally upward from blastomylonitic granodioritic gneiss just above the Chocolate Mountains thrust to the basal dacite member of the Winterhaven Formation, are interrupted only by a couple of northwest-trending Tertiary (and Mesozoic?) faults (fig. 2). The vertical separation across these faults is probably appreciable, at least several kilometers, but the blastomylonitic gneiss northeast of the northeastern fault is clearly derived from the undeformed granodiorite to the southwest. These relations indicate that the

Winterhaven Formation was originally part of the upper plate of the Chocolate Mountains thrust.

The map pattern in the Arrastra Wash area (fig. 2) and the low metamorphic grade of the Winterhaven Formation compared to the Orocopia Schist and gneissic and granitic rocks of the base of the upper plate of the Chocolate Mountains thrust strongly suggest that the Winterhaven Formation originally was at a high structural level within the upper plate. This implies that where the Winterhaven Formation and the Orocopia Schist are in direct contact they must have been juxtaposed by faulting younger than the Chocolate Mountains thrust. In several areas east of the longitude of Picacho Peak (fig. 2), the contact between the Winterhaven Formation and both plates of the Chocolate Mountains thrust is, or was, a late Mesozoic low-angle normal fault younger than and distinct from the Chocolate Mountains thrust.

Evidence for the existence of this younger fault is found chiefly in three areas. In the first area, the antiform culmination between Little Picacho Wash and White Wash (fig. 2), the Winterhaven Formation entirely surrounds and largely faces outward from an antiform culmination consisting of Orocopia Schist and upper-plate gneiss separated by a short segment of the Chocolate Mountains thrust (fig. 3). The Winterhaven Formation, in turn, is surrounded by middle Tertiary sedimentary and volcanic rocks that dip outward on three sides from this crude dome. On the south side of the dome, the Winterhaven Formation and gneiss are separated by an intrusive tongue of the granite of Marcus Wash. Around most of the rest of the circumference of the dome the Winterhaven Formation is separated from the schist and gneiss by one of several faults that dip steeply to moderately outward toward the Winterhaven Formation. The overall geometry and tectonic setting of this fault system strongly argues against appreciable strike-slip movement. The north-dipping fault on the north side of the dome continues to the west, where it displaces middle Tertiary volcanic and sedimentary rocks downward against the Winterhaven Formation. The south-dipping fault along the southwest side of the dome is paralleled, 400 m to the south, by another south-dipping fault along which the middle Tertiary strata are faulted down against the Winterhaven Formation. The faults separating the Winterhaven Formation from the schist and gneiss are thus Tertiary dip-slip normal faults along which the Winterhaven Formation has been faulted downward against the schist and gneiss. This configuration suggests that, before Tertiary faulting, the Winterhaven Formation overlaid the schist and gneiss.

This conclusion is confirmed by relations in the second area, about 0.7 km southwest of Little Picacho Peak. Here, a small body of volcanic rocks of the basal dacite member of the Winterhaven Formation subhorizontally overlies upper-plate gneiss and, on its southeast side, Orocopia Schist and the Chocolate Mountains thrust (fig. 7). The rocks of this area are intimately intruded and strongly hydrothermally altered by the granite of Marcus Wash. In the few places where the actual contact between the volcanic rocks and schist or gneiss is exposed, either the two rock types are separated by a thin dike of granite, or

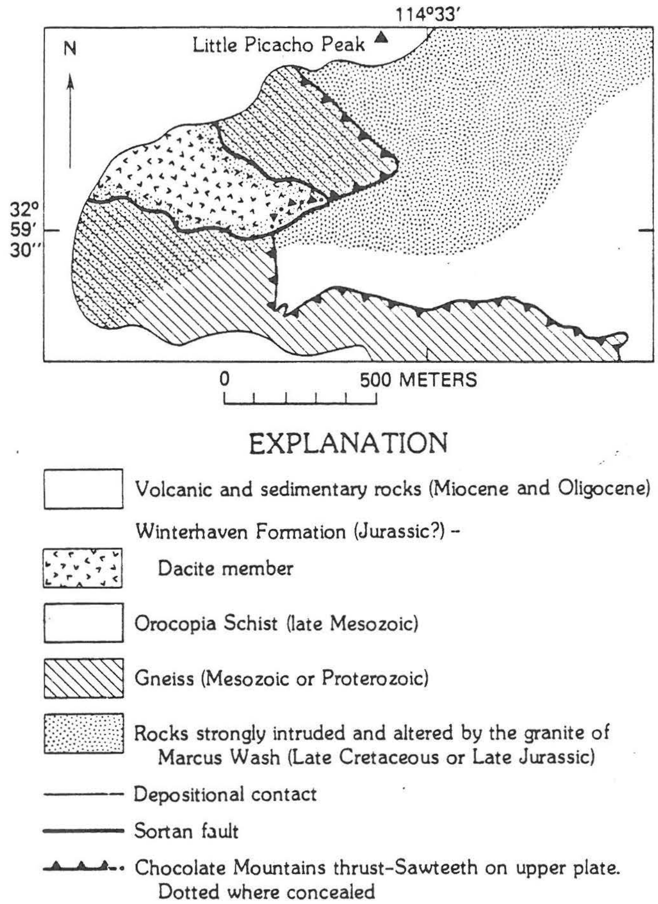


Figure 7. Relations between the Winterhaven Formation and the Orocopia Schist and Chocolate Mountains thrust in a small area southwest of Little Picacho Peak (see fig. 2 for location).

the rocks straddling the contact are so severely altered that the contact can be located only to within a meter or so and its nature is unclear.

In the third area, along Sortan Wash, metamorphosed rocks of the Winterhaven Formation overlie the Orocopia Schist and a short segment of the Chocolate Mountains thrust along a low-dipping contact (fig. 8). Where locally relatively well exposed, this contact is marked by gouge and (or) microbreccia, and in several places it truncates the contact between the dacite and quartz arenite members of the Winterhaven Formation. This fault is here referred to as the Sortan fault.

The Sortan fault may be in part localized along the older Chocolate Mountains thrust (figs. 2, 8), in a manner analogous to localization of middle and late Tertiary normal faults along Mesozoic thrust faults (Haxel and Grubensky, 1984; Tosdal and Sherrod, 1985). In the area east of lower Marcus Wash and on the west side of Arrastra Wash (figs. 2, 8), the granite of Marcus Wash forms a small hemilaccolith intruded largely along the Sortan fault between the Winterhaven Formation and the Orocopia Schist (Haxel, 1977, app. 3).

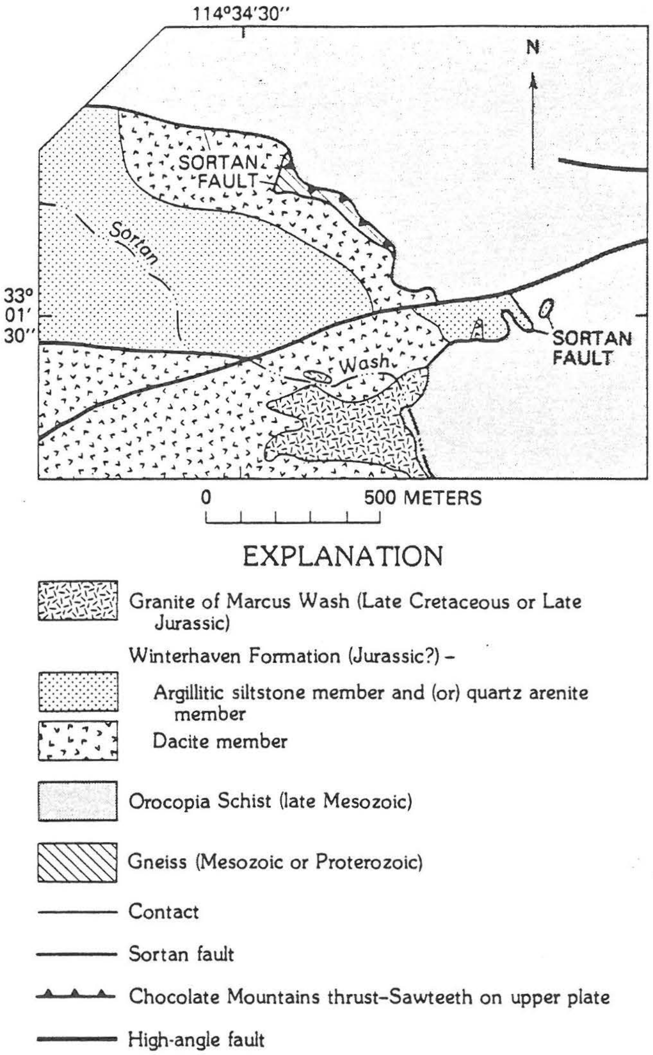


Figure 8. Relations among the Winterhaven Formation, the Orocopia Schist, and the granite of Marcus Wash in a small area along Sortan Wash (see fig. 2 for location).

The altered subhorizontal contact southwest of Little Picacho Peak (fig. 7) evidently is a segment of the Sortan fault, and the Sortan fault apparently also was the pre-middle Tertiary contact along which the Winterhaven Formation overlaid the Orocopia Schist and Chocolate Mountains thrust in the area west of Little Picacho Wash (fig. 3). Field relations in the three small areas where it is best preserved (figs. 3, 7, 8) unequivocally show that the Sortan fault postdates the Chocolate Mountains thrust and predates the granite of Marcus Wash; thus, this fault is of late Mesozoic age. The Sortan fault or fault system probably originally extended at least as far west as the Indian Pass area (fig. 2) and at least as far east as the southern Castle Dome Mountains (fig. 1). The Sortan fault appears to be a major structure in that a substantial thickness, probably about 5 to 10 km, of rocks of the upper plate of the Chocolate Mountains thrust evidently has been excised along the fault (fig. 9). The tectonic affinities of the Sortan fault are discussed below.

Distinction of the Winterhaven Formation from the Protolith of the Orocopia Schist

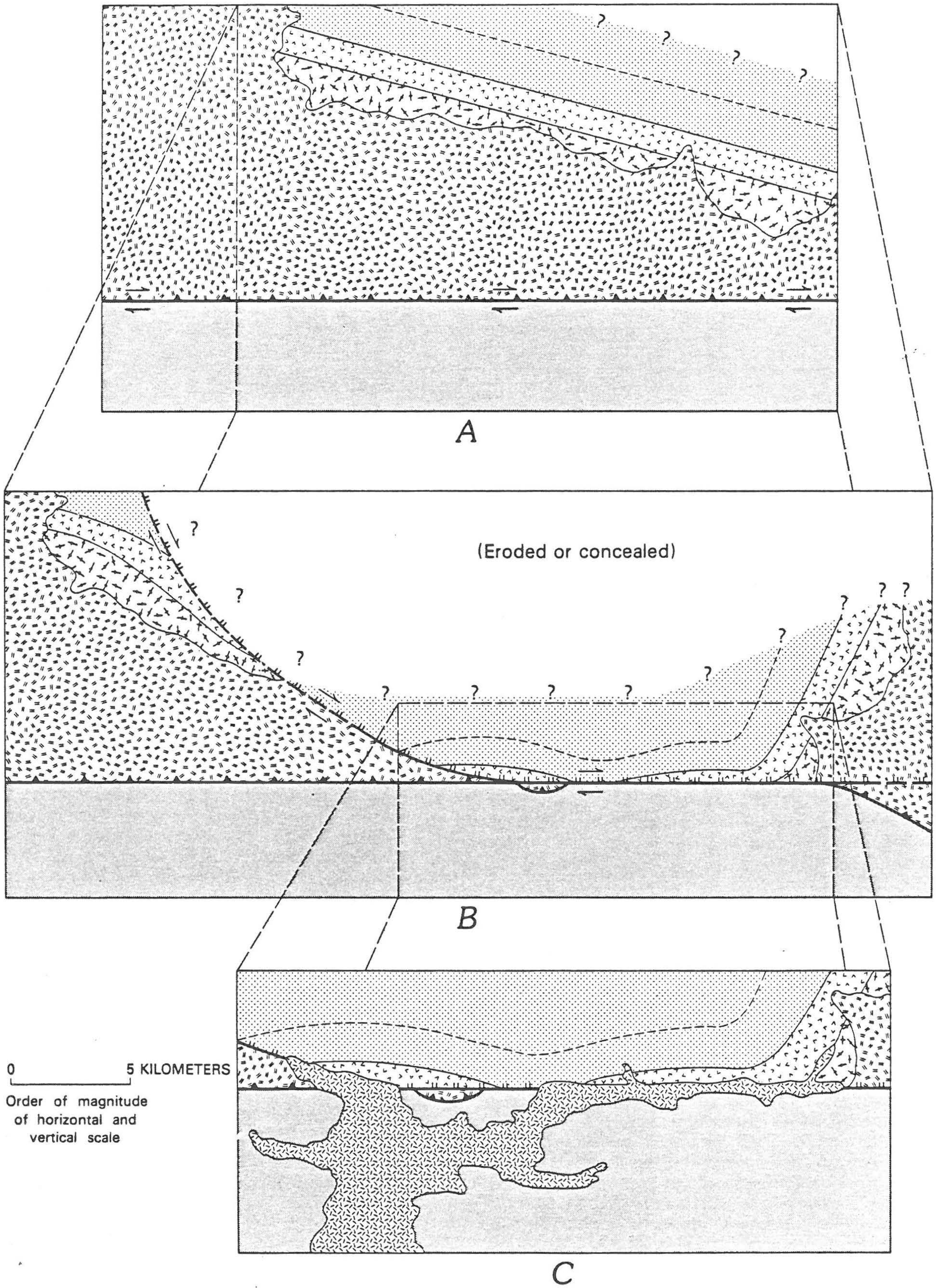
A suggestion in connection with the Winterhaven Formation is that it might represent a facies of the protolith of the Orocopia Schist. This possibility is not likely for several reasons. Although the Winterhaven Formation and the Orocopia protolith are both dominated by quartzofeldspathic to semipelitic sedimentary rocks of continental provenance, the two units have several significant lithologic, chemical, and tectonic contrasts indicative of deposition in distinct environments. The presence within the Orocopia protolith of basalt, ferromanganiferous chert, and peridotite indicates an oceanic or ensimatic environment; the Winterhaven Formation lacks mafic or ultramafic rocks, evidently rests on subaerial rhyolitic volcanic rocks (including welded tuff), and is inferred to represent an epicontinental environment. Quartz arenite and derivative quartzite in the Winterhaven Formation are detrital and lack the ferromanganiferous composition of the metachert of the Orocopia Schist. Psammitic and semipelitic rocks in the Orocopia Schist are commonly carbonaceous (graphitic), whereas those in the Winterhaven Formation are not. Metamorphosed dacitic and (or) andesitic volcanic rocks in the Winterhaven Formation of the Arrastra Wash-Marcus Wash area locally resemble some of the metabasite of the Orocopia Schist in outcrop but typically are finer grained, have a lower color index, and lack the albitic porphyroblasts that are rather common in Orocopia metabasite. Finally, the Winterhaven Formation and Orocopia Schist belong to the upper and lower plates, respectively, of the Chocolate Mountains thrust, which is part of a regionally extensive and presumably far-traveled thrust system in southern California and southwestern Arizona (Haxel and Dillon, 1978). Not only are the two formations separated by the thrust, but the oceanic protolith of the Orocopia Schist was deposited where it could subsequently be subducted or otherwise deeply tectonically buried, whereas the epicontinental Winterhaven Formation has evidently remained at relatively shallow crustal levels.

TECTONIC SIGNIFICANCE OF THE WINTERHAVEN FORMATION

As mentioned in the Introduction, the Winterhaven Formation is important for two reasons: because it is a part of the Mesozoic sedimentary record of the southeastern California-southwestern Arizona region and because of its relations to the Orocopia Schist.

Implications for the Age of the Orocopia Schist

Consideration of the significance of the Winterhaven Formation with respect to the Orocopia Schist requires some additional evidence from the central Transverse Ranges northeast of Los Angeles (fig. 1). This terrane was, before Neogene displacement along the San Andreas fault system



?
(Eroded or concealed)
0
5 KILOMETERS
Order of magnitude of horizontal and vertical scale
A
B
C

EXPLANATION

Granite of Marcus Wash (Late Cretaceous or Late Jurassic)

Winterhaven Formation and underlying volcanic rocks and the sedimentary and volcanic rocks of Slumgullion, undivided (Jurassic?)-Divided into:

Sedimentary and volcanic rocks

Intermediate-composition volcanic rocks

Rhyodacitic volcanic and hypabyssal rocks

Granitoid and gneissic rocks (Mesozoic and Proterozoic?)-Includes Jurassic granodiorite

Orocopia Schist (late Mesozoic)

Contact

Trace of bedding

Sortan fault (late Mesozoic)-Ticks on upper plate. Dashed where approximately located; queried where uncertain. Arrows indicate direction of relative movement

Chocolate Mountains thrust (late Mesozoic)-Sawteeth on upper plate. Arrows indicate direction of relative movement

Figure 9. Schematic tectonic diagrams showing how strata of the Winterhaven Formation and the sedimentary and volcanic rocks of Slumgullion, originally part of the upper plate of the Chocolate Mountains thrust (A), were displaced downward onto the Orocopia Schist (lower plate of the thrust) by movement on the Sortan fault (B). Development of the Sortan fault was followed by intrusion of the granite of Marcus Wash (C). Figure 9B represents upper-crustal extension of area of figure 9A; figure 9C is an enlargement of part of figure 9B. The Chocolate Mountains thrust and the Sortan fault are both late Mesozoic—younger than 163 m.y. and older than the pre-earliest Tertiary (pre-60 m.y.) granite of Marcus Wash. Granitoid and gneissic rocks of the upper plate of the Chocolate Mountains thrust include the Jurassic granodiorite that intrudes the Slumgullion unit and the volcanic rocks underlying the Winterhaven Formation. These diagrams are not cross sections through any single area of the crust but, instead, are composite sketches, not to scale, based largely on map patterns in the area from the Gavilan Hills eastward to Sortan Wash and northward to upper Arrastra Wash (figs. 2, 8), and in the southern Castle Dome Mountains (fig. 1).

(Crowell, 1979), adjacent to the southern Chocolate Mountains (Dillon, 1976; Ehlig, 1981; Powell,1981; Silver, 1982). The Pelona Schist and the synmetamorphic Vincent thrust of the central Transverse Ranges are considered tectonically equivalent to the Orocopia Schist and Chocolate Mountains thrust of southeastern California. (The Rand Schist of the northern Mojave Desert, though similar to the Orocopia and Pelona Schists, is not discussed here because it apparently was never contiguous with them, at least at presently exposed crustal levels.)

The role of the Orocopia and Pelona Schists in the tectonic evolution of the southern Cordillera remains uncertain (Haxel and Dillon, 1978; Burchfiel and Davis, 1981; Crowell, 1981; Ehlig, 1981; Jacobson, 1983a; Silver, 1983; Vedder and others, 1983). Because of the rapid tempo of events during Late Cretaceous and early Tertiary time (Dickinson, 1981), the age of the Orocopia Schist needs to be determined as precisely as possible. The relations described above between the Orocopia Schist and Winterhaven Formation are important in this regard.

The Orocopia and Pelona Schists were pervasively metamorphosed under high-pressure upper greenschist- to lower amphibolite-facies conditions and have undergone multiple penetrative folding and transposition (Graham and England, 1976; Haxel and Dillon, 1978; Jacobson, 1983a, b). In contrast, much of the Winterhaven Formation is only incipiently or partially recrystallized, probably in the lower greenschist facies, and has not been penetratively deformed. (Where locally more strongly recrystallized and deformed, the Winterhaven Formation was affected by a separate and younger metamorphic and magmatic event that also remetamorphosed the Orocopia Schist.) The Winterhaven Formation clearly has not been subjected to the deformational and metamorphic event that produced the Orocopia Schist. The Orocopia Schist was metamorphosed at considerable depth beneath the upper plate of the synmetamorphic Chocolate Mountains thrust (Dillon, 1976; Haxel, 1977; Ehlig, 1981; Jacobson, 1983c). The Winterhaven Formation, originally part of the upper plate of the thrust, has not been subject to this deep tectonic burial, and it overlies both plates of the thrust along the pre-60-m.y. (Frost and Martin, 1983), shallow-level Sortan fault. Therefore, the Orocopia Schist was returned to upper-crustal levels, and the overlying Chocolate Mountains thrust breached, before 60 m.y. ago.

This conclusion implies that metamorphism of the Orocopia and Pelona Schists was somewhat earlier than previously thought. The currently accepted metamorphic age of these schists is based largely on Rb-Sr mineral-isochron and K-Ar whole-rock minimum ages of 52-59 m.y. from the Pelona Schist and the Vincent thrust zone (Ehlig, 1981). A sequence of several major events—return of the Orocopia Schist to the upper crust, juxtaposition against the Winterhaven Formation, remetamorphism, and intrusion by the granite of Marcus Wash—intervened between the metamorphism of the Orocopia Schist and setting of K-Ar dates about 60 m.y. ago. Thus, the 52- to 59-m.y. isotopic dates for the Pelona Schist and Vincent thrust are postmetamorphic cooling ages. The primary metamorphic age of the Orocopia and Pelona Schists must be appreciably older than 60 m.y. and is almost certainly pre-Tertiary.

The 80±10-m.y. U-Pb zircon age (Carter and Silver, 1972) of a granodiorite apparently in the upper plate of the Vincent thrust has been considered a maximum age for the Vincent thrust and metamorphism of the Pelona Schist (Ehlig, 1981).

However, three factors indicate that this isotopic age may not provide a straightforward maximum age for the thrust and schist. First, the dated granodiorite lithology cannot be unequivocally tracked into the Vincent thrust zone (L.T. Silver, oral commun., 1983; P.L. Ehlig, oral commun., 1984). Second, the Chocolate Mountains thrust has been modified or replaced by both the late Mesozoic low-angle Sortan fault and numerous middle and late Tertiary low-angle faults, and Tertiary low-angle faults in the southern Arizona-southeastern California region are not uncommonly localized along Mesozoic thrust faults (Frost and others, 1982; Haxel and Grubensky, 1984; Tosdal and Sherrod, 1985). Third, observations presented by Evans (1982) suggest that some segments of the Vincent thrust may have been reactivated during faulting younger than the original formation of the fault zone and metamorphism of the Pelona Schist. The second and third of these factors suggest that the 80-m.y.-old granodiorite in the central Transverse Ranges may be cut not by the Vincent thrust but by younger fault(s).

The principal data bearing on the metamorphic age of the Orocopia and Pelona Schists can be summarized as follows. A concordant U-Pb age of 163 m.y. on zircon from a metamorphosed dioritic dike in the Orocopia Schist (Mukasa and others, 1984) provides a maximum age. As explained above, metamorphism must be appreciably earlier than 60 m.y. (K-Ar dates of Frost and Martin, 1983). Field relations and isotopic ages in the central Transverse Ranges (Carter and Silver, 1972; Ehlig, 1981; D.J. May, oral commun., 1985) suggest, but do not prove, that the metamorphism is Late Cretaceous or earlier. The probable age of metamorphism of the Orocopia and Pelona Schists is thus Late, but not latest, Cretaceous; an early Tertiary age is unlikely, and a Late Jurassic age cannot be precluded.

Tectonic Affinities of the Sortan Fault

A puzzling aspect of the low-dipping late Mesozoic Sortan fault is its normal-fault geometry—it places the Winterhaven Formation, originally part of the upper plate of the Chocolate Mountains thrust, over the Orocopia Schist, the lower plate of the thrust (figs. 3, 7-9). Pre-Tertiary low-angle normal faults have not been widely reported in the southern Cordillera, the late Mesozoic tectonic evolution of which was generally characterized by thrust faulting and crustal shortening rather than normal faulting and crustal extension. It is unclear whether the Sortan fault represents local extension within the overall framework of late Mesozoic shortening or a widespread but previously unrecognized late Mesozoic extensional episode.

Field relations in the Sortan Wash-Arrastra Wash area (figs. 2, 8, 9c) suggest that movement on the Sortan fault was part of the same event as metamorphism of the Winterhaven Formation and emplacement of the granite of Marcus Wash. If so, this composite event may be related to the Late Cretaceous and early Tertiary episode of thrust faulting, regional metamorphism, and granitic plutonism that affected the region from southeastern Arizona to southeastern California (Keith and others, 1980; Reynolds, 1980; Hamilton, 1982; Miller and others, 1982; Haxel and others, 1984; Tosdal, 1984b). Within this crustal-shortening regime, localized extension might have occurred by either of two mechanisms. First, extensional faults might have formed as a result of gravitational relaxation along a topographic front within the thrust belt (Royden and Burchfiel, 1985). Second, extension could have taken place within the upper plate of a downward-steepening, thick-skinned thrust fault (Coward, 1983), in particular the Mule Mountains thrust; the Sortan fault might thus be akin to a keystone fault (Wise, 1963).

Two considerations, in addition to the existence of the Sortan fault, indicate that late Mesozoic low-angle normal faults could be more common than previously suspected. (1) Evidence presented by Silver and others (1984) and C.E. Postlethwaite and C.E. Jacobson (written commun., 1985) suggests that one of the faults overlying the Rand Schist (which is similar to the Orocopia Schist) is not the thrust fault beneath which the schist was originally metamorphosed but, instead, a late Mesozoic or early Tertiary low-angle normal(?) fault comparable to the Sortan fault. (2) Coney and Harms (1984) hypothesized that Tertiary crustal extension in the Cordillera was caused by lateral spreading consequent to Mesozoic crustal thickening, and that extension was initiated or facilitated by the thermal input accompanying Tertiary magmatism. This model suggests that the Tertiary extensional episode was not necessarily unique. Late Mesozoic crustal extension may have occurred, boundary conditions permitting, in regions where earlier Mesozoic crustal thickening was followed by a separate, late Mesozoic thermal episode. In this context, crustal thickening caused by emplacement of the upper plate of the Chocolate Mountains thrust may have been followed by extensional deformation, including development of the Sortan fault, at the time of the thermal episode in which the granite of Marcus Wash was emplaced and the Winterhaven Formation metamorphosed.

If there was a widespread episode of late Mesozoic crustal extension, some or much of the postmetamorphic uplift of the tectonically buried Orocopia and Pelona Schists may have taken place during that episode (C.E. Postlethwaite and C.E. Jacobson, written commun., 1985). In southeastern California, the original tectonic stratigraphy that characterizes the Chocolate Mountains thrust zone at the top of and overlying the Orocopia Schist is widely preserved (figs. 1, 2; Dillon, 1976; Haxel, 1977); only locally has the thrust been disrupted by the Sortan fault. This observation has two important implications. First, the Chocolate Mountains thrust and part of its crystalline upper plate were uplifted along with the Orocopia Schist. Second, because the Chocolate Mountains thrust is extant over a wide area, the Sortan fault is not simply a wholesale reactivation of the thrust but, instead, a new and independent structure.

Possible Correlation with the McCoy Mountains Formation

The McCoy Mountains Formation is a Jurassic and (or) Cretaceous siliciclastic sedimentary and metasedimentary sequence, as much as 7 km thick, exposed in the region around Blythe, Calif., and Quartzsite, Ariz. (fig. 1; Pelka, 1973; Harding and Coney, 1985). This formation is definitely older than latest Cretaceous K-Ar minimum ages of crosscutting plutons, faults, and veins (Pelka, 1973; Reynolds, 1980; Tosdal, 1984a; L.B.G. Pickthorn, oral commun., 1985), but other data as to the age of the formation are equivocal or seemingly contradictory. The basal strata of the McCoy Mountains Formation are apparently interbedded with volcanic rocks of probable Early and (or) Middle Jurassic age (Harding, 1982), and paleomagnetic data suggest that the formation, or at least its lower part, is older than middle Late Jurassic (Harding and others, 1983). However, the upper part of the formation contains fossil angiosperm wood of probable mid-Cretaceous or younger age. These data, if all taken at face value, imply that either the McCoy Mountains Formation spans a considerable part of Jurassic and Cretaceous time or, more likely, the formation consists of two distinct sedimentary units, one Early and (or) Middle Jurassic and the other middle and (or) later Cretaceous, separated by an unrecognized unconformity (compare with Miller, 1966).

The southern boundary of the known extent of the McCoy Mountains Formation is the south-dipping late Mesozoic Mule Mountains thrust (Tosdal, 1982), the upper plate of which is composed largely of Jurassic granodiorite. This granodiorite extends southward to the lithologically identical granodiorite of Trigo Peaks that intrudes the metavolcanic rocks beneath the Winterhaven Formation (fig. 2). The presence of several distinctive lithologic units cut by (and thus older than) the Mule Mountains thrust in both plates of the thrust indicates that displacement on the thrust is relatively small, probably about 1-10 km (Tosdal, 1984a, b).

The Winterhaven Formation and the lower part of the McCoy Mountains Formation are both of probable Jurassic age, have a broad lithologic similarity, are exposed within about 70 km of one another, and are separated by a fault of minimal displacement. These considerations suggest that the two units could be correlative and related.

The Winterhaven Formation and the lower part of the McCoy Mountains Formation have two significant stratigraphic similarities. First, both formations evidently rest depositionally on and, at least locally, interfinger with Jurassic silicic volcanic rocks. Second, the quartz arenite member and the argillitic siltstone member of the Winterhaven Formation appear to correspond to the basal sandstone members and the mudstone member, respectively, of the McCoy Mountains Formation (stratigraphic nomenclature of Harding and Coney, 1985). In particular, the quartz arenite member of the Winterhaven Formation, the probably correlative unit within the sedimentary and volcanic rocks of Slumgullion (fig. 6), and basal sandstone member 1 of the McCoy Mountains Formation in the area southeast of Quartzsite all consist of or include a lithologic association of interbedded light-tan or gray quartz arenite, dark-purplish or maroonish-gray siltstone or mudstone, and minor quartzite-pebble conglomerate and brown-weathering arenaceous limestone. This distinctive lithologic association suggests that the Winterhaven Formation, the Slumgullion unit, and the lower part of the McCoy Mountains Formation may all record the same depositional episode or sedimentary environment. Despite the general similarity of the silicic volcanic (and related hypabyssal) rocks beneath the Winterhaven and McCoy Mountains Formations, the dacite member of the Winterhaven Formation has no counterpart in the McCoy Mountains Formation. If correlation of the Winterhaven Formation with the lower part of the McCoy Mountains Formation is valid, then the dacite member is more limited in extent than the underlying silicic volcanic rocks and overlying sedimentary rocks, and probably was deposited over a smaller area. This restricted distribution may, in part, reflect the lesser mobility of intermediate volcanic flows compared to silicic ash-flow tuff. In summary, correlation of the Winterhaven Formation and the lower part of the McCoy Mountains Formation is reasonable, even likely, but cannot be proven or disproven until additional geochronologic data are available.

The Mule Mountains thrust has been interpreted as a tectonostratigraphic terrane boundary separating the McCoy Mountains Formation, which has a North American provenance, from suspect terranes to the southwest (Harding and Coney, 1985). This interpretation is based largely on the apparent absence in the region southwest of the McCoy Mountains Formation of Proterozoic and Paleozoic rocks of cratonic North American affinities. However, the several similarities between the McCoy Mountains and Winterhaven Formations and their underlying volcanic and hypabyssal rocks, in addition to the evidence for minimal slip along the Mule Mountains thrust, indicate caution in inferring a major late Mesozoic tectonostratigraphic terrane boundary between the McCoy Mountains Formation and the Winterhaven Formation. Although these stratigraphic and structural ties are geometrically imprecise and do not necessarily preclude some displacement of the Winterhaven Formation along and (or) perpendicular to the continental margin, they do suggest that the Winterhaven Formation is indigenous to southwestern North America. If future research shows that the Winterhaven Formation (and the sedimentary and volcanic rocks of Slumgullion) are, indeed, related to the McCoy Mountains Formation, then any late Mesozoic or Tertiary suture between indigenous and suspect or exotic tectonostratigraphic terranes must lie either within the upper plate of the Chocolate Mountains thrust south of the outcrop area of the Winterhaven Formation or structurally below the upper plate of the Chocolate Mountains thrust.

REFERENCES CITED

Anderson, T.H., and Silver, L.T., 1978, Jurassic magmatism in Sonora, Mexico [abs.]: Geological Society of America Abstracts with Programs, v. 10, p. 359.

Burchfiel, B.C., and Davis, G.A., 1981, Mojave Desert and environs, in Ernst, W.G., ed., The geotectonic development of California (Rubey volume 1): Englewood Cliffs, N.J., Prentice-Hall, p. 217-252.

Carter, Bruce, and Silver, L.T., 1972, Structure and petrology of the San Gabriel anorthosite-syenite body, California: International Geological Congress, 24th, Montreal, Canada, 1972, Proceedings, sec. 2, p. 303-311.

Coney, P.J., Harms, T.A., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550-554.

Coward, M.P., 1983, Thrust tectonics, thin skinned or thick skinned, and the continuation of the thrusts to deep in the crust: Journal of Structural Geology, v. 5, no. 2, p. 113-123.

Crowe, B.M., 1973, Cenozoic volcanic geology of the southeastern Chocolate Mountains, California: Santa Barbara, University of California, Ph.D. dissertation, 117 p.

Crowe, B.M., Crowell, J.C., and Krummenacher, Daniel, 1979, Regional stratigraphy, K-Ar ages, and tectonic implications of Cenozoic volcanic rocks, southeastern California: American Journal of Science, v. 279, p. 186-216.

Crowell, J.C., 1979, The San Andreas fault system through time: Geological Society of London, v. 136, p 293-302.

---- 1981, An outline of the tectonic history of southeastern California, in Ernst, W.G., ed., The geotectonic development of California: Englewood Cliffs, N.J., Prentice-Hall, p. 583-600.

Crowl, W.J., 1979, Geology of the central Dome Rock Mountains, Yuma County, Arizona: Tucson, University of Arizona, M.S. thesis, 76 p.

Dickinson, W.R., 1981, Plate tectonic evolution of the southern cordillera: Arizona Geological Society Digest, v. 14, p. 113-135.

Dillon, J.T., 1976, Geology of the Chocolate and Cargo Muchacho Mountains, southeasternmost California: Santa Barbara, University of California, Ph.D. dissertation, 575 p.

Ehlig, P.L., 1981, Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges, in Ernst, W.G., ed., The geotectonic development of California: Englewood Cliffs, N.J., Prentice-Hall, p. 253-283.

Evans, J.G., 1982, The Vincent thrust, eastern San Gabriel Mountains, California: U.S. Geological Survey Bulletin 1507, 15 p.

Frost, E.G., and Martin, D.L., 1983, Overprint of Tertiary detachment deformation on the Mesozoic Orocopia Schist and Chocolate Mountains thrust [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 6, p. 577.

Frost, E.G., Martin, D.L., and Krummenacher, Daniel, 1982, Mid-Tertiary detachment faulting in southwestern Arizona and southeastern California and its overprint on the Vincent thrust system [abs.]:Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 164.

Graham, C.M., and England, P.C., 1976, Thermal regimes and regional metamorphism in the vicinity of overthrust faults--an example of shear heating and inverted metamorphic zonation from southern California: Earth and Planetary Science Letters, v. 31, p. 142-152.

Hamilton, Warren, 1982, Structural evolution of the Big Maria Mountains, northeastern Riverside County, southeastern California, in Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers, p. 1-28.

Harding, L.E., 1982, Tectonic significance of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Tucson, University of Arizona, Ph.D. dissertation, 197 p.

Harding, L.E., Butler, R.F., and Coney, P.J., 1983, Paleomagnetic evidence for Jurassic deformation of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Earth and Planetary Science Letters, v. 62, p. 104-114.

Harding, L.E., and Coney, P.J., 1985, The geology of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Geological Society of America Bulletin, v. 96, p. 755-769.

Haxel, G.B., 1977, The Orocopia Schist and the Chocolate Mountains thrust, Picacho-Peter Kane Mountain area, southeasternmost California: Santa Barbara, University of California, Ph.D. dissertation, 277 p.

Haxel, G.B., and Dillon, J.T., 1978, The Pelona-Orocopia Schist and Vincent-Chocolate Mountains thrust system, southern California, in Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the Western United States: Pacific Coast Paleogeographic Symposium 2: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 453-469.

Haxel, G.B., and Grubensky, M.J., 1984, Tectonic significance of localization of middle Tertiary detachment faults along Mesozoic and early Tertiary thrust faults, southern Arizona region [abs.]: Geological Society of America Abstracts with Programs, v. 16, p. 533.

Haxel, G.B., Tosdal, R.M., May, D.J., and Wright, J.E., 1984, Latest Cretaceous and early Tertiary orogenesis in south-central Arizona: Thrust faulting, regional metamorphism, and granitic plutonism: Geological Society of America Bulletin, v. 95, p. 631-653.

Haxel, G.B., Wright, J.E., May, D.J., and Tosdal, R.M., 1980, Reconnaissance geology of the Mesozoic and lower Cenozoic rocks of the southern Papago Indian Reservation, Arizona: A preliminary report, in Jenney, J.P., and Stone, Claudia, eds., Studies in western Arizona: Arizona Geological Society Digest, v. 12, p. 17-29.

Jacobson, C.E., 1983a, Structural geology of the Pelona Schist and Vincent thrust, San Gabriel Mountains, California: Geological Society of America Bulletin, v. 94, p. 753-767.

----- 1983b, Complex refolding history of the Pelona, Orocopia, and Rand Schists, southern California: Geology, v. 11, p. 583-586.

----- 1983c, Relationship of deformation and metamorphism of the Pelona Schist to movement on the Vincent thrust, San Gabriel Mountains, southern California: American Journal of Science, v. 283, p. 587-604.

Keith, S.B., Damon, P.E., Reynolds, S.J., Shafiqullah, Muhammad, Livingston, D.E., and Pushkar, P.D., 1980, Evidence for multiple intrusion and deformation within the Santa Catalina-Rincon-Tortolita metamorphic core complex, in Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic ore complexes: Geological Society of America Memoir 153, p. 217-267.

Miller, C.F., Howard, K.A., and Hoisch, T.D., 1982, Mesozoic thrusting, metamorphism, and plutonism, Old Woman-Piute Range southeastern California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers, p. 561-581.

Miller, F.K., 1966, Structure and petrology of the southern half of the Plomosa Mountains, Yuma County, Arizona: Stanford, Calif., Stanford University, Ph.D. dissertation, 107 p.

Morton, P.K., 1977, Geology and mineral resources of Imperial County, California: California Division of Mines and Geology County Report 7, 104 p.

Mukasa, S.B., Dillon, J.T., and Tosdal, R.M., 1984, A late Jurassic minimum age for the Pelona-Orocopia schist protolith, southern California [abs.]: Geological Society of America Abstracts with Programs, v. 16, p. 323.

Olmsted, F.H., Loeltz, O.J., and Ireland, B., 1973, Geohydrology of the Yuma area, Arizona and California: U.S. Geological Survey Professional Paper 485-H, 227 p.

Parker, F.Z., 1966, The geology and mineral deposits of the Silver district, Trigo Mountains, Yuma County, Arizona: San Diego, Calif., San Diego State College, M.S. thesis, 195 p.

Pelka, G.J., 1973, Geology of the McCoy and Palen Mountains, southeastern California: Santa Barbara, University of California, Ph.D. dissertation, 162 p.

Powell, R.E., 1981, Geology of the crystalline basement complex, eastern Transverse Ranges, southern California: Constraints on regional tectonics interpretations: Pasadena, California Institute of Technology, Ph.D. dissertation, 441 p.

Reynolds, S.J., 1980, Geologic framework of west-central Arizona, in Jenny, J.P., and Stone, Claudia, eds., Studies in western Arizona: Arizona Geological Society Digest, v. 12, p. 1-16.

Royden, L.H., and Burchfiel, B.C., 1985, Localized thin-skinned north-south extension in the High Himalaya [abs.]: Geological Society of America Abstracts with Programs, v. 17, no. 6, p. 405.

Silver, L.T., 1982, Evidence and a model for west-directed early to middle Cenozoic basement overthrusting in southern California [abs.]: Geological Society of America Abstracts with Programs, v. 14, no. 7, p. 617.

----- 1983, Paleogene overthrusting in the tectonic evolution of the Transverse Ranges, Mojave and Salinian regions, California [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 438.

Tosdal, R.M., 1982, The Mule Mountains thrust in the Mule Mountains, California and its probable extension in the southern Dome Rock Mountains, Arizona: A preliminary report, in Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Calif., Cordilleran Publishers, p. 55-60.

----- 1984a, Mesozoic crystalline rocks of the Mule Mountains and Vincent-Chocolate Mountains thrusts, southern California and southwestern Arizona: Juxtaposed pieces of the Jurassic magmatic arc of southwest North America abs., in Howell, D.G., Jones, D.L., Cox, Allan, and Nur, Amos, eds., Circum-Pacific Terrane Conference, 1983, Proceedings: Stanford, Calif., Stanford University Publications in Geological Sciences, v. 18, p. 193-194.

----- 1984b, Tectonic significance of the Late Mesozoic Mule Mountains thrust, southeast California and southwest Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 16, p. 676.

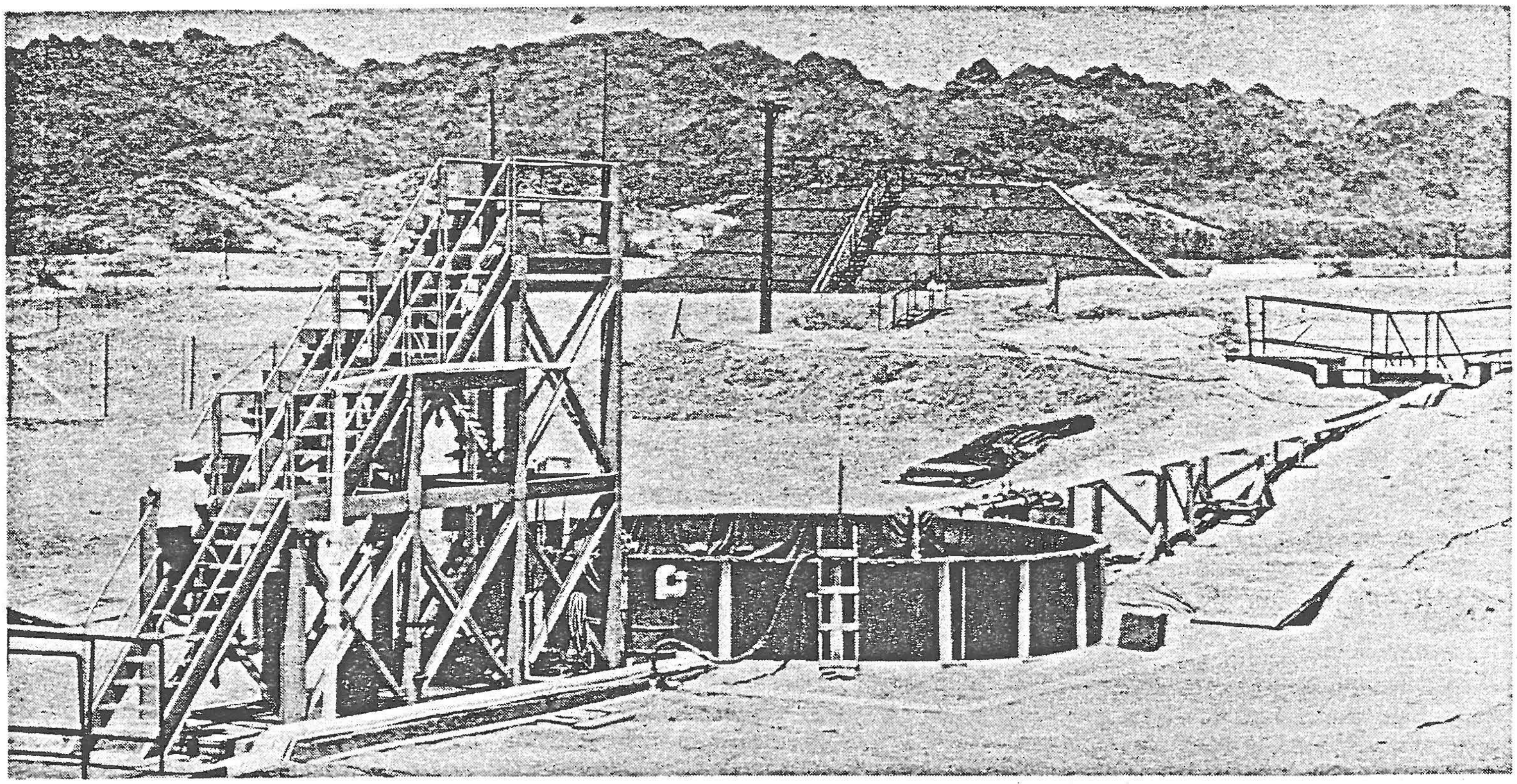
Tosdal, R.M., and Sherrod, D.R., 1985, Geometry of Miocene extensional deformation, lower Colorado River region, southeastern California and southwest Arizona: Evidence for the presence of a regional low-angle normal fault abs., in Papers presented to the Conference on Heat and Detachment in Crustal Extension on Continents and Planets: Houston, Tex., Lunar and Planetary Institute.

Vedder, J.G., Howell, D.G., and McLean, H., 1983, Stratigraphy, sedimentation, and tectonic accretion of exotic terranes, southern Coast Ranges, California, in Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 471-496.

Wilson, E.D., Moore, R.T., and Cooper, J.R., 1969, Geologic map of Arizona: Arizona Bureau of Mines and U.S. Geological Survey, scale 1:500,000.

Wise, D.U., 1963, Keystone faulting and gravity sliding driven by basement uplift of Owl Creek Mountains, Wyoming: American Association of Petroleum Geologists Bulletin, v. 47, p. 586-598.

Wright, J.E., Haxel, G.B., and May, D.J., 1981, Early Jurassic uranium-lead isotopic ages for Mesozoic supracrustal sequences, Papago Indian Reservation, southern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 13, p. 115.



Important parts of the pilot test work at Mesquite were the trial heap leach pad in the center background and the adsorption tank in the foreground. In the background looms the rugged, desolate Chocolate Mountains. (Photo courtesy Gold Fields Mining.)

Golds Fields begins Mesquite mine construction

$66 million gold project in California desert to be on line in January

By Bill Epler
Staff Reporter

Construction has begun on the Mesquite gold mine of Gold Fields Mining Corporation in the southeastern California desert, a $66 million project scheduled to come on line next January.

Gold Fields, a wholly-owned subsidiary of Consolidated Gold Fields, announced in March that it was going ahead with development after receiving the necessary major permits and clearances.

Robin J. Hickson, manager at Mesquite, said several minor permits were still in process, but was confident they would be issued without problems.

This will be the second major gold property for Gold Fields, which developed and operates the highly successful Ortiz mine in New Mexico.

The Mesquite property is located in Imperial County, about 45 miles northeast of El Centro and some 50 miles northwest of Yuma, Arizona.

Mesquite will be an openpit mine and gold will be produced through heap leaching and carbon-in-pulp recovery.

Ore production will start at the rate of 2.1 million tpy and is expected to reach the rated and permitted capacity of 3 million tpy by the end of the second year of operation.

Gold production will range between 110,000 and 130,000 ounces per year.

About 56 million tons of low-grade reserves have been delineated on 2,000 acres of mining claims. Hickson declined to reveal the ore grade, saying it was proprietary information.

Ore reserves are sufficient for a life of more than 15 years. Drilling is being continued to delineate additional reserves more accurately and the company is hopeful the property will operate considerably beyond the presently-projected 15 years.

Ore will be mined from two adjacent pits, the Lena and The Big Chief. Each will be about 2,500 by 1,000 feet and will be excavated to a maximum depth of 60 feet.

The mines and the heap leach pads and adjacent recovery plant are separated by Highway 78. A primary crusher with a rated capacity of 800 tph will be installed near the two open pits.

Crushed ore will be carried by a 3,100-foot-long covered conveyor over the highway to the processing section and the fine crusher.

The heap leach pads will be big ones, about 4,200 feet long and 400 feet wide, covering about 38½ acres each.

Height of the leach pads will vary between 30 feet and 80 feet, depending on the percolating characteristics of the contained material.

Over the projected 20-year life of the operation, as many as 20 leach pads are expected to be built.

MOVING AHEAD FAST

When the decision was made to go ahead, Gold Fields moved fast to give the final go-ahead on contracts it had been negotiating with a number of firms:

—**The Industrial Company** of Steamboat Springs, Colorado was awarded the contract for completion of design and all construction of process facilities, including crushers, conveyor and recovery plant. (See details below.)

—**Bechtel** has been retained to provide construction management on the process plant.

—**Argee Corporation** of Denver received a contract for construction of leaching pads and site grading. The company is on-site and has begun work. (See details below.)

—**Hydrostorage** has been awarded a contract for a number of tanks.

—**Interect** of Salt Lake City was awarded a contract for furnishing four pre-engineered buildings.

—**Bomur** of Albuquerque has been awarded a contract for providing the security system.

—**American Fence Company** of El Centro received the contract for boundary fencing

Mesquite project . . .

and for security fencing around the processing plant.

The Industrial Company (TIC) is the major contractor. Portions of the design of the process plant were completed earlier by another firm and TIC is working with Davy McKee Corporation of San Ramon, California to provide the balance of the design engineering.

TIC had previously been awarded a contract by Gold Fields for the approximately 4,300 feet of conveyors. This will be done in conjunction with Conveyor Engineering Inc. of Boise, Idaho, which will provide detailed engineering and fabrication of the units.

Work to be performed by TIC includes pipelines (construction started February 15th on freshwater lines), structural excavation, concrete, structural steel, process pipe, leach pad pipe, mechanical, electrical and instrumentation. The latter two items will be done by Canyon Valley Electric Inc. of Grand Junction, a TIC subsidiary.

Major areas of construction by TIC include primary crushing, reclaim structures, secondary crushing, a sampling and agglomeration facility, a truck loadout bin, leach pad piping and the final process area.

Argee Corporation, a contract mining and heavy civil construction contractor, will initially construct two adjacent leach pads.

One will be lined with a PVC and CPE lining, while the other will be rough graded at this time. The solution trenches and collection ditches, approximately a mile long, will also be lined.

The work is to be completed late this fall.

Argee is doing several sizeable projects in the West. It recently began work in Utah as primary contractor for removal of the old Vitro uranium tailings from the mill site in South Salt Lake City to a remote site near Tooele, southwest of the Great Salt Lake.

Argee is mining for Tenneco Minerals at the Borealis gold mine near Hawthorne, Nevada. This past winter it completed pre-mine stripping, aggregate production and construction of several earthen dams for Homestake Mining Company at its McLaughlin gold mine in northern California.

MOST EQUIPMENT ON HAND

Anticipating that the permits would come together, Gold Fields ordered an impressive array of equipment for the mine and for building the heap leach piles. Thanks to the slow equipment market, most of the equipment could be acquired on short notice from factory or dealers' inventory.

Major equipment items ordered, with some delivered as of mid-April, included:

—Nine WABCO 85-ton haulage trucks, with four on site.

—Two Caterpillar 992C loaders with 13-yard buckets, both on site.

—One Hitachi 11-yard hydraulic shovel, on site.

—Two water trucks for dust control, fabricated by Magnum of Albuquerque on WABCO chassis. One on site.

—Two Driltec rotary drills for blast holes, both on site.

—Three Caterpillar D-8 bulldozers, all on site.

—One rubber-tired 814 Caterpillar bulldozer, on site.

—One 14G Caterpillar grader, on site.

NO PERMIT PROBLEMS

The last major permit for Mesquite was received January 30th, Hickson said, and the remainder were expected "with no problem."

Hickson said he was favorably impressed with the permitting system of local, state and federal agencies. He said applications for all the major permits were filed last August and all were granted by the end of January.

"We heard a lot of horror stories about getting permits," Hickson said. "I found them (the agencies) strict, but wanting the project and helpful to us.

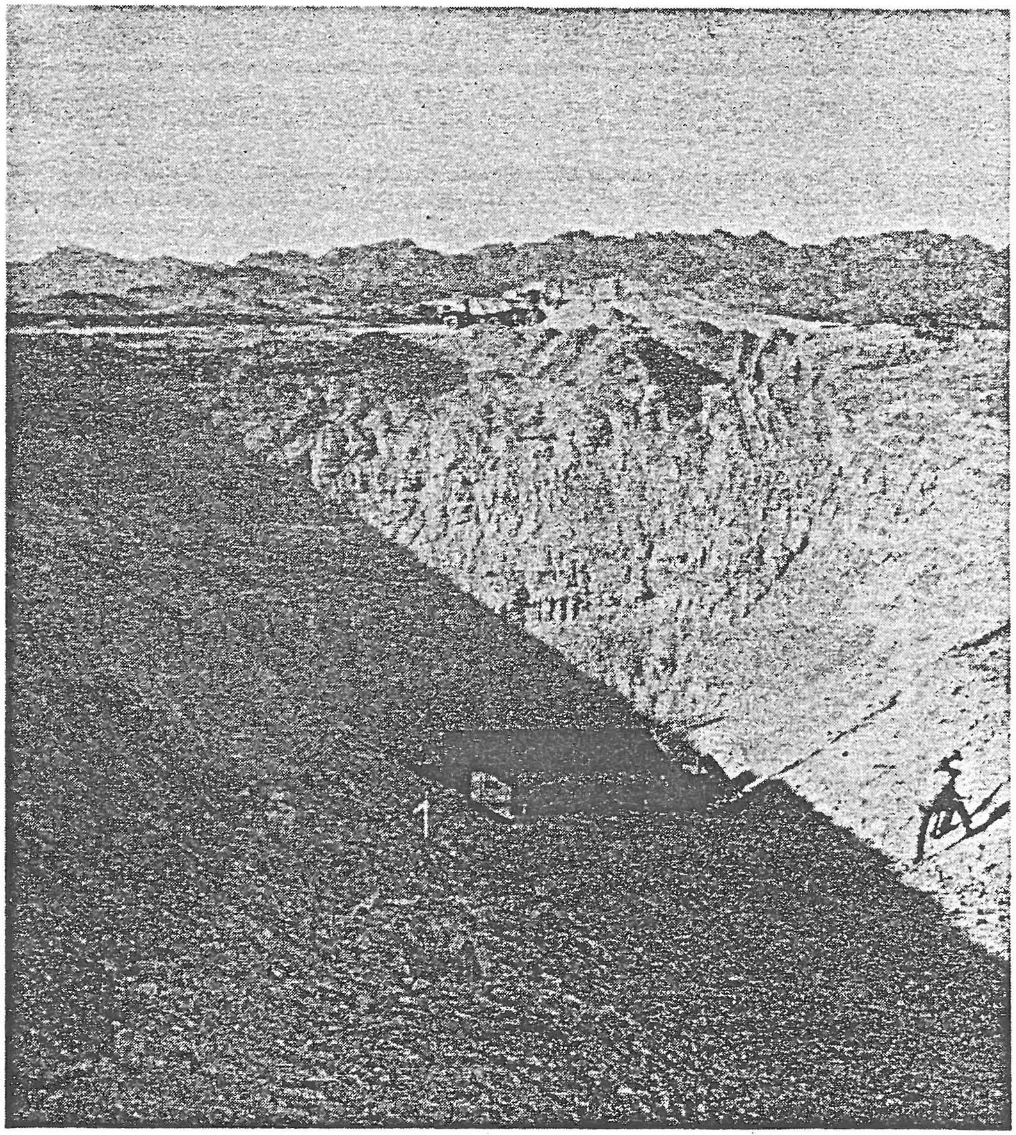
"I found them firm but fair. I can't say anything negative about them," Hickson stated.

After that last major permit was acquired at the end of January, Gold Fields on February 12th hired its first production people to operate the first equipment that had arrived the previous week.

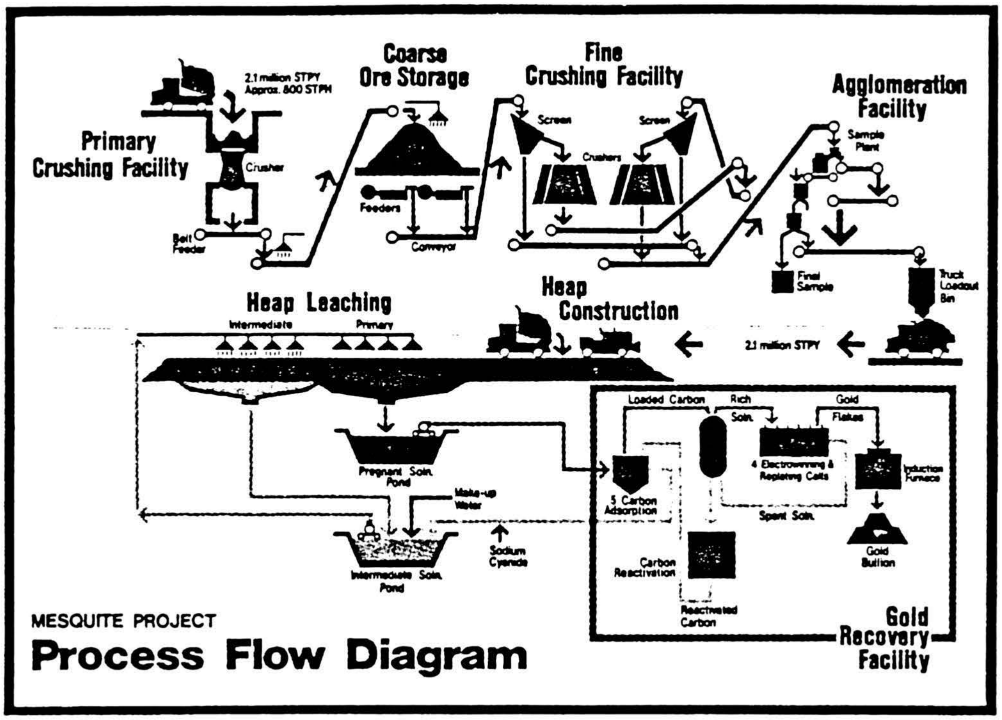
GOOD COMMUNITY RELATIONS

Hickson said Gold Fields is making a major effort to cultivate good community relations. A big step in that direction are its hiring policies.

Except for certain technical people, Gold Fields is hiring locally—even though it means



Setting the forms for the concrete foundation for the 800 tph primary crusher. Crushed ore will be delivered to a 3,100-foot long covered conveyor that will transport it over a nearby highway to the secondary crusher in the ore processing area. (Photo courtesy Gold Fields Minging.)



MESQUITE PROJECT
Process Flow Diagram

Mesquite project . . .

training the employees how to operate equipment.

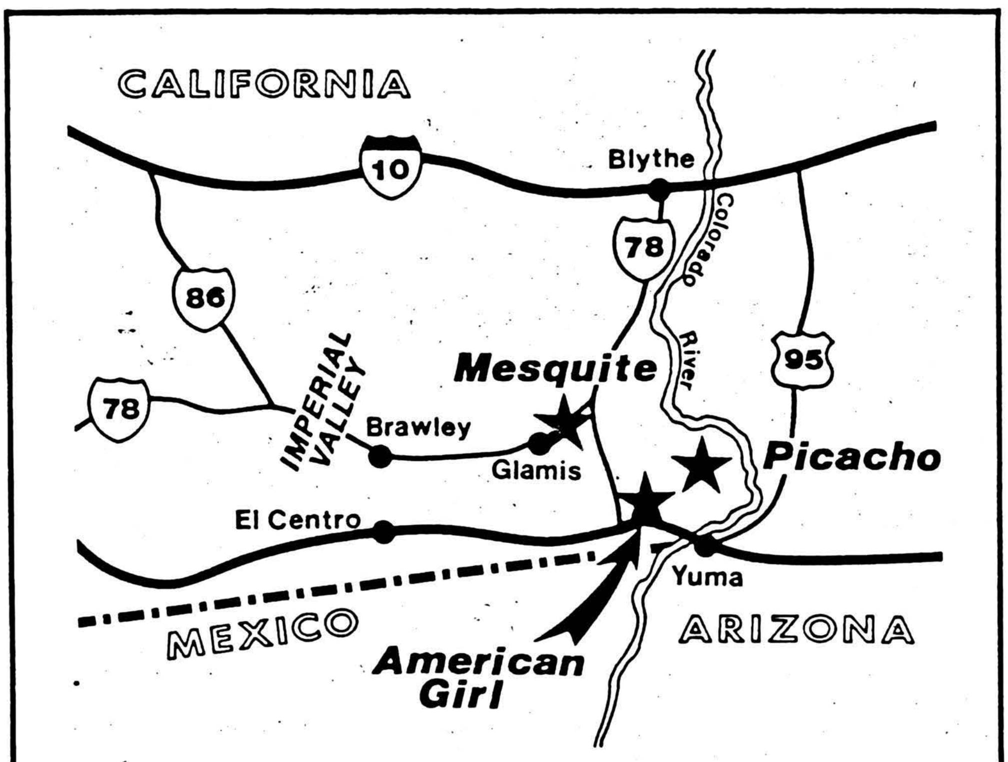
Imperial County, Hickson said, has been struggling with a 43 percent unemployment rate, one of the highest in the nation. County officials and most everyone else in the area were enthused about the jobs and taxes the new mine will provide and went out of their way to be cooperative.

"So, we are doing everything we can to hire locally," Hickson said.

To implement its policy to hire locally, Gold Fields elected to do the pre-mining stripping itself. It ordered some of the equipment in early to provide extra time for training.

Hickson said the firm has been hiring about eight potential equipment operators per week and starting them on their training programs. They are soon put to work on the stripping projects, learning as they go.

By late February, stripping began on a one-shift basis as part of the training program.



"It's working out very well," he said. "They are hard workers, quick to learn and anxious to please. They are doing surprisingly well and the work is starting out very well.

"We're already moving about 8,000 tpd and that is steadily increasing. It won't be long until the production figures will be up to where they should be and we will have a darned good force when ore production starts," Hickson said proudly.

STARTED IN 1980

Gold Fields' interest in the Mesquite area began in 1980, when it attracted the attention of the exploration staff based in Denver. After some exploratory poking around, Gold Fields began leasing mineral rights that grew to more than 16,000 acres.

After the property package was put together, Gold Fields began its exploratory drilling program in September 1981 and—bingo—hit the orebody with the first hole!

Several hundred holes were eventually drilled, most of them about 500 feet deep. Several deep holes were drilled to 1,000 feet. Drilling above the water table was done with the reverse circulation method, while those below were diamond drilled.

The exploration drilling, along with geophysical and geochemical surveys and surface sampling, established a low-grade orebody averaging 0.05 ounce of gold per ton at Brownie Hill. As of early 1984, geological reserves—not necessarily all recoverable—were estimated at between 26 million and 41 million tons.

Since that time, reserves have been increased to 56 million tons, but the average grade has not been reported.

Gold Fields put a lot of time and money into careful evaluation of the deposit and what would be required to develop and bring it into production.

"We don't rush in," Hickson said. "We do the ground work, check and test, and be sure we have a viable operation.

"That way," said Hickson, "there are no nasty surprises. We know what we have and can plan and mine accordingly."

Mine planning studies were done by Pincock, Allen & Holt, Tucson-based mineral consultants, which developed pit designs and waste dump layouts.

Bechtel Civil and Minerals Inc. of San Francisco designed the ore processing facilities and developed a feasibility study.

20,000-TON SAMPLE

To get what could be considered a truly representative bulk sample of the ore for metallurgical testing, Gold Fields decided to drive a long decline into the deposit.

The 15-degree decline was started in November 1982 by the contractor, J.S. Redpath Corporation of Tempe, and completed the following May. The decline was 2,390 feet long and ended 210 feet below the

Mesquite project . . .

surface, about one-third of the depth of the deposit.

The excavation provided a bulk sample of about 20,000 tons, with most of it processed through the sampling plant.

On-site pilot heap leaching tests were done, utilizing a pilot plant designed by Mountain States Engineers of Tucson.

Metallurgical testing on some of the bulk sample was started in February 1982, under direction of George M. Potter, a Tucson consultant. Included in the program were agitation, carbon-in-pulp, gravity, vat leaching and heap leaching tests.

Although all the processes are viable, heap leaching was preferred to agitation and vat leaching because of lower operating costs and experience with this process at the Ortiz mine.

The gold recovery system will be similar to the Ortiz plant in New Mexico, but updated to improve recovery efficiency and time.

To provide adequate water supply in that barren land, Gold Fields was able to come up with 842-foot-deep well about five miles away. It will provide up to 2,500 gpm.

KEY MAN AT MESQUITE

The key man at the Mesquite project is Hickson, who brought considerable experience with him when he was appointed manager July 1, 1983. He had been with the company's Ortiz project from concept through construction and its first three years of operation.

Gold Fields became interested in the Ortiz gold mining district near Cerrillos, midway between Albuquerque and Santa Fe, in the 1970s.

Although Consolidated Gold Fields had held American mining and industrial interests for many years, it had not done any exploration in this country.

It began doing so in 1971, but on a small scale. This changed during the 1970s as gold prices increased sharply and as significant advances were made in ore processing technology.

This all led Gold Fields to the Ortiz area. After nearly five years of exploration and feasibility studies, full-scale development of the Ortiz mine and processing plant began in October 1978 and production started in February 1980.

Gold production at Ortiz is running about 40,000 ounces of gold annually from leaching of 850,000 tons of ore. This places the operation among the 10 leading gold producers in the U.S.

Hickson was appointed manager at Ortiz in July 1978, some three months before construction of the project began. He herded it through development, brought it on line and supervised its operation for more than three years of production.

Thus, he brings unequaled experience and expertise to the Mesquite project, which will have a production rate approximately three times larger than Ortiz.

During the construction period, a maximum number of 550 will be employed at Mesquite. When the mine is fully operational, there will be approximately 220 employees.

Annual production expenses will average around $22 million, including a payroll of some $6 million. The operation will also pay sizeable county, state and federal taxes.

Gold mining in Mesquite area has a mighty long history

By Bill Epler
Staff Reporter

Gold mining is old hat along both sides of the Lower Colorado River, in that hot and tortuous 150-mile section from Needles to Yuma.

The Mesquite Mining District is near the lower end of the approximately 65-mile-long stretch from Blythe to Yuma.

Those barren, remote reaches with their hostile environment were investigated early because they were easy to reach over that broad liquid highway—the Colorado River.

Spanish explorers, working their way up the west coast of Mexico by boat, sailed up the river to the future site of Yuma and even further in the 1540s in their never-ending quest for gold.

Although the conquistadores looked, they apparently never found much. It was not until 1780 that gold mining was recorded by a Spanish settlement near the Cargo Muchacho Mountains and the Pothole placers northwest and north of Yuma.

An Indian uprising in 1781 broke up the activity, however, and sent the inhabitants fleeing back to the mouth of the Colorado and further south into Mexico.

Activity picked up again when the area received protection by creation of the Mexican republic in 1823.

Although there are no production records, the Mexican prospectors and small miners left abundant workings behind to indicate there was substantial mining activity in the area.

The big surge of activity came after the California gold rush, particularly after the Civil War and the beginning of the big push of the nation westward. By then, the area was now part of the United States, thanks to the Gadsden Purchase of 1853.

Yuma became a thriving center of many kinds of activities, including mining. A number of steamboats operated on the Colorado River, many of them running up the river as far as the present site of Davis Dam, due west of Kingman. Some even went further, to the very mouth of the Grand Canyon itself.

The area along both sides of the river literally crawled with prospectors. Numerous discoveries were made and a host of mines went into production, serving as major customers for the steamboats.

In the general vicinity of Mesquite, the area of interest in this article, mills along the western shores of the river were processing ores from mines in the Cargo Muchacho and Picacho areas.

The next big step in mine development began in 1877 when the Southern Pacific Railroad, building eastward out of Los Angeles, built through the Glamis and Mesquite areas and reached Yuma in 1877.

Rail stations at Glamas and Mesquite became shipping points for heavy equipment and supplies for mines throughout the area and as far north as Blythe.

But this activity gradually pooped out as small, high-grade deposits were worked out. Numerous properties were located and investigated in the years that followed, but little was done with them. The unfavorable combination of low ore grades, low gold prices and the high costs of operating in the remote, desolate areas was just too much to overcome.

But the situation began to change in the 1970s when factors in the quotient began to change: gold prices rose rapidly, heap leaching technology was developed to recover the "invisible" gold and huge machinery made it possible to move big tonnages at low cost.

During this period, the Mesquite group of claims was explored and drilled by several companies. But Gold Fields was the first to put it all together.

About 20 miles to the southeast of Mesquite, there are two other gold operations—one active, the other under consideration.

Chemgold Inc. for several years has been producing about 15,000 ounces of gold per year from its small openpit mine and heap leaching operation at Picacho Peak. It is located about five miles from the Colorado River and 30 miles from the Mexican border.

In the Cargo Muchacho Mountains to the southwest of Picacho Peak, Newmont Mining Corporation has discovered the American Girl gold deposit. It conducted a major exploration project that included a reported 1,200 drill holes.

Newmont has yet to announce any development plans.

Anaconda Minerals has also been active in the general area, having interests in a number of gold prospects.

Depending upon gold prices and the luck of the draw, additional discoveries and mine developments in the area are considered highly likely.

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...mong the patented mining ...laims covered by the agree-...ent is the Horn Silver Mine, ...ich produced significant ...ounts of silver, lead, cop-...er, zinc and gold during inter-...tent operations that were ...ducted on the properties ...etween 1875 and 1947. The ...orn Silver Mine properties ... located on approximately ...00 acres in the San Francisco ...ining district in Beaver Coun-...y, Utah. Horn Silver Mines, ... and Tintic Mineral ...ources, Inc. jointly own ...hese properties.

Gold Fields Mining Announces Imperial County Discovery

WALL STREET JOURNAL, Nov. 1982.

NEW YORK, NY — Gold Fields Mining Corporation reported that it has discovered gold mineralization of possible economic significance on mineral claims under its control in Imperial County, California.

For the past two years, the company has been acquiring mineral rights in Imperial County. Presently, through its own claims and claims acquired from others, the company has mineral rights covering a total of some 40,000 acres.

A comprehensive exploration program, including geochemical and geophysical surveys, and diamond and reverse circulation drilling, was commenced a little over a year ago. Approximately 327 relatively shallow holes have been completed to date. In an area approximately 2,000 ft. long and 1,000 ft. wide, situated mostly on a single block of claims known as the Big Chief Group, and held under an option to purchase and royalty agreement, 165 of these holes drilled on 144 ft. centers have intersected a flatlying mineralized zone containing potentially significant gold values. Depending on the cut-off grade selected, and assuming the mineralization is continuous between holes, the zone may contain in situ between 26 million tons at a grade of .075 ozs. per ton and 41.5 million tons at a grade of .056 ozs. per ton. The drilling completed so far may not have fully delineated the mineralization in all directions.

A program to determine the possible economic potential of the deposit is presently underway. This program includes additional drilling, bulk sampling, metallurgical testing, hydrologic and environmental studies and a review of the conditions under which the necessary operating permits can be obtained. All of these factors will have to be investigated to determine the commercial significance of the deposit.

Following a public hearing in Heber, Imperial County, on October 27, the Imperial County Planning Commission granted the company a Conditional Use Permit to carry out an underground exploratory program to obtain bulk samples, and to prepare to conduct pilot plant scale heap leach tests on the site. A contract has been awarded to the J.S. Redpath Corporation, contractors of Phoenix, Arizona, to carry out the underground program. It is planned to drive some 3,000 ft. of tunnel through the mineralized zone.

Coal Supply

Hampshire Energy Negotiating With Carter Mining Co.

Mining Record Staff Reporter

GILLETTE, WY — Hampshire Energy Co. said it is negotiating with Carter Mining Co. for a contract to initially supply coal to Hampshire's proposed coal liquefaction plant south of Gillette.

Hampshire officials told a meeting of the Wyoming Industrial Siting Council that coal would be hauled by truck from Carter's Caballo Mine to the Hampshire facilities. The Hampshire plant is designed to convert 15,000 tons of coal daily into about 20,000 gallons of unleaded gasoline and other liquid products.

The ISC is conducting hearings on Hampshire's siting permits. The company is pressing to obtain at least conditional state permits by Nov. 30 when final negotiations begin with the U.S. Synthetic Fuels Corp. for federal financial supports.

Ed McCann, Hampshire environmental manager, presented to the council 20 pages of stipulations Hampshire agreed to in response to problems noted in an ISC staff review before hearings began Oct. 25, then recessed Nov. 1, and resumed Nov. 13 for an 11-day period.

McCann and Rick Moore, administrator for the Wyoming Siting Administration, agreed that a major stumbling block in the permitting process is Hampshire's plans for handling some 3 million tons of ash annually that will result from the coal conversion process.

Texas Energy Services, two subsidiaries of Hampshire Energy's partners, is seeking a federal lease on 445 tons of coal not far from the Hampshire plant. Texas Energy submitted a bid of $22,337,600, or $4,600 per acre, for the 4,355 acre Rocky Butte tract located seven miles southeast of Gillette.

Texas Energy submitted the higher bid at a special sale in October conducted by the Bureau of Land Management at Cheyenne, Wyo. This reoffering of the Rocky Butte tract was ordered after the U.S. Minerals Management Service rejected Texas Energy's original bid of $11.1 million for the tract. The Minerals Management Service said the bid did not represent a fair market value.

The latest bid by Texas Energy is under review by the Departments of Interior and Justice before issuance of a lease. Texas Energy is a joint venture of Kaneb Services of Houston and Northwestern Mutual Life Insurance of Milwaukee. Kaneb and Northwestern are among the four partners in the Hampshire Energy project.

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REGIONAL STRATIGRAPHY, K–Ar AGES, AND TECTONIC IMPLICATIONS OF CENOZOIC VOLCANIC ROCKS, SOUTHEASTERN CALIFORNIA

BRUCE M. CROWE,* JOHN C. CROWELL,** and DANIEL KRUMMENACHER***

ABSTRACT. Volcanic and volcaniclastic rocks of early-to-mid Cenozoic age crop out within linear mountain ranges of southeastern California, east of the San Andreas fault. Regional mapping and 32 newly obtained K–Ar age determinations disclose a tripartite stratigraphic division of major volcanic rock units at individual volcanic centers. From oldest to youngest, the stratigraphy includes: (unit A) a basal sequence of basaltic to rhyodacitic lava flows and breccia dated at 26 to 35 m.y.; (unit B) rhyodacitic to rhyolitic lava flows, domes, volcaniclastic rocks, including several major ignimbrite sheets. These rocks yield ages largely in the range of 22 to 28 m.y.; and (unit C) mafic lava flows that are divided into two subunits dated at 25 to 29 m.y. (unit Ca) and 13 to 22 m.y. (unit Cb). Plutonic rocks with K–Ar ages between 21 and 26 m.y. intrude unit A in the Chocolate Mountains and may be present at depth beneath many of the major volcanic centers in the region.

The volcanic rocks of units A and B are classified as calc–alkaline based on major-element abundances. They are characterized by a slight excess of K_2O *"over"* Na_2O. Volumetrically these lavas are largely of silicic composition with a subordinance of andesite. Volcanic rocks of unit C range in composition from hypersthene normative basalt to quartz normative andesite and dacite. They have relatively high Al_2O_3 and slightly high TiO_2. $K_2O + Na_2O/K_2O$ averages 0.35.

Volcanism commenced in southeastern California about 33 m.y. ago following a pronounced early Cenozoic magmatic hiatus that may mark the presence of a proto-San Andreas fault system in coastal California. Oligo-Miocene age volcanic rocks of the region overlap in age with dated volcanic rocks of Arizona and New Mexico. These rocks probably record an early Cenozoic subduction system off the coast of the Western United States. The age of termination of subduction in southeastern California is inferred to be slightly older than 22 to 25 m.y. A transition to mafic and intermediate volcanism in the region is dated at 13 to 19 m.y. This age is significantly younger than the generally cited age of transition to basaltic volcanism in the southwestern United States and the probable age of inception of basin-range faulting. The dated volcanic transition overlaps in time with the probable age of inception of the San Andreas system in southern California.

The Salton Creek fault is a major east-west trending fault of southeastern California. It was active during mid-Cenozoic time and marked the northern boundary of the Cenozoic volcanic and plutonic province. The fault ceased to be a major boundary during mid-Miocene time, inasmuch as it is overlapped by mafic volcanic rocks of mid-Miocene age. The Salton Creek fault is parallel to and may be an ancestral element of the Transverse Range structural province.

INTRODUCTION

Volcanic rocks of known and presumed Cenozoic age crop out over much of southern California east of the San Andreas fault and south of the Garlock fault within the Mojave and Colorado Deserts (fig. 1). Their distribution in this broad region is known largely from reconnaissance mapping, but little is known about their petrography, chemical characteristics, and K–Ar ages. In the Mojave Desert, volcanic rocks are exposed slightly less than 30 km from the San Andreas fault (Tropico Volcanics of Dibblee, 1967a), and the volcanic fields of the Newberry and Bullion

* Geological Research Group, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

** Department of Geological Sciences, University of California, Santa Barbara, Santa Barbara, California 93106

*** Department of Geology, San Diego State University, San Diego, California 92182

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THE PICACHO MINE:

A GOLD MINERALIZED DETACHMENT IN SOUTHEASTERN CALIFORNIA

Peter A. Drobeck*, Frank L. "Bud" Hillemeyer**,

Eric G. Frost***, Gail S. Liebler****

ABSTRACT

Chemgold's Picacho Gold Mine is an important gold producer in southeasternmost California. It is also important as an example of a detachment-related gold deposit. Ore is mined from several open pits within the crushed rock along the Chocolate Mountains Detachment Fault of mid-Tertiary age. The crushed and highly weathered nature of the ore, a low stripping ratio, and excellent recoveries from a heap-leaching process add to the economic viability of this efficiently run mine.

The region surrounding Picacho has undergone three major structural disturbances. In Late Jurrasic or Cretaceous time, a series of Precambrian and Jurassic gneisses and intrusive rocks were thrust over the Jurassic Orocopia Schist along the mylonitic Chocolate Mountains Thrust System. In Oligocene and Miocene time, extension of the crust culminated in producing the Chocolate Mountains Detachment Fault (CMDF). The brecciated fabric and low-temperature mineralogy of the fault zone, as well as the stratigraphic reconstruction of the upper plate, indicate the detachment fault formed as shallowly as 1 km in the vicinity of the Picacho Mine. Seismic studies by CALCRUST indicate that detachment-related deformation extends to at least mid-crustal levels in the Chocolate Mountains region. The upper plate of the shallowly dipping CMDF includes primarily the Jurassic(?) Winterhaven Formation and Oligocene-Miocene fanglomerates and volcanic rocks. The lower plate includes the Orocopia Schist, Precambrian and Jurassic metamorphic rocks, and the Cretaceous(?) Marcus Wash Granite. The last major structural event was an intense episode of normal faulting that dissected both the Chocolate Mountains Thrust and the Chocolate Mountains Detachment Fault. This deformation may be related to progressive extensional deformation within the detachment system or later deformation genetically related to the San Andreas system of transform tectonics.

The four orebodies that comprise the Picacho Mine are localized along breccia zones associated with the CMDF. The Mesozoic thrust fault does not seem to have had any influence on the ore deposit except in helping to localize the detachment fault. The hanging wall to all the hypogene ore is barren Oligocene-Miocene Quechan Volcanics. The uppermost surface of the CMDF usually shows an abrupt termination of gold mineralization. Mineralization in the footwall is a gradational and erratic feature, suggesting that it was the feeder zone for the ore. Ore is comprised of brecciated Precambrian and Jurassic metamorphic rocks and the Cretaceous(?) Marcus Wash Granite, which have been mineralized with pyrite, hematite, quartz, and gold. Felsic gneisses and Marcus Wash Granite form the best grades of ore because of their tendency to shatter and take up a disproportionately large share of extensional strain. The most shattered rocks were the most porous to mineralizing solutions and show the best gold grades. Biotite gneisses and schists are commonly less brecciated and mineralized. A large share of the hypogene orebody was eroded from post-ore horsts and preserved as talus breccias.

Preliminary fluid inclusion work indicates homogenization temperatures in syn-mineralization quartz of 201° to 226° C with salinities of 0.5 to 0.7 wt. % NaCl equivalent. Trace-element geochemical studies show anomalous As and Sb associated with the ore. Both the As and Sb form a halo extending outward from the ore deposit, providing an exploration target of varying size, depending on the rock type. These temperatures and trace-element anomalies are typical of epithermal deposits.

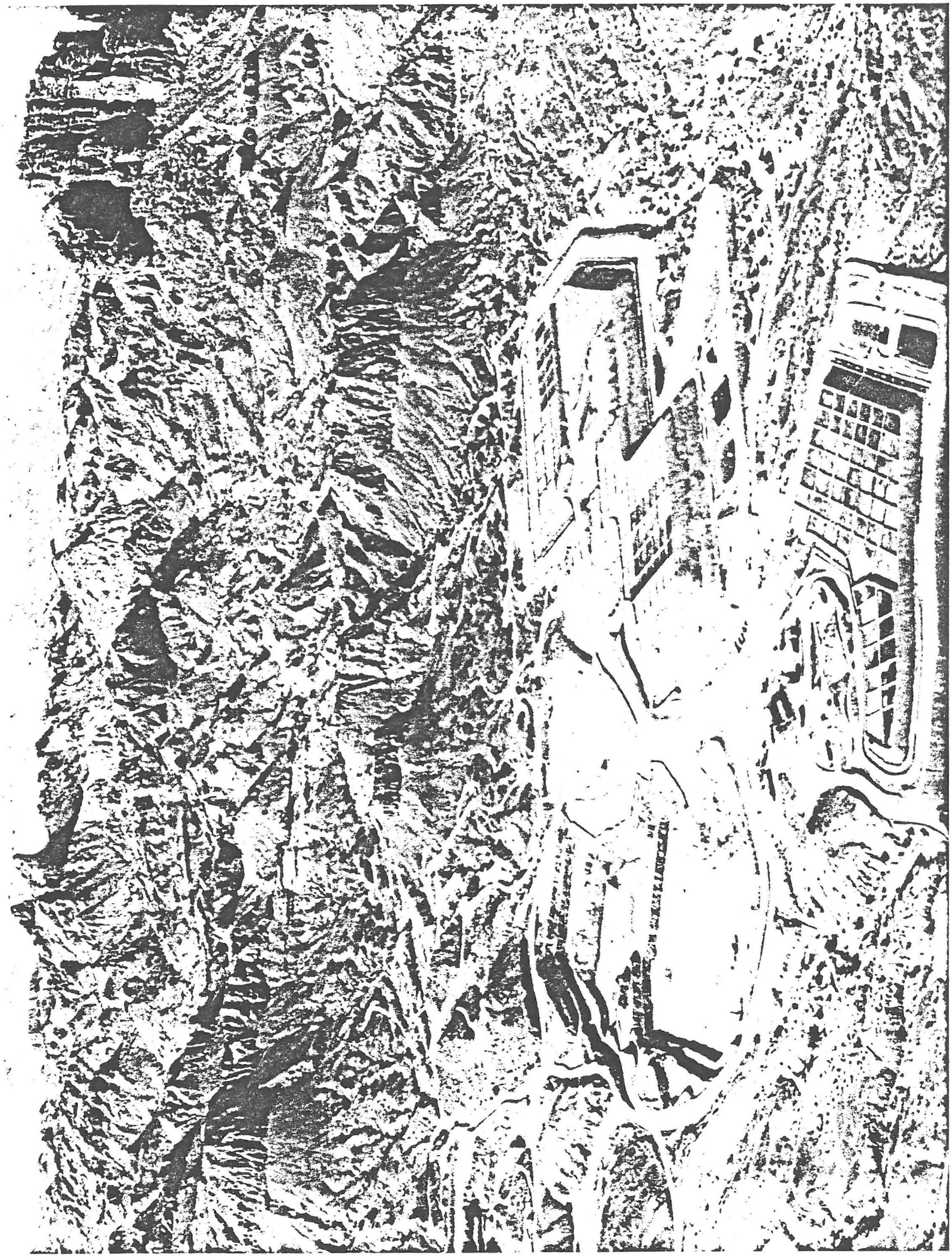
* ~~Western States Minerals~~, 37 Bluejay Road, Kingman, Arizona 86401

** Fischer-Watt Mining, 114 Tucker - #7, Kingman, Arizona 86401

*** Dept. of Geol. Sci., San Diego State Univ., San Diego, California 92182 (current address: CALCRUST, Dept. of Geol. Sci., Univ. of Calif., Santa Barbara, Santa Barbara, California 93106)

**** Dept. of Geosciences, University of Arizona, Tucson, Arizona 85721

Page 113 Air view of the Picacho Mine looking to the west with Picacho Peak in the background. Orebodies and pits are on the left, with leach tanks and pads in center. Picacho detachment fault is exposed in the area just off the lower right corner of the photo.



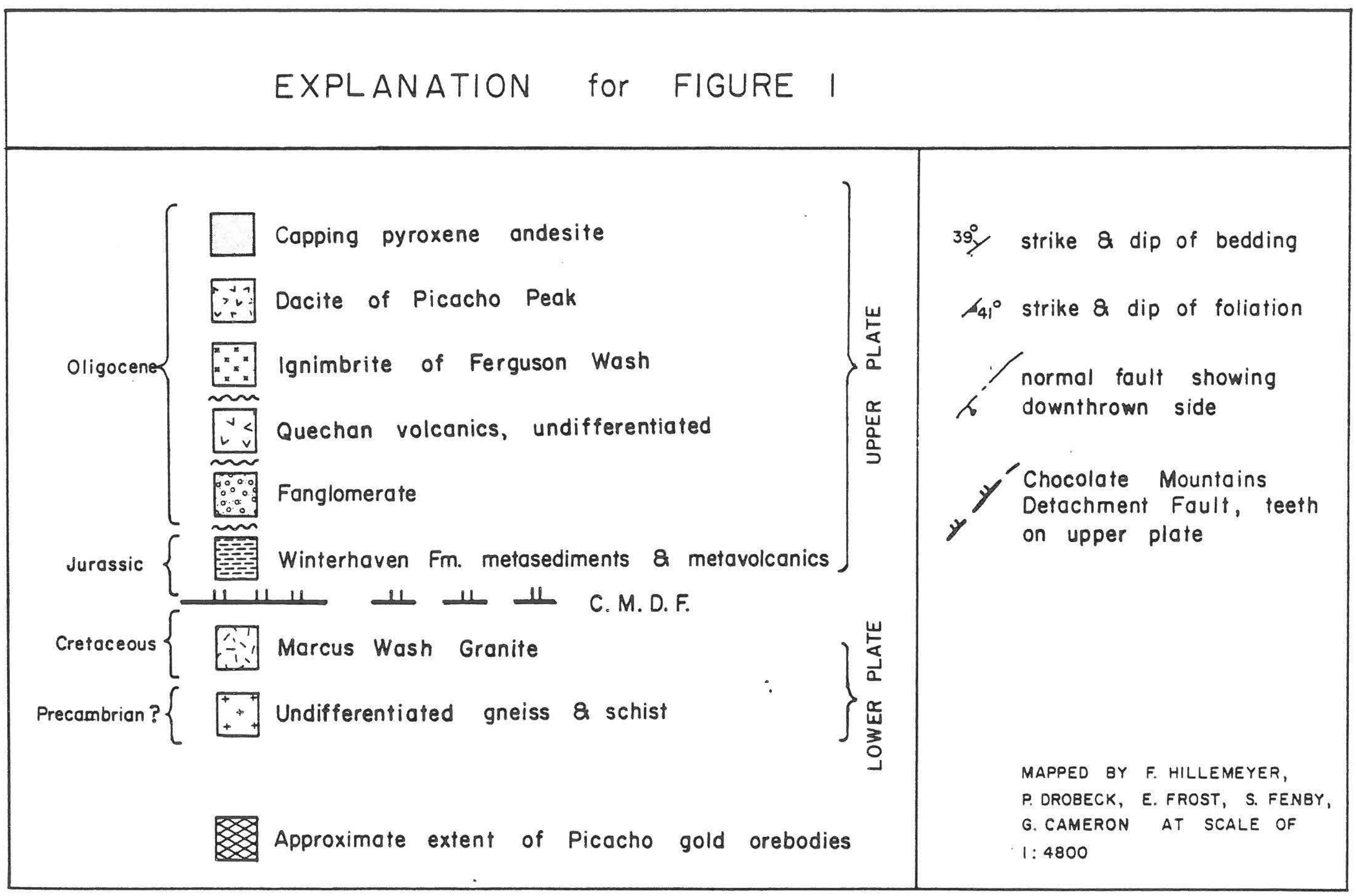
Porosity and permeability developed by brecciation within the CMDF zone provided access for the mineralizing fluids. Breccia zones along the main fault zone, between adjacent strands of the detachment fault, and along upper-plate normal faults appear to be the primary localizers of the orebodies. The Picacho gold mineralization appears to have formed when rising epithermal fluids, carrying gold in bisulfide complexes, intersected the CMDF breccia or shatter zones. The fault zone was probably a fresh-water aquifer until these epithermal fluids reached it. When the fresh water oxidized the epithermal fluids, the gold was precipitated with and onto pyrite grains. The association of the gold with primary pyrite and hematite indicates varying conditions of oxidation as these fluids mixed. The structural aspects of this explanation are applicable to many gold, silver, manganese and copper deposits in the southwestern U.S., but the geochemical mechanism may be more unique to the Chocolate Mountains region.

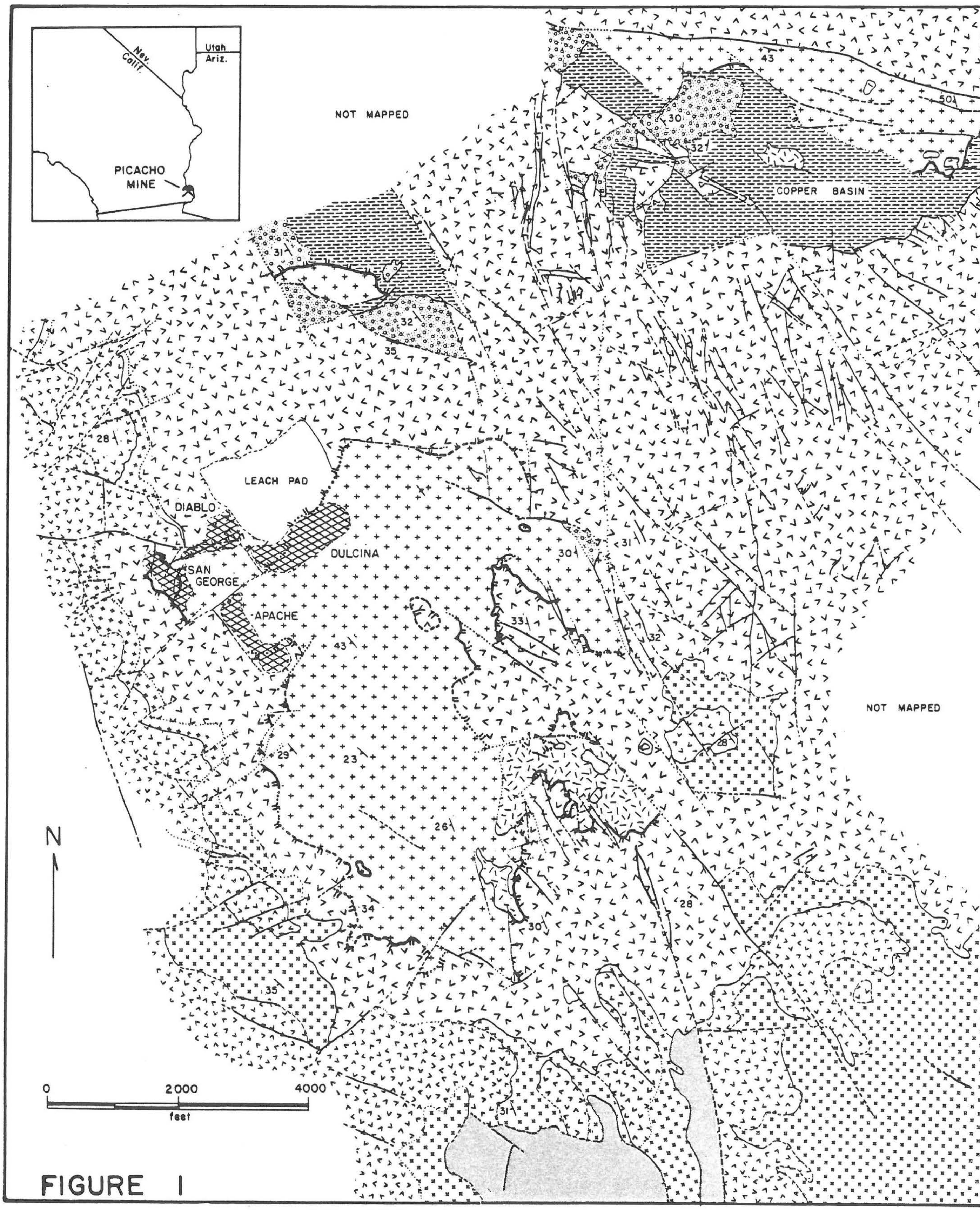
INTRODUCTION

The Picacho Gold Mine is located in the Chocolate Mountains of southeasternmost California, approximately 15 miles (24 km) NNW of the city of Yuma, Arizona (Fig. 1). The mine produced on the order of 150,000 oz. of gold from underground workings between 1860 and 1910 (Harris and Van Nort, 1975; Van Nort and Harris, 1984). Chemgold Inc. has been operating the mine since 1981 as an open-pit operation (Fig. 2). Reserves in early 1985 were 9.7 million short tons grading .038 oz./ton gold (1.3ppm). The present mining rate is approximately 100,000 tons of ore per month with a 1:1 stripping ratio (Wood, pers. commun., 1985). The ore is strongly oxidized by weathering so that gold occurs in the free state. Most of the gold is between 10 and 100 microns in size making the ore readily amenable to heap leaching. The pronounced brecciation and weathering of the rock make the ore very crumbly so that crushing is unnecessary. These favorable features, in combination with a very efficiently run operation, allowed Chemgold to produce gold at approximately $125/oz. in fiscal 1984-5.

The mine occurs in a structurally complex region, which has undergone Jurassic-Cretaceous metamorphism and thrusting, Oligocene-Miocene detachment faulting, and Miocene-Pliocene basin-and-range and/or San Andreas related faulting. No genetic relationship has been established between mineralization and thrust faulting, but the ore is found to be localized along the Chocolate Mountains Detachment Fault (CMDF) System. The lower plate of the detachment fault is comprised of Precambrian or Jurassic gneiss and schist, the Jurassic Orocopia Schist, and the Late Cretaceous(?) Marcus Wash Granite. The upper plate of the detachment fault is comprised of the Jurassic Winterhaven Formation (Haxel and others, in press), Tertiary olivine basalt and overlying fanglomerate, and a series of Oligocene-Miocene calc-alkaline volcanic rocks ranging from trachybasalt to rhyolite (Crowe, 1973a, b, 1978; Crowe and others, 1979).

Geologic mapping, petrography, geochemical analyses, and fluid inclusion studies have shown that the gold ore at Picacho occurs in breccia zones developed in the detachment system, that the gold was intro-





GEOLOGY OF THE PICACHO MINE AREA

duced along with pyrite into the cataclasite matrix, and that the mineralization is epithermal in nature. Keith and others (1984) and Wilt and Keith (1984) have developed a theoretical geochemical model that they feel links the Picacho mineralization to the Laramide(?) Marcus Wash Granite. Tosdal and others (1985) have found a regional empirical association of gold with rocks similar to lower-plate rocks at Picacho.

LOWER-PLATE LITHOLOGIC UNITS

Precambrian Metamorphic Rocks

The predominant rocks in the lower plate of the CMDF in the region around the Picacho Mine are paragneiss of probable Precambrian age (Fig. 1). The supracrustal origin of these gneisses was demonstrated by Dillon (1975), who found layers of calc-silicate marble and micaceous quartzite in gneisses in the central Chocolate Mountains. Dillon (1975) reported an age determination on an augen gneiss in the Pilot Knob range (28 km south of the Picacho Mine) of 1.7 Ga by L. T. Silver. This augen gneiss intrudes banded and laminated gneisses similar to those found throughout eastern Imperial County. Recognition of these rocks indicates that the Picacho Mine area was continental in mid-Proterozoic time. However, recent studies by Haxel and others (in press) have indicated that some of these rocks are Jurassic rather than Precambrian.

In the Picacho region, as well as throughout the Precambrian of southeast California, Arizona, and Colorado, the older gneisses have been intruded by coarsely porphyritic biotite granite and quartz monzonites commonly showing rapikivi texture (Anderson, 1983; Wasserberg and Lanphere, 1965; Anderson and others, 1979). The age of this widespread magmatic event is approximately 1.4 Ga (Silver and others, 1977) in the southwestern Arizona-southeastern California area (Silver and others, 1977; Anderson, 1983). The general absence of a metamorphic foliation in this unit distinguishes it as being post orogenic and helps make it relatively easily identifiable in the field.

Volumetrically the predominant lower-plate rocks

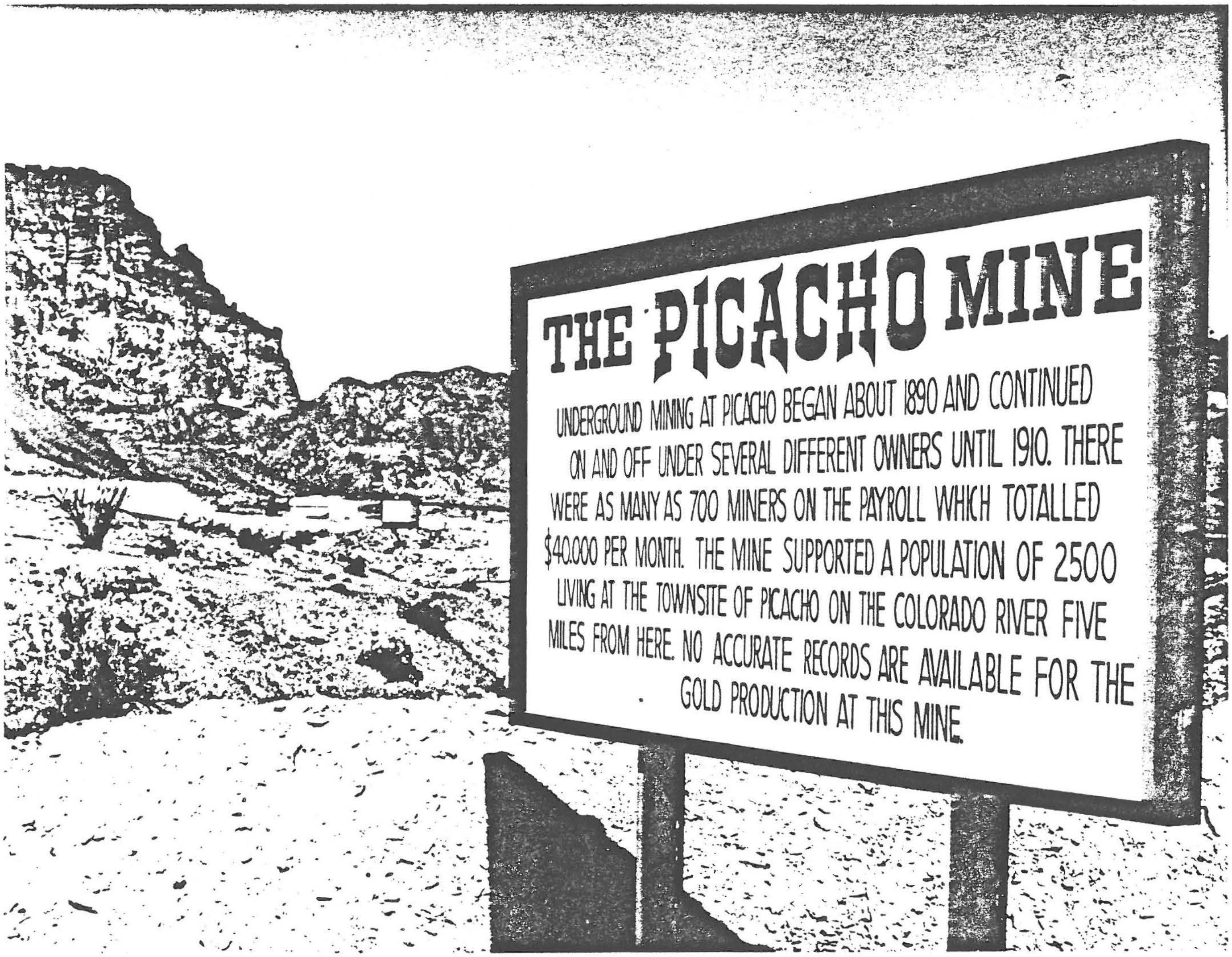


Figure 2. View of the Picacho Mine and Picacho Peak, looking west from the Picacho road. Sign notes some of the historic aspects of the mine. Leach pad and some of mine buildings visible in center. Foreground is composed of Precambrian(?) gneiss in the lower plate of the detachment system.

in the mine area are the Precambrian(?) schists and gneisses exposed in much of the Picacho region (Figs. 1, 2). Along the periphery of the deposit, especially on the arching hill just south of the mine, the predominant variety of this suite of rocks is a microcline "augen schist-gneiss." Here, the microcline forms blocky subhedra and euhedra generally 1 to 3 cm in longest dimension. The matrix of the rock is comprised of microcline, quartz, oligoclase, biotite, and minor hornblende. Although most microcline subhedra have their longest dimension rotated parallel to foliation, many do not. One can observe all gradations of rotation of the subhedra into the foliation, sometimes with wispy pressure shadows of biotite, feldspar and quartz. Locally the microcline crystals have been concentrated into 1 to 2 cm thick bands and show some recrystallization, thus forming a true gneissic texture. No strong linear fabric or mylonitic textures have been found in this rock in the mine area, although mylonitic textures are present in the region near the Chocolate Mountains Thrust.

The textures imply that the microcline crystals are phenocrysts from an originally coarsely porphyritic granite. The field appearance of this rock is similar to the 1.4 Ga rapakivi granite, except that it is well foliated in most places. If this unit is the rapakivi granite, it would require that the unit was metamorphosed and deformed during Mesozoic time. Alternatively, and probably more likely, the coarsely crystalline unit may be a Jurassic plutonic body that has intruded the Precambrian country rock. Such a scenario has been suggested by Tosdal and others (1985) and Tosdal (pers. commun., 1985) on the basis of their regional geologic and isotopic studies.

Although this augen gneiss is common in the periphery of the gold deposit, it is only rarely seen in the mine and even more rarely as ore. Because the ore is so characteristically highly broken, this rheologically strong, homogeneous rock body appears to have behaved as a solid mass rather than breaking and forming a host for the ore fluids.

The most abundant Precambrian(?) rock in the mine is an oligoclase-quartz-biotite ± microcline ± augite ± sphene ± hornblende ± garnet ± apatite gneiss. Tosdal (pers. commun., 1985) has indicated that this rock may also be part of the suite of Jurassic intrusive and metamorphic rocks. In places, a moderately developed foliation has segregated the biotite ± sphene ± augite into a melanosome and the oligoclase + quartz ± microcline into a leucosome. Generally, the segregation is incomplete, giving the appearance of a schist. Although the primary mineralogy is fairly consistent, with oligoclase + quartz comprising 70-80% of the rock and biotite comprising 15-20%, the secondary mineralogy is quite variable. In thin section one can observe shearing along leucosome-melanosome boundaries and within and around biotite grains. Near the detachment fault in the mine, the rock is usually weakly brecciated at best. This biotite-oligoclase-quartz gneiss occurs within and peripheral to the orebodies, but it is generally mineralized to only low grades. It comprises much of the low-grade ore (.010 - .040 oz./ton Au or .34 - 1.4 ppm Au) in the mine. Large volumes of this rock have been mineralized with gold to subeconomic grades, i.e., .002 - .010 oz./ton Au (.07 - .34 ppm).

A less abundant, but very important Precambrian(?) rock in the mine is a felsic gneiss. This rock unit has only been observed in the mine and in proximity to the detachment fault where textures are largely destroyed by the detachment-related deformation. The rock is composed of oligoclase, quartz, and minor microcline with trace to minor amounts of biotite. It is easily confused with the Marcus Wash Granite when there is very little biotite as the foliation becomes indistinct. This felsic gneiss is the primary ore host in the San George orebody.

Orocopia Schist

The Jurassic Orocopia Schist occurs in the Picacho region but not in the immediate vicinity of the mine. A small body of Orocopia Schist is exposed about 3.5 miles (5.6 km) north of the Picacho Mine. The predominent lithology of the Orocopia Schist is quartzo-feldspathic schist with abundant muscovite. The protolith is believed to be largely a proximal facies greywacke (Haxel, 1975, 1977; Dillon, 1975). The schist is usually strongly foliated, commonly lineated, and shows compositional layering that is parallel to the foliation. Intrafolial folds and inconsistent facing directions of compositionally graded beds were described and interpreted by Haxel (1977) to indicate that sedimentary bedding has been completely transposed. The grade of metamorphism that accompanied this deformation is fairly consistently middle greenschist grade.

Haxel (1977) showed that metamorphism of the Orocopia Schist was coincident with probable Cretaceous emplacement of the Precambrian-Jurassic Chocolate Mountains Thrust allochthon. Regional studies of the Pelona-Orocopia Schist and Vincent-Chocolate Mountains Thrust System suggest that metamorphism and deformation occurred synchronously (Ehlig, 1958, 1968, 1981; Jacobson, 1980, 1983). The thrust and the Orocopia Schist are exposed in the Picacho region within the core of a large-scale, east-west trending antiform. This antiform is best developed in the Gavilan Hills, just northwest of the Picacho Mine, where classic localities of the Orocopia Schist and Chocolate Mountains Thrust are located (Fig. 3). The Gavilan Hills antiform is an extension of the main Chocolate Mountains antiform, which continues into Arizona for at least several tens of kilometers.

Marcus Wash Granite

The youngest rocks in the lower plate of the CMDF are the Marcus Wash Granite and associated pegmatite dikes as defined by Haxel (1977). The Marcus Wash is a leucocratic quartz monzonitic to alaskitic body with equigranular to porphyritic to foliated textures. The rock is generally composed of subhedral quartz and microcline with minor plagioclase, magnetite, and biotite (Haxel, 1977). Muscovite is found only in related pegmatitic stringers. No whole-rock chemistry or petrographic studies have been published on the Marcus Wash Granite. It is believed to be a siliceous, metaluminous, epizonal-mesozonal intrusive body. It intrudes the Winterhaven Formation, Orocopia Schist, and Precambrian gneiss. It is structurally overlain by Oligocene rocks above the CMDF. In Marcus Wash the granite appears to have intruded along the Chocolate Mountains Thrust and shows ductile flow foliations suggesting that it may have been intruded synchronously with movement on the Chocolate Mountains Thrust. For this reason a Laramide (Late Mesozoic) age and genetic association have been inferred. Alternatively, the Marcus Wash could be Tertiary in age, intruding the CMDF and its overprint on the Chocolate Mountains Thrust System.

The Marcus Wash Granite is a very important rock unit in the Picacho Mine. In the mine it is a medium to coarse-grained hypidiomorphic-granular oligoclase-quartz-microcline quartz monzonite. It contains 0 to 3% biotite and traces of garnet, zircon and allanite. In places it is white colored, but iron oxide staining has usually discolored the rock to reddish-brown and gray colors.

Nearly all the contacts between the Marcus Wash Granite and other rocks in the mine are faults. However, many of these faults have followed intrusive contacts between the granite and metamorphic rocks. The pattern of the intrusive relationships is complex, with the Marcus Wash intruding as pods, dikes, and sills. Most of these intrusive contacts have been overprinted by detachment-related shattering and brecciation. A large body of Marcus Wash granite crops out about 1 km southeast of the mine. The mine thus occurs along the overall contact zone between the Marcus Wash Granite and pre-existing metamorphic rocks. It appears that the complex interfingering of Marcus Wash Granite and metamorphic country rocks provided a zone of contrasting rheological properties that localized the mid-Tertiary detachment system and its attendent shattering and brecciation. Flow of fluids through these shatter zones appears to have formed the Picacho ore bodies.

The Marcus Wash Granite dikes, pods, and sills served as loci for detachment-related brecciation. Where exposed in the Picacho Mine, as well as in other areas near the detachment fault in the region, the granite is typically much more intensely deformed than the metamorphic rocks (Fig. 4), and consequently richer in gold. The primary reason for the difference in brecciation between the granite and the metamorphic rocks appears to be compositional, with the hypidiomorphic granite shattering rather than slipping on foliation planes or grain boundaries. The interlocking grains of the Marcus Wash granite appear to have shattered in response to detachment-related stresses, probably over a period of several millions of years of time. Distinct cataclastic textures of complexly overprinted periods of brecciation characterize the granite in the vicinity of the mine.

In contrast, the metamorphic rocks are more likely to strain along foliation planes, forming microfaults, but leaving most of the intervening rock textures intact. Motion within the metamorphic rocks appears to have been localized along compositional boundaries and within biotite-rich layers. The metamorphic rocks are thus left largely intact, with neither the porosity nor the permeability to provide a good host for ore fluids.

Brecciated Marcus Wash Granite forms a significant proportion of the ore at the Picacho Mine. Furthermore, the granite and felsic gneiss form the highest grade of ore in the mine. The samples with the highest gold grades are also the most cataclasized rocks (Table 1). Samples of cataclasized Marcus Wash Granite and felsic gneiss assayed .045 to .210 oz./ton Au (1.3 to 6.1 ppm). The granite is clearly an essential element in forming the Picacho orebodies.

UPPER-PLATE LITHOLOGIC UNITS

Winterhaven Formation

The Winterhaven Formation is the oldest rock unit in the upper plate of the CMDF, except for small bodies of Precambrian gneiss. The Winterhaven was originally thought to be Paleocene in age (Haxel, 1977; Haxel and Dillon, 1978) because it appeared to depositionally overlie the Chocolate Mountains Thrust of apparent Late Cretaceous age. Further work has demonstrated that the Winterhaven is actually involved in the thrusting and is probably Jurassic or Cretaceous in age (Frost and Martin, 1983b; Haxel and others, in press). As currently defined by Haxel and others (in press), the Winterhaven Formation has three members: a basal dacite, a medial quartz-arenite, and an upper argillitic siltstone. The total known thickness of the unit is about 450 m. Further stratigraphic and isotopic work is being completed on the unit by Mike McDowell as an SDSU Master´s thesis (McDowell, 1986).

The entire formation is metamorphosed to phyllites of lowermost greenschist grade and is easily differentiated from the Orocopia Schist. Haxel and others (in press) have shown the two formations are lithologically distinct as well. They do not appear to be the same formation metamorphosed to different grades. However, there is still the possibility that the Winterhaven represents the uppermost portion of the lithostratigraphic sequence of which the lower portion is the Orocopia Schist (Frost and Martin, 1983a, b). How the Winterhaven and Orocopia Schist relate to the 7 km thick McCoy Mountains Formation (Pelka, 1973; Harding, 1980; Harding and others, 1982, 1983; Tosdal, 1982) to the north is still open to question. CALCRUST deep-seismic profiling in the area between the Orocopia-Winterhaven outcrops and the McCoy Mountains Formation should help resolve this major regional enigma.

Depositional contacts have not been unequivocally documented between the Orocopia Schist and the Winterhaven Formation. Haxel and others (in press) found a lower depositional contact to the Winterhaven Formation where it rests on Jurassic(?) metarhyolite. The age relationship between the metarhyolite and the Orocopia Schist is at present unknown, although both are probably Jurassic. The contacts between the Orocopia Schist and the Winterhaven are cryptic in many places, but most appear to be faults. The Tertiary volcanic and sedimentary sections are clearly deposited on the Winterhaven, and both the Tertiary and Winterhaven are downdropped on normal faults into juxtaposition with the Orocopia Schist. This large-scale relationship along with some suggestive depositional relationships, led Haxel (1977) and Haxel and Dillon (1978) to suggest that the Winterhaven was depositional on the Orocopia and the Chocolate Mountains thrust system. This initial interpretation of the age and contact relationship of the Winterhaven has been revised in favor of a probable Jurassic age for the Winterhaven and a realization that the Winterhaven was involved in at least some of the same metamorphism and deformation that affected the Orocopia Schist and produced the Chocolate Moun-

Figure 3. (Facing page) Antiform of Orocopia Schist in the Gavilan Hills is visible in this view looking east toward Picacho Peak (large dark mass on right) and Picacho Mine. Mine sits on the southwest flank of the antiform. Gavilan Hills detachment fault is located at the base of the slope, structurally above the Chocolate Mountains Thrust, which helps form the resistant ridge along the northern flank of the Orocopia Schist antiform. Cross faults offset the thrust and detachment fault. Longitudinal fault, which is marked by color contrast within Orocopia Schist, drops dark klippe of upper-plate (to the thrust) rocks down into schist (Haxel, 1977).

Figure 4. Close-up view of shattered dike of Marcus Wash Granite in much less shattered, dark-colored Jurassic(?) or Precambrian(?) gneiss within the Picacho Mine. Rock control on the degree of shattering and resultant mineralization is pronounced.

tains Thrust System (Frost and Martin, 1983a, b; Haxel and others, in press).

No Winterhaven Formation occurs within the mine proper, but a large body of highly deformed Winterhaven is present 0.5 mile (800m) north of the mine in Little Picacho Wash just above an excellent exposure of the Chocolate Mountains Detachment Fault (Fig. 1). The original sedimentary and volcanic origin of the Winterhaven is still well preserved in these exposures as is the intense overprint of detachment-related deformation. The well-preserved bedding makes it possible to easily discern the penetrative extension within the Winterhaven, just above the detachment fault. Elsewhere in the area just north of the mine, the Winterhaven is less deformed by high-angle normal faults and more deformed by foliation-parallel slip. The best section of Winterhaven is exposed approximately 3 miles north of the mine, where the Winterhaven defines a large antiform (Haxel, 1977; McDowell, 1986). Here the Winterhaven is near vertical in places, exposing a good cross section of its stratigraphic components. The most interesting of the units in this exposure is a light-colored, relatively clean quartzite that may be correlative with the Aztec Sandstone. Exposures of similar quartzite units are present northeast of the Mesquite Mine in the southwestern Chocolate Mountains and were described by Dillon (1975) as an arkose within his retrograde Orocopia Schist unit. Frost and Martin (1983b) suggested that the unit could be correlative with the Aztec Sandstone, which is present just to the north in the Big Maria Mountains (Hamilton, 1982; Ellis, 1982; Stone and others, 1983). It also appears to be present to the southeast of Yuma in northernmost Mexico at El Capitan (LeVeille, 1984; LeVeille and Frost, 1984).

Basalt of Little Picacho Wash

All other rock units that occur in the upper plate of the CMDF are Tertiary. The oldest Tertiary rock unit exposed in the region is the basalt of Little Picacho Wash. It has only been recognized in Little Picacho Wash, where it disconformably overlies the Winterhaven Formation and is truncated by the CMDF. The basalt is approximately 75 m thick and is comprised of iddingsite-altered olivine phenocrysts and altered clinopyroxene phenocrysts in an intergranular, interstitial labradorite-clinopyroxene matrix. It is thought to be Eocene or Early Oligocene in age, although it is so altered that isotopic age dating has as yet been unsuccessful. The basalt was erupted into paleovalleys, indicating an irregular topography at the time of eruption. The unit is not shown on Figure 1 because it is too small for the map scale.

Fanglomerates

A 190 m thick sequence of fanglomerates overlies this basal basalt. The fanglomerate is poorly sorted and is comprised primarily of clasts of Winterhaven Formation and lesser amounts of Precambrian(?) gneiss. These alluvial-fan deposits indicate an irregular topography with substantial relief. The coarseness and angularity of the clasts suggest that fault scarps may have been present, giving the initial indication of extensional tectonism. The fanglomerate is tilted to 30 to 60° where exposed near Little Picacho Wash (Fig. 1). Elsewhere in the Picacho basin, the fanglomerate is tilted to steeper angles, including being overturned in the area several kilometers southeast of the mine.

Quechan Volcanics

The fanglomerate is overlain by a sequence of trachybasalt, basaltic andesite and pyroxene rhyodacite named the Quechan Volcanics (Crowe, 1973a, b). These volcanic rocks appear to have been erupted as agglomerates, simple flows, aa flows, and laharic breccias. Marker units within the Quechan are difficult to map, hiding much of the structure within the unit. Because there is extensive faulting within the unit, its true thickness is difficult to estimate. Crowe (1978) suggested a thickness of over 300 m and determined a radiometric age of 31.8 ± 3.2 Ma for the base of the Quechan. Since the Quechan was extruded onto fanglomerate units, which appear to record the beginning stages of extension, these volcanic units are interpreted as post-dating the initiation of normal faulting and related detachment faulting in the region. In Little Picacho Wash, the base of the Quechan Volcanics appears to be conformable with the underlying fanglomerate and basalt of Little Picacho Wash (Fig. 1).

The Quechan Volcanics are severely tilted and faulted throughout the Picacho region. Although the commonly massive flows show few bedding features, where cooling joints or flow laminations are preserved they usually strike N 10 to N 30° W and have 30 to 60° southwestward dips. The reason for this structural complexity is that the Quechan Volcanics are usually within only a few hundred meters (structurally) of the CMDF. The repeated southwestward dips are caused by numerous northwest-striking, northeast-dipping normal faults, which characterize the upper plate of the CMDF. Similar styles of faulting are seen in the upper plates of most detachment faults in the Mojave region. The growth-fault character of the volcanic and sedimentary sections are also typical of the Tertiary sections in many detachment complexes in the region (Teel, 1982; Teel and Frost, 1982; Teel and others, 1983; Pridmore and Craig, 1982; Pridmore and others, 1983; Pridmore and Frost, 1985) and are a clear guide to detachment faults in general. The volcanic rocks overlie more sedimentary and metamorphic rocks (Winterhaven) and effectively hide the detachment fault and related deformation in many places. The clear likelihood of the presence of hidden gold deposits overlain by a veneer of late volcanic rocks makes understanding the regional geometry and Tertiary depositional history of the detachment system a necessity.

The Quechan Volcanics are an essential part of the Picacho orebodies. They are the only upper-plate rocks in the mine and they consistently form a barren hanging wall to the ore. Contacts between the volcanics and the lower-plate rocks are either the detachment fault or post-detachment faults (Figs. 1, 5). This understanding was an aid to explaining the district both for old-time prospectors and miners, as well as for the modern operators of the mine.

Ignimbrite of Ferguson Wash

In the vicinity of the Picacho Mine, the next youngest rock unit is a rhyolite to rhyodacite ash-flow tuff (Fig. 1). Crowe (1978) referred to these rocks as the Ignimbrite of Ferguson Wash, and obtained two age determinations of 25.9 ± 0.9 and 24.7 ± 2.1 Ma. Crowe (1973b) noted that the unit has a basal rhyodacite air fall tuff with the rest of the tuff being rhyolite ash flow tuff. The ignimbrite ranges up to 350 m thick and formed as a single cooling unit. The tuff appears to have been extruded onto an underlying topography of northwest-trending ridges (Crowe, 1973b). The ignimbrite has been tilted by detachment-related faulting, but much less so than the Quechan Volcanics. The tuff is not exposed in the mine, but forms the rugged hills west of the mine (Frontispiece and Fig. 2). It effectively covers a large area of more deformed rocks, hiding both detachment-related deformation and mineralization. Looking at the prominent hills formed by the tuff and younger volcanic rocks has led many workers to conclude that this region is only slightly affected by Tertiary extension, a conclusion that greatly oversimplifies the overall geologic relationships.

Picacho Peak Dacite

A dacite dome complex known as the Picacho Peak Dacite (Crowe, 1978) developed partly contemporaneous with and partly succeeding eruption of the ignimbrite of Ferguson Wash. Flows and flow breccias cover the ignimbrite west of the Picacho Mine but Crowe (1978) noted the reverse relationship 1 km north of Picacho Peak. The dacite flows are tilted similarly to the ignimbrite. Hence the dacite is also late syntectonic with respect to the CMDF. These dacite flows were intruded by a similar appearing hypabyssal plug which underlies part of Picacho Peak about 1.5 km west of the Picacho Mine (Fig. 2).

POST-DETACHMENT LITHOLOGIC UNITS

Basalt of Black Mountain

Within the Picacho region, Crowe (1973b) described the middle Miocene (~13 Ma) basalt of Black Mountain, which marks the change to fundamentally basaltic magmatism as seen in much of the Basin-and-Range Province (Suneson, 1980; Leeman, 1974, 1979). However, the basalt is not exposed in the immediate mine vicinity. This unit is widespread in the general Picacho region, forming the prominent mesas just northwest of Yuma, which form much of the eastern skyline as the mine is approached from Yuma. The basalts also form the prominent mesa (Black Mountain)

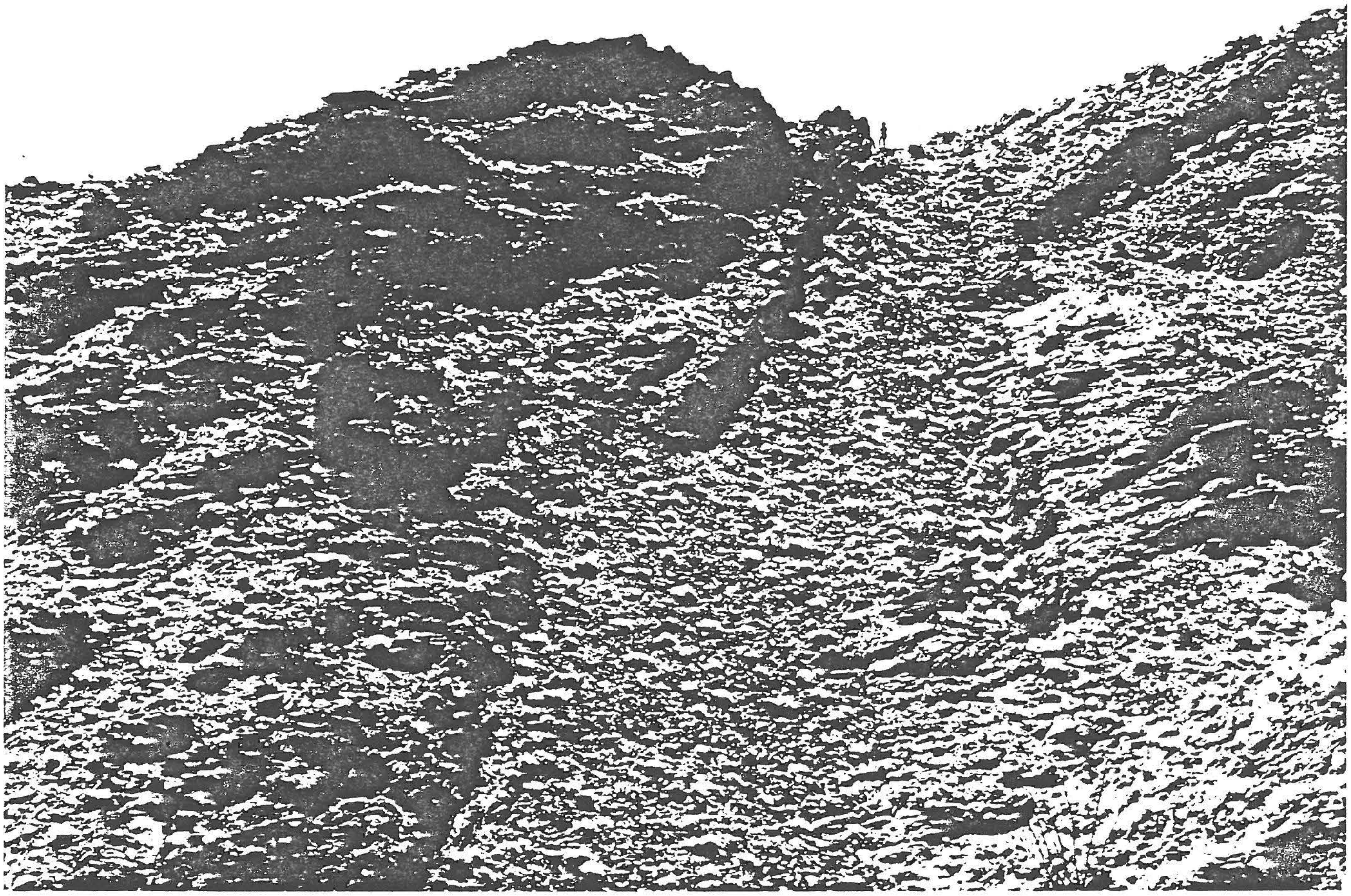


Figure 5. View of the Chocolate Mountains Thrust Fault in the Gavilan Hills looking to the east. Fault produces a several meter thick mylonite zone that forms dark cliff across photo, just to the left of the person on the skyline. Upper-plate gneisses are truncated by the mylonite zone, and indicate a northward transport by their angular relationship with the thrust (Haxel, 1977). Lower-plate Orocopia Schist glimmers in the light, displaying its schistosity.

north of the mine in the Gavilan Hills, covering much of the Orocopia Schist outcrop between the Picacho Mine and the Mesquite Mine. These dark basalts are present on a regional scale and typically provide the younger age control on the cessation of detachment faulting (Davis and others, 1980; Eberly and Stanley, 1978; Shafiqullah and others, 1980; Reynolds, 1980).

Talus Breccias

A talus breccia forms a prominent lithology in the mine, itself, and is well developed in the upper portion of several of the orebodies. Three compositional types of talus breccia were mapped as follows: 1) clasts of unmineralized Quechan Volcanics, 2) clasts of mineralized metamorphic and granitic rocks, and 3) mixtures of the previous two types. The clasts within the talus breccias are deeply weathered, irrespective of their lithology. Most clasts are angular to sub-angular and range from 0.5 cm to 5 m in size. The breccias are both clast and matrix supported, and appear to be devoid of any noticeable bedding. The matrix material is generally composed of fine-grained rock fragments identical to the clasts. Some clay or soil is present as matrix material, reflecting the talus origin of the breccias. Little or no cementation is present making the talus piles very amenable to the mining operation.

These talus breccias comprise a significant portion of the ore at Picacho. The talus breccia of mixed rock and of lower-plate rocks contain highly variable amounts of gold-bearing metamorphic and granitic rocks. The gold grade in the talus breccias is erratic due to mixing of ore with waste. Assays range from barren to 0.25 oz./ton Au (8.6 ppm). However, most of the talus breccia ore is low grade, i.e., 0.010 to 0.030 oz./ton Au (0.34 to 1.0 ppm).

The talus breccias are best displayed in the northeastern part of the Apache pit (Fig. 11), where they occur along an eastnortheast post-ore fault that has downdropped ore to the south and uplifted barren lower-plate rocks to the north. The proximal relationship to this post-ore fault, the non-bedded character of the breccias, the intense weathering of the breccia clasts, and the inclusion of ore fragments in

Figure 6. Close-up view of the Chocolate Mountains Thrust Fault in the cliff shown in Figure 5. Light-dark contact is within the mylonitic zone and marks the contact between lower-plate Orocopia Schist and upper-plate gneiss. The thrust zone has almost no porosity or permeability, which keeps the Mesozoic thrust from being mineralized by Tertiary epithermal fluids.

the breccias indicate the talus breccias developed along post-ore scarps. The erratic and low grade of the talus breccias is attributed to erosion of part of the hypogene orebody along fault scarps, dilution of the eroding orebody with waste rock, and supergene redistribution of some of the gold.

CHOCOLATE MOUNTAINS THRUST

The Chocolate Mountains Thrust is a major tectonic feature in much of the western Mojave desert region (Ehlig, 1958, 1968, 1981; Haxel and Dillon, 1978). The thrust places Precambrian and Jurassic gneiss and intrusive rocks over the Mesozoic Pelona-Orocopia Schist (Fig. 5). The time of thrusting was once considered to be Late Cretaceous or early Tertiary (Ehlig, 1968, 1981; Ehlig and others, 1975; Haxel and Dillon, 1978), largely on the basis of Rb/Sr studies done in the San Gabriel Mountains. Continued study by these and other researchers has raised the possibility that multiple periods of deformation occurred over a significant period of time (C. Simpson, pers. commun., 1985). Full understanding of both the time of thrusting and its direction of tectonic transport will require more detailed structural and isotopic studies.

Irrespective of the time and direction of thrusting, the thrust formed at significant depth as demonstrated by the detailed studies of Jacobson (1980, 1983), Graham and England (1976), and Haxel and others (in press) following the suggestion of such deep-seated thrusting by Ehlig (1968, 1981), Dillon (1975), Haxel (1977), and Haxel and Dillon (1978). In the general Picacho Mine area, the thrust is best exposed in the nearby Gavilan Hills (Fig. 5) as mapped by Haxel (1977). Here the thrust is marked by a distinct zone of mylonites up to 3 m thick, which separates the lower-plate Orocopia Schist from upper-plate gneiss of Precambrian or Jurassic age. The recrystallization fabric produced along the thrust zone suggests mid-crustal levels of formation (Fig. 6). The thrust zone has almost no porosity or permeability, making the thrust zone perhaps the worst host for mineralizing fluids in the region. Rocks on either side of the thrust are more open because they have not been as recrystallized as the thrust zone itself. This is in very marked contrast to the areas of gold mineralization, which are characterized by broken, brecciated rock with pronounced open-space filling.

In some places, the contact between the Orocopia Schist and overlying rocks is a broken, brecciated zone. Some of these contacts are mineralized and have led some explorationists to pursue the Chocolate Mountains thrust as an exploration target. However, wherever the contact between the Orocopia Schist and other rocks is mineralized, it appears to be because of the overprint of later Tertiary low- to high-angle normal faults. The Chocolate Mountains thrust, itself, does not appear to act as a host for mineralization, but contacts mapped as "thrusts" do in some places. Especially where the actual contact between Pelona-Orocopia Schist is poorly exposed, the "thrust" nature of the contact has been, by necessity, inferred. With the current recognition of the overprint of Tertiary detachment faulting on the Pelona-Orocopia Schist and Vincent-Chocolate Mountains thrust system, the mapped contacts of the "thrust" are a distinct exploration target. They are a target, however, not because they are the thrust, but rather because they may actually be the Tertiary detachment fault.

In the Picacho Mine area, the Chocolate Mountains thrust is well exposed in most places and is clearly not mineralized. The schist does not occur in the mine and is not present in drill holes as deep as 150 m (B. Stannus, pers. commun., 1985). In the nearby Gavilan Hills area, the thrust is not mineralized, but controls the location of the detachment fault, which is mineralized. The thrust appears to have created a pronounced anisotropy within the crust, such that the overprinted Tertiary extensional tectonisim was localized, at least in part, in the vicinity of the thrust (Fig. 3). The detachment fault is not localized along the thrust zone, but along the zone between the thrust-related mylonitic rocks and the less deformed upper-plate gneisses. In some areas, the detachment fault or upper-plate normal faults cross cut the Mesozoic thrust fault, juxtaposing upper-plate (to the thrust) rocks against the lower-plate Orocopia Schist. In these places, the thrust is cut out (down-dropped) and replaced by shattered or brecciated fault structures that are variably altered and mineralized. The Gavilan Hills area is an excellent example of this relationship (McDowell, 1986).

CHOCOLATE MOUNTAINS DETACHMENT FAULT

The Chocolate Mountains Detachment Fault (CMDF) is a regionally developed fault system that is one of the products of crustal-scale, mid-Tertiary extension. The lower Colorado River region is distinctly outside the corridor of "metamorphic core complexes" (Davis and Coney, 1979; Crittenden and others, 1980) in this region, which stretches from Las Vegas, through the Whipple Mountains (Davis and others, 1980; Carr and Dickey, 1980; Carr, 1981) and across west-central Arizona (Shackelford, 1976, 1980; Lucchitta and Suneson, 1982; Suneson, 1980; Otton, 1981a, b, 1982; Rehrig and Reynolds, 1980; Reynolds and Rehrig, 1980) to the Tucson region (Davis, 1980) and into Sonora (Anderson and others, 1980). The discovery of the CMDF was, therefore, not a natural outflowing of the study of core complexes in California or Arizona, where the emphasis on "core-complex" type deformation concentrated workers' efforts in mountain ranges composed primarily of lower-plate rocks with upper-plate rocks fringing them. Core complexes were widely thought to require lower-plate mylonitic rocks to form part of their intrinsic identity, making the southeastern California-southwestern Arizona area a poor candidate for detachment faulting because no Tertiary or "core-complex" type mylonitic rocks are, or were, known from this region.

Development of the Detachment Concept at Picacho

Mapping by Crowe (1973b), Dillon (1975), and Haxel (1977) and their major papers on their work were completed prior to the widespread realization of the extent of detachment faulting in the southwestern U.S. The complexity of the deformation in the Chocolate Mountains region and the clear differences it has from ranges such as the Whipples or Rincons, make it very understandable that detachment faulting was not recognized as such in these early studies. Work by Haxel (1977), in particular, illustrates that the geometric relationships that are now appreciated as part of the mid-Tertiary detachment system were observed and mapped, but not fully understood. It is a distinct credit to these workers that they documented the relationships, even though they appeared to make little sense. The major exposures of detachment faults in the Picacho basin and Gavilan Hills can be drawn on Haxel's (1977) map simply by reidentifying some of his contacts between the highly altered "mw-gb" unit and overlying bodies as the detachment fault. Haxel's mw-gb unit is, in most places, the altered zone along and often just above the detachment fault. The detachment fault in the Gavilan Hills was correctly mapped by Haxel as a major normal fault, which followed and cross cut the Chocolate Mountains Thrust Fault. Thus, our current understanding of detachment tectonics in the Picacho Mine-Gavilan Hills area is not one of discovering what others completely missed, but of better understanding complex relationships in light of a newly discovered tectonic framework. Our current understanding will surely be surpassed by even more insightful studies in the future. Anyone working in the Chocolate Mountains region using the maps of Dillon (1975) or Haxel (1977) is impressed by the quality of their work and their tremendous insight into an extremely complicated and critically important area.

Study of the Picacho region as a product of detachment faulting began in 1981 during regional studies of the lower Colorado River region. Numerous excellent exposures of detachment-deformation were found in ranges to the north (Midways---Berg and others, 1982; Jorgensen and others, 1982), northeast (Castle Domes---Logan and Hirsch, 1982, Gutmann, 1982; Kofas---Dahm and Hankins, 1982; Dome Rocks---Dahm, 1983), east (Baker Peaks and Wellton Hills---Pridmore and Craig, 1982, Pridmore, 1983, Pridmore and others, 1983; Mohawks---Mueller and others, 1982, Haxel and others, 1982), and west (Wallace and English, 1982, Wallace, 1982, English, 1984; English and others, 1983; Wallace and others, 1983). The major normal fault in the Gavilan Hills was studied in 1981-1982 by Carl Lothringer and Brian Bryant, who concluded that it was a detachment-related fault, which was controlled, in part, by the Chocolate Mountains Thrust (Lothringer and Bryant, written commun., 1981). They did not write up their findings for the Anderson-Hamilton Volume because they felt that the area was still too poorly understood.

Recognition of specific detachment fault exposures in the Picacho Mine area is first known to have

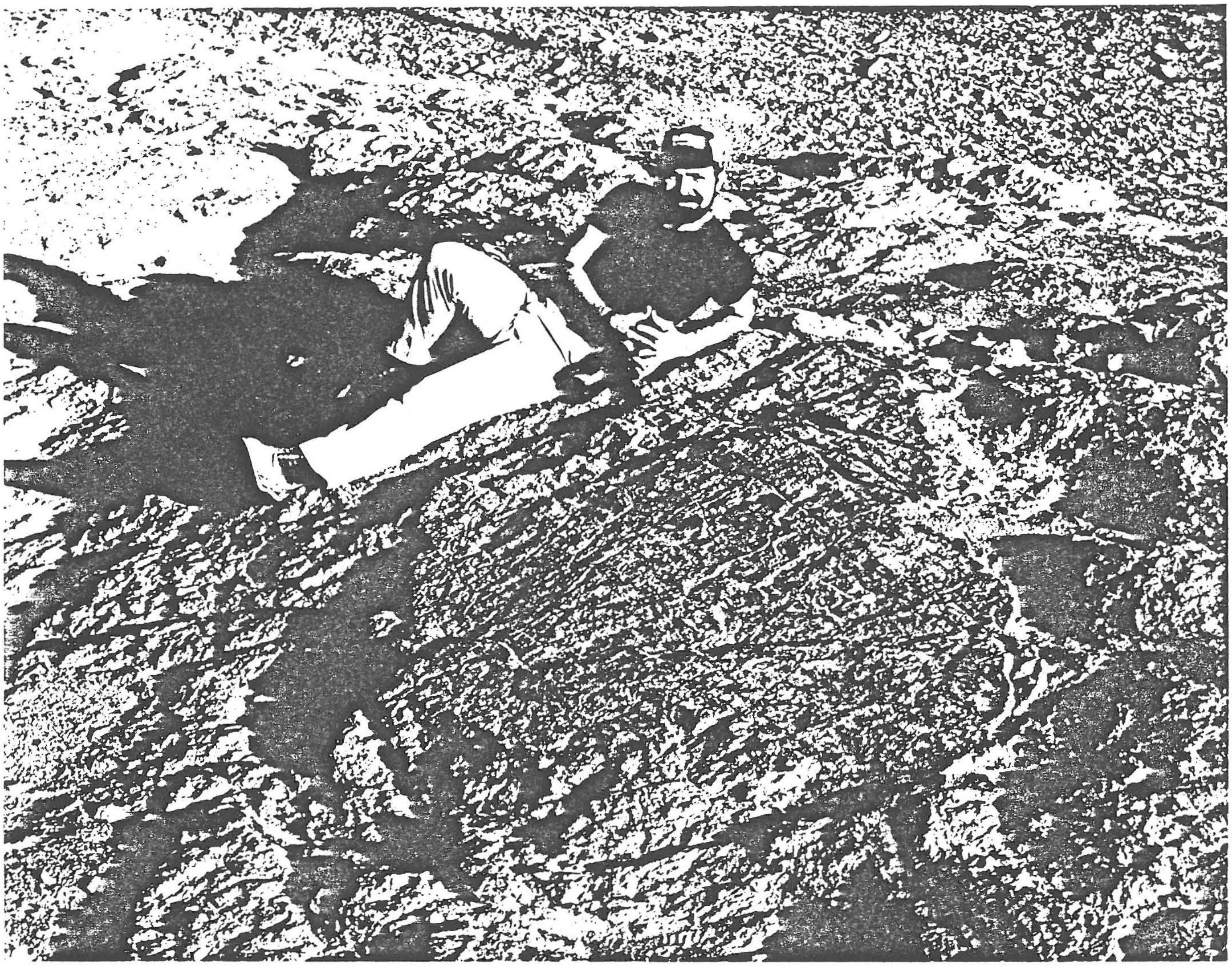


Figure 7. View of the Chocolate Mountains Detachment Fault in Little Picacho Wash with Tom Skaug for scale. Dark ledge is the microbreccia layer, which is underlain by a thin brecciated breccia layer and about 75 m of shattered and altered rock. Picacho orebodies are about 800 m from this locality. Small-scale faulting that cuts the ledge is typical of large scale, also.

occurred in 1982, while choosing mapping areas for the undergraduate mapping class at SDSU. Exposures along the Picacho road, just north of the mine were studied and convincing evidence was found that detachment tectonics had profoundly affected the area. Members of the mapping class, as well as of a graduate tectonics class, began studying various aspects of the Picacho-Chocolate Mountains region. Exposures in the Little Picacho Wash area (Fig. 7) were first mapped as detachment faults by Tom Skaug, Lenny Sinfield, and Steve Koester. These three students also studied the character of detachment faulting in the Picacho Mine with the kind permission of the Chemgold staff. Several of the other exposures of the detachment fault in the Picacho area were found and mapped by Hillemeyer (1984), during detailed studies of lower-plate deformation in the Colorado River detachment terrane. Independent study of the Picacho Mine as being related to detachment faulting was done by Joe Wilkins (Wilkins, 1984b), Bill Rehrig (pers. commun., 1984), and Ann Terry (pers. commun., 1982).

Mapping done in conjunction with this study has demonstrated that there are numerous excellent exposures of the CMDF in the Picacho Mine region, as well as in the mine itself (although exposures in the mine are transitory). The fault has a variable appearance in different exposures, a characteristic of the fault that is best appreciated by following the fault in outcrop and seeing how differently it appears within fairly short distances. Locally the fault is marked by a 1 to 3 m thick zone of cataclasis, but is 10 to 80 m thick in other places. These differences in the fault character make recognition of the detachment fault more difficult in the Picacho and Chocolate Mountains region than it typically is in areas such as the Whipple Mountains. However, the character of the detachment fault in the Picacho region is almost a synthesis of the character of detachment faults in many of the ranges in the region such as the Whipples, Riversides, Big Marias, Kofas, Castle Domes, Moon, Buckskin, Rawhide, Sacramento, and Chemehuevi Mountains. Most of the exposures in the Picacho region are not easily found, however, unlike some of these other ranges where the detachment faults are visible from distances of tens of kilometers. The Riversides (Carr, 1981; Lyle, 1982), in particular, are a close analogy to the character of detachment faulting in the Picacho Mine area.

Variability of the Fault Exposures

There seem to be three primary reasons for the variability in the nature of the exposures of the CMDF. The first of these reasons is that the fault appears to be such a shallow feature. Most of the current outcrops of the fault are in small horsts formed by late normal faults, thus producing a series of isolated exposures that sample different parts of the detachment system. Because different rocks are juxtaposed across the different segments of the fault, the faults have a wide range of field appearances. Where the volcanic rocks, in particular, form the upper plate, the detachment fault is relatively unimpressive. Where crystalline rocks form the upper plate, the fault exposures are quite well developed. Exposure of slightly different structural levels of the detachment fault along the late normal faults, thus produces distinct differences in the appearance

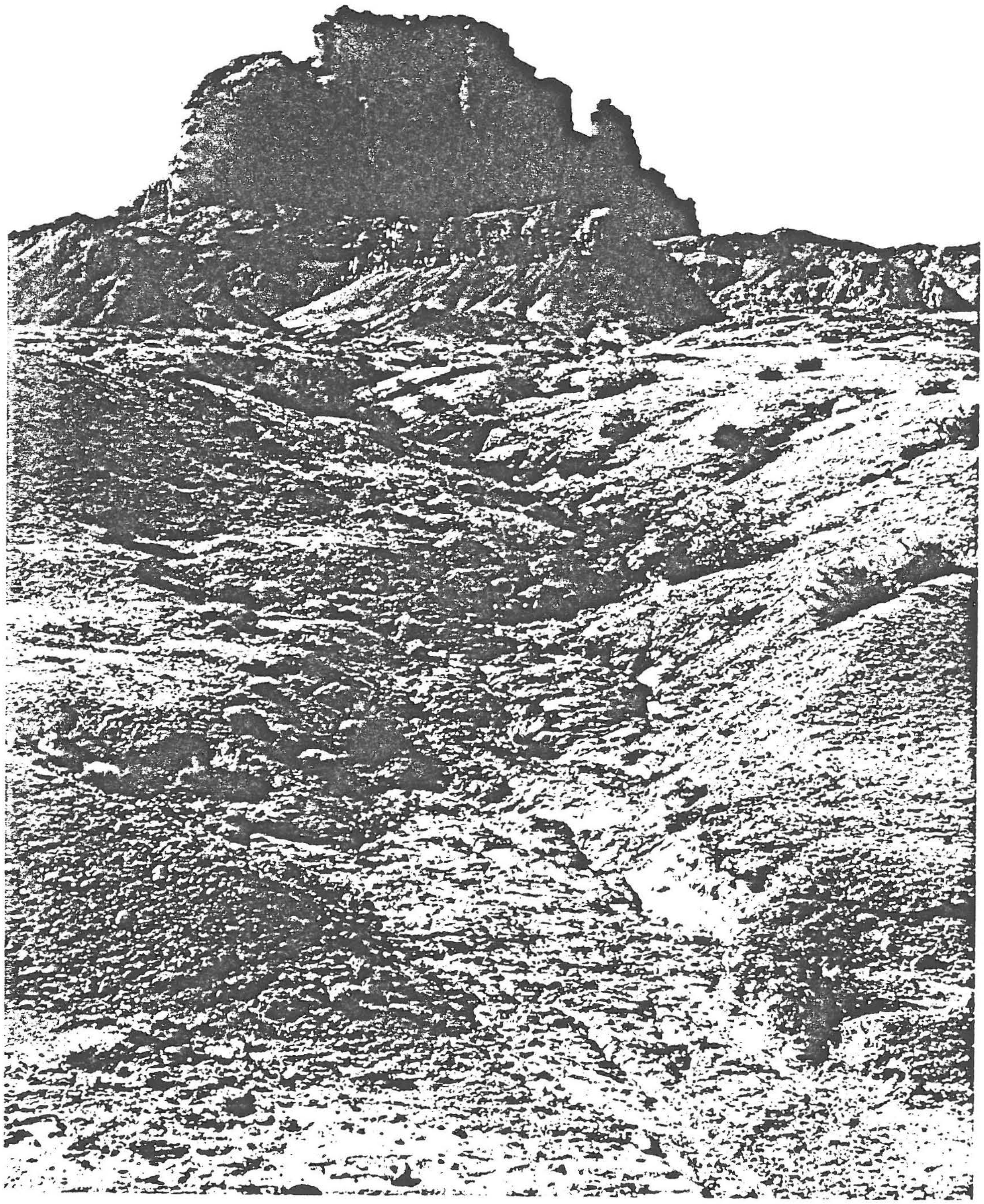


Figure 8. Detachment fault exposed in Little Picacho Wash in a view looking west toward Picacho Peak. Detachment fault forms the resistant ledge at the base of the small wash with upper-plate rocks on the right side of the wash. If the wash had eroded down a meter or so less than it has, the detachment fault would not be exposed.

of different outcrops.

The second reason for the fault variablity is that the detachment fault is the product of progressive deformation over several millions of years of time. Detachment faulting appears to have occurred during Oligocene to middle Miocene time, a time constraint that the Tertiary volcanic and sedimentary sections help define. Different exposures of the detachment fault appear to represent different degrees of deformation. Exposures with well developed microbreccia zones and "chlorite breccia zones" and attendent alteration probably imply a prolonged period of formation. Innumerable seismic events and resultant periods of fluid flow through the broken rock, by a mechanism such as that suggested by Sibson (1975, in press), are probably typical of these highly shattered and altered exposures. A shorter period of deformation, perhaps along faults that offset other segments of the detachment fault, are probably more typical of the relatively less deformed exposures. Viewing the various outcrops of the detachment fault as the products of varying degrees of progressive deformation makes the variability of the detachment faults in the Picacho region more understandable. As an example, juxtaposition of the Quechan Volcanics against lower-plate rocks represents a late-stage motion along the fault and typically produces a fairly unimpressive fault surface. Deformation in the Quechan Volcanics is minor compared to that in older units such as the Mesozoic Winterhaven Formation, which records deformation for the entire period of the detachment-related deformation.

The third, and probably most important reason for the changing fault character is the different rheological properties of different rocks in the CMDF zone, as discussed in the lithologic descriptions. Biotite-bearing rocks tend to deform partially by slippage along biotite cleavage planes and recrystallization of the biotite. Hence, less cataclasis occurs when these rocks form the fault zone. The Precambrian(?) felsic gneiss and Marcus Wash Granite deformed more brittlely, forming a thicker and more porous zone, which is obviously more favorable for mineralization.

Character of the Picacho Detachment Fault

The cataclastic character of the fault is well displayed in Little Picacho Wash (Figs. 1, 7, 8), just 800 m north of the Picacho orebodies. Here the rotated beds of the Winterhaven Formation, the basalt of Little Picacho Wash, the fanglomerate, and the Quechan Volcanics are faulted down onto a thick cataclasite zone, which forms the CMDF. The uppermost surface of the fault is fairly smooth and shallowly dipping. Elsewhere the fault reaches dips as high as 30°, dips that appear to largely be the product of rotation to steeper dips by the late normal faults. The uppermost fault surface is a microbreccia (Fig. 7) much like that present along many other detachment faults. This microbreccia is a dark brown, dense, aphanitic layer that typically overlies a thin zone of brecciated breccia fragments. This thin zone of brecciated breccia is often present just below the microbreccia and appears almost like a pebble conglomerate with the clasts of breccia in a fine-grained matrix. The cataclastic zone below the microbreccia and broken breccia layer is locally over 75 m thick. Petrographic study of the zone shows cataclastic fragments of microcline, plagioclase, and quartz in a cataclastic matrix that is nearly a rock flour. This cataclasite appears to have been derived from the Precambrian(?) felsic gneiss. A surprising feature of the fault zone is that the minerals have been comminuted, but only minor recrystallization has taken place. These relations suggest a relatively shallow fault zone where temperatures and pressures were not sufficient to produce recrystallization.

The macroscopic appearance, petrographic textures, local pods of silicification, and anomalous Au, As, and Sb in this outcrop of the CMDF are identical to ore that was exposed in the upper levels of the Dulcina pit of the Picacho Mine (see samples 25, 29, 30 on Table 1). It was this comparison that convinced us that Chemgold is mining the CMDF.

Another exposure of the CMDF occurs 2.5 km north of the mine along the Picacho Road. Here the fault zone is marked by a breccia zone, is argillically altered, and is composed of boudin-shaped faults pods (Adams and others, 1983; Hillemeyer, 1984). Another exposure a few hundred meters further eastnortheast displays a classic microbreccia ledge, which carries 2.4 ppm Au, 355 ppm As, and 12 ppm Sb (Fig. 9a, 9b). We believe this occurrence to be strong evidence for gold mineralization being localized at the CMDF.

A third exposure of the CMDF is 1.2 km southeast of the Picacho Mine where Quechan Volcanics are faulted down onto brecciated Marcus Wash Granite. Here the fault zone is a rubbly non-cemented breccia of Marcus Wash Granite fragments at least 15 m thick. The fault zone has milled the rock to such a degree that the breccia fragments are partly subrounded. However, no mineralogical change from the host rock is seen except for minor clay and sericite alteration. The overlying Quechan Volcanics show no significant brecciation.

In most of the exposures around the Picacho Mine, the Quechan Volcanics lie directly above the CMDF zone, the other upper-plate formations having been faulted out (Fig. 9a, 9b). The volcanic rocks are almost always unbrecciated and unaltered. Although this uppermost surface of the fault zone is a very distinct break, the bottom of the fault zone is gradational into less broken rock. This gradation occurs over distances of several meters to several tens of meters.

Structural Style of Detachment Faulting at Picacho

The structural style of the upper plate is typical of the detachment environment. Northnorthwest-striking normal faults cut and rotate the upper-plate rocks 20 to 90°. The upper-plate faults do not penetrate the CMDF, but feed into or join it, demonstrating that the low-angle surface has had normal-fault offset along it. Normal faults that feed into the detachment fault are typically high-angle to almost the level of the detachment fault where they curve sharply into the gently tilted detachment surface. Exposures in Little Picacho Wash and the Gavilan Hills show this relationship well (Figure 10). Extension of the upper plate appears to have taken place along a series of upper-plate normal faults that progressively rotate both upper-plate rocks and pre-existing upper-plate normal faults in a style like that suggested by Proffett (1977). The upper-plate normal faults do not appear to have a listric geometry, although the upper-plate normal faults have an exposed structural relief of only tens of meters in any single outcrop. However, the join of the normal faults with the detachment faults is visible

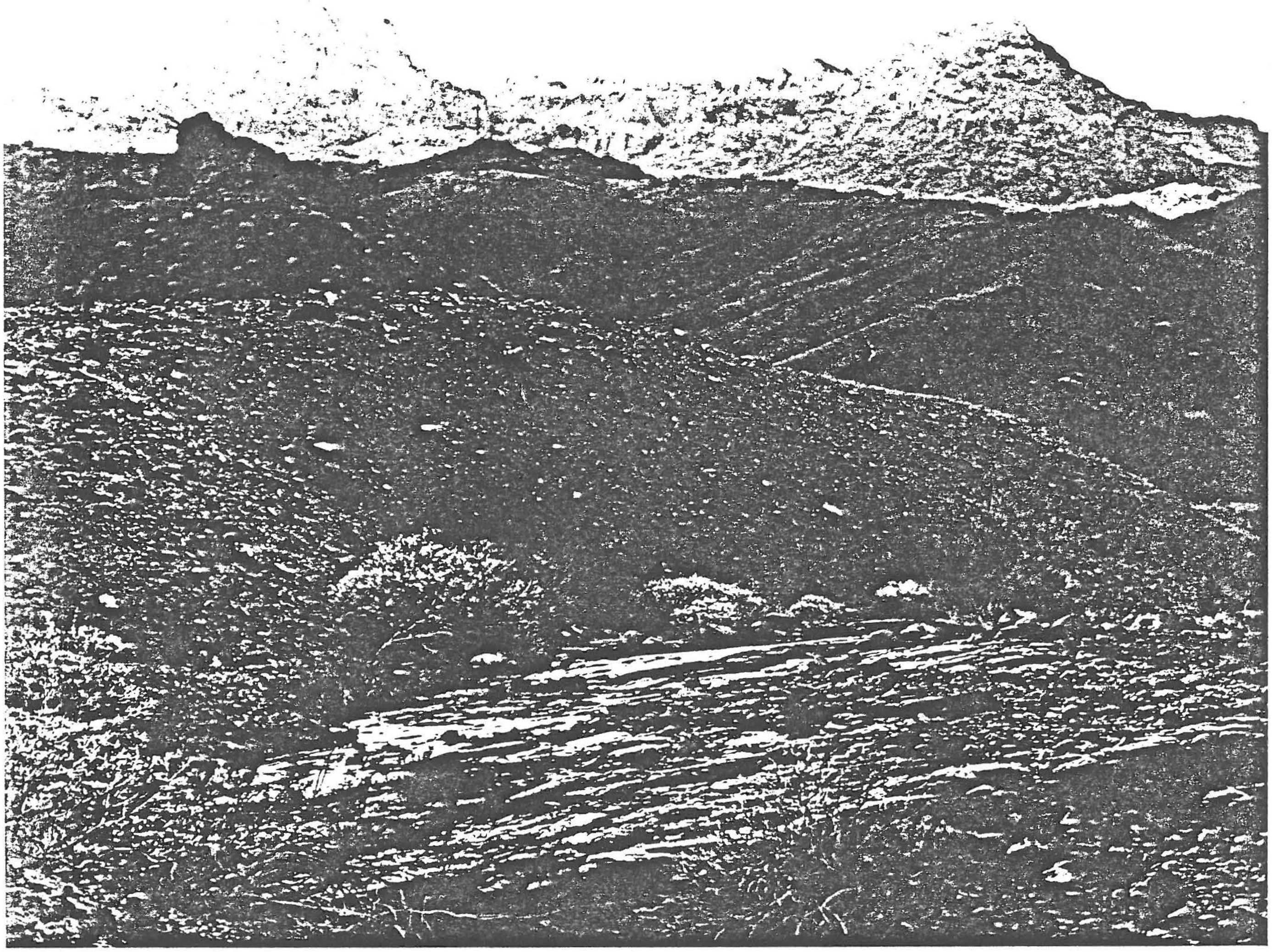


Figure 9a. View of the Chocolate Mountains Detachment Fault 2.5 km northeast of the Picacho Mine showing classic microbreccia ledge. Picacho Peak is in the background. Fault is covered by alluvium and volcanic rocks for much of the distance to Picacho Peak, showing how many of the gold prospects in this area would be hidden.

in many places, and is uniformly high angle. The individual upper-plate fault blocks are pervaded by innumerable small faults, facilitating the rotation of the upper plate. The term "fault-block complexes" as suggested by Gross and Hillemeyer (1982) is particularly appropriate in the Picacho region. The presence of this penetratively developed intra-block faulting makes efforts to balance upper-plate cross sections difficult, at best.

In the Picacho Mine area, the detachment fault is cut by many normal faults as it is in the adjacent Gavilan Hills. These normal faults that cut the detachment fault may bottom into a lower detachment fault or they may be completely post-detachment. Most of the late normal faults have orientations distinctly different from the syn-detachment normal faults. The late normal faults have a profound effect on the Picacho Mine area, in that they offset the detachment zone and associated mineralization into small horst-and-graben blocks. The complexity of this late faulting tends to hide the overall geometry of detachment faulting. Offset on the late faults is not great in most places, measuring a few meters to a few tens of meters. In the adjacent Gavilan Hills, the late normal faults offset both the detachment fault and Chocolate Mountains thrust fault, giving them both a zigzag appearance in outcrop (Fig. 3). Detailed study of these post-detachment faults in the Gavilan Hills suggests that they are part of progressive deformation related to detachment tectonics, rather than related to Basin-and-Range or San Andreas type faulting (McDowell, 1986).

Deformation in the lower plate, below the CMDF, is similar to that in the upper plate except that the normal faults end upward in the diffuse myriad of faults within the detachment zone. Faults within the lower plate are largely semi-parallel to the detachment fault, but numerous high-angle normal faults are also well developed. Numerous geometric scenarios can obviously be constructed to incorporate such high-angle normal faulting in the lower plate. However, exposures in the Picacho Mine area are not

Figure 9b. Same surface of the Chocolate Mountains Detachment Fault, but looking to the east.

sufficient to do much more than speculate on how and when they formed. A good example of these high-angle normal faults is displayed in the east wall of the Dulcina Pit, where exposures are progressively deeper in the lower plate going eastward. No detachment-related mylonitic fabrics are visible in the lower plate---a feature that indicates that the fault formed at shallow depths. Mylonitic rocks related to detachment faulting may be present at depth, but such ductile fabrics of mid-Tertiary age do not appear to be exposed in the Picacho Mine area.

The textures visible in exposures of the CMDF indicate a shallow level of faulting. Stratigraphic evidence corroborates this idea. Before eruption of the Ignimbrite of Ferguson Wash, the only rocks known to occur in the upper plate of the CMDF are the 450 m thick Winterhaven Formation (Haxel and others, in press), the 30-75 m thick basalt of Little Picacho Wash, the 200 m thick fanglomerate, and the 300 m thick Quechan Volcanics (Crowe, 1978). Hence, there was only a maximum of 1025 m of rocks above the shallow portion of the Picacho fault during its early development.

The CMDF appears to have formed over an extended period of time. The depositional environment of the basalt of Little Picacho Wash and the overlying fanglomerate support the idea that extension began prior to the beginning of the deposition of the Quechan Volcanics (32 Ma). Crowe (1973b) found that the Ignimbrite of Ferguson Wash and the Picacho Dacite flowed into linear paleovalleys. These linear paleovalleys were probably formed by upper-plate normal faults that offset the Quechan Volcanics and older rocks in multiple half grabens as seen in many other detachment complexes in this region (e.g., Davis and others, 1980; Teel and Frost, 1982; Mathis, 1982; Pridmore and Craig, 1982; Morris and Frost, 1985; Morris and Okaya, 1986; Pridmore and others, 1986). These upper volcanic units (~25 Ma) were then also rotated by upper-plate faults to dips of 25 - 30°. Hence the CMDF was probably active before 32 Ma, through 25 Ma and was over by 12 Ma. More exact controls on the timing of detachment faulting will require both detailed field studies and Ar/Ar dating.

POST-DETACHMENT FAULTS

A late set of faults has severely deformed the southeastern Chocolate Mountains. One prominent set

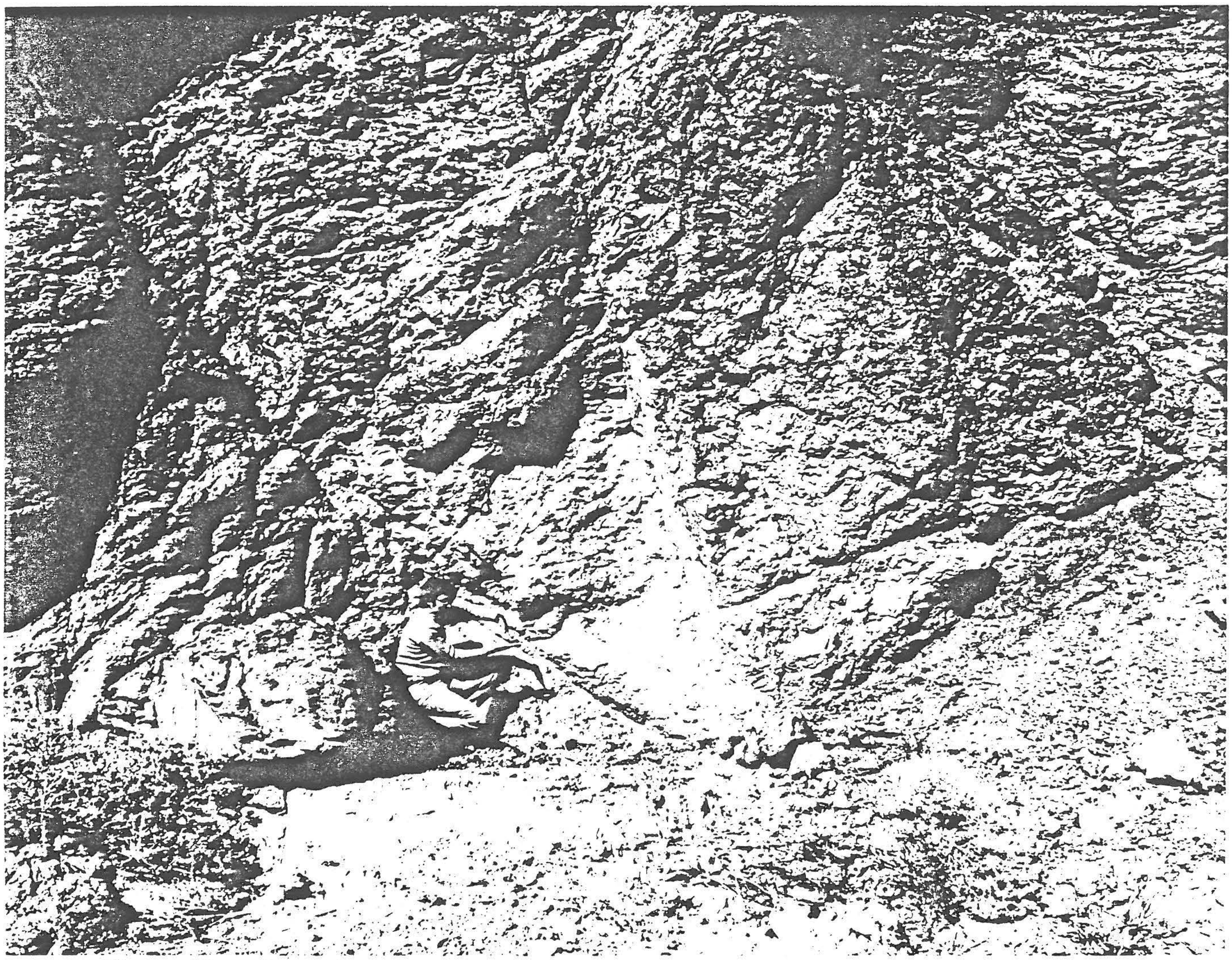


Figure 10. View of upper-plate normal faults where they join the detachment fault in the Gavilan Hills. Most such exposures in this area show the upper-plate normal faults to be steep nearly all the way to the detachment fault, where they bend sharply into the detachment surface. Detachment fault is exposed at the base of the wash; person is standing on the detachment fault surface. Light-colored rocks form the lower plate.

is northnorthwest-striking faults, which parallel the upper-plate normal faults (Fig. 1). These may be "Basin-and-Range" faults or upper-plate faults above a younger, not yet exposed detachment fault. Within the Picacho Mine, the prominent strike of the post-detachment and post-ore faults is N 50 - 55° E. The major effect these faults have had is to dissect the originally continuous Picacho orebody into the four or more discontinuous bodies that now form the Picacho Mine. These faults cut the CMDF, the orebody, and all the volcanic rocks on the hills west of the mine. All of the faults that have distinguishable offset are normal or oblique-normal faults. Their displacements are on the order of one to 100 m. Whether these faults are tear faults occurring late in the detachment extensional regime, or are related to the San Andreas system is not presently known. The orientation of these faults must be viewed in light of possible rotation of the southern Chocolate Mountains during Miocene or Pliocene microplate rotation. Such rotation has been documented in the Chocolate Mountains region by Costello (1985). Our imprecise understanding of the timing of the various deformations makes it difficult to determine if the late normal faults fit geometrically into the detachment or San Andreas systems (Crowell, 1981).

Recognition of this latest set of faults is very important as they are actually what one observes most readily when visiting the Picacho Mine. They are responsible for much of the original orebody being uplifted and eroded, as well as for forming the variably mineralized fault-scarp talus breccias. They have so complexly deformed the orebody that it was not possible to map the CMDF through the mine as a coherent fault zone. Instead, the CMDF is found only in small scattered fault slices.

ALTERATION AND MINERALIZATION

The Picacho Mine is composed of four orebodies (Figs. 1, 11, 12). The Dulcina orebody is the largest and is presently being mined. The Apache orebody was largely mined out in 1983 but a new extension to the south of the main Apache pit is also being mined at the present time. The San George and

Diablo orebodies have been drilled out, but have not been developed. We have studied the upper levels of the Dulcina (which are now mined out), the mined out portion of the Apache, and the San George.

There are three major ore types in the mine: 1) unsilicified CMDF breccia forms most of the Dulcina orebody, 2) silicified CMDF breccia forms most of the San George orebody and part of the Apache orebody, and 3) fault-scarp talus breccias form most of the Apache orebody and some of the Dulcina orebody. There is a zonation in the mine of increasing silicification to the north and west.

Type 1 and 2 ores occur along the contact of the Quechan Volcanics and the lower-plate rocks, within the CMDF breccia zone. Van Nort and Harris (1984) noted that most of the old underground workings followed brecciated rubble zones along this contact. The grade of ores is directly related to the degree of brecciation and amount of hematite (Table 1). Much of the hematite occurs as replacements of pyrite euhedra but specular hematite veinlets are also common. Much of the hematite has been altered to goethite, giving some of the ore a reddish-brown color.

The only other major alteration noted in the mine is a strong sericitic alteration of plagioclase and locally developed clay alteration of plagioclase, microcline, and rock flour. Both these alterations appear to be post-ore weathering phenomena.

Dulcina Orebody

The Dulcina contains ore around the old Dulcina glory hole and related underground workings. These workings were mined out by the open pit operation. It also contains the smaller Mars and Venus orebodies referred to by Van Nort and Harris (1984). The approximate dimensions are 400 m northeast-southwest by 150 m northwest-southeast by 15 to 40 m thick. Although the orebody is irregular, its general shape is tabular, with unaltered and unmineralized Quechan Volcanics covering the ore. The orebody occurs within the CMDF zone. The bottom of the orebody is crudely planar, dips northwesterly 10 to 20°, and is marked by a decrease in gold, brecciation, and oxidation (Wood and Samuels, pers. commun., 1985). Some good gold grades persist downdip along this tabular zone underneath the leach pads but this rock is not considered ore because it is less oxidized and has a very high stripping ratio.

The ore in the Dulcina occurs as a mixture of brecciated Marcus Wash Granite and Precambrian(?) gneiss with lesser talus breccia ore. Much of the ore is so intensely brecciated and hematite-stained that determination of ore host rock is difficult. Our mapping indicated that volumetrically more ore is brecciated granite than Precambrian(?) metamorphic rocks in the upper benches. In places the breccia is so rubbly and weathered that it is difficult to discern from talus breccia made of lower-plate clasts. Van Nort and Harris (1984) and our petrography (Table 1) indicate a close association between degree of cataclasis and gold grade. This relationship indicates that structurally developed porosity was important in allowing passage of mineralizing fluids. The bottom of the ore zone coincides with the bottom of the CMDF zone of brecciation and a corresponding decrease in porosity.

The breccia matrix of the ore was mineralized with pyrite, hematite, and gold. The pyrite has been oxidized to hematite. The hematite pseudomorphs after pyrite are restricted to brecciated rock flour, fractures through clasts, and, to a much lesser extent, grain boundaries. The hematite pseudomorphs and rare unoxidized pyrite occur as subhedral to euhedral grains that are not brecciated by the brecciation event. Petrographic and geochemical analyses of the mine rocks indicate a close relationship between the amount of hematite (most as pyrite pseudomorphs and some as specular hematite) + goethite and the amount of gold (Table 1). The reddish stain from hematite + goethite is a guide to ore (Stannus, pers. commun., 1983). Van Nort and Harris (1984) had concentrated pyrite from less oxidized Dulcina ore and found that it contained nearly all the gold in the sample. Polished sections have shown that the gold occurs within oxidized pyrite pseudomorphs and also along fractures due to supergene remobilization. These observations indicate that the gold was precipitated cogenetically with pyrite and that this mineralization occurred near the end of, or after brecciation. Intense oxidation by weathering remobilized some of the native gold.

Much of the ore and waste in the Dulcina has a slight greenish-black cast that was originally mapped as chloritic alteration. Petrographic inspection of these samples found no chlorite. The coloration is due to a mixture of fine-grained hematite on fractures and strong supergene sericitic alteration of plagioclase.

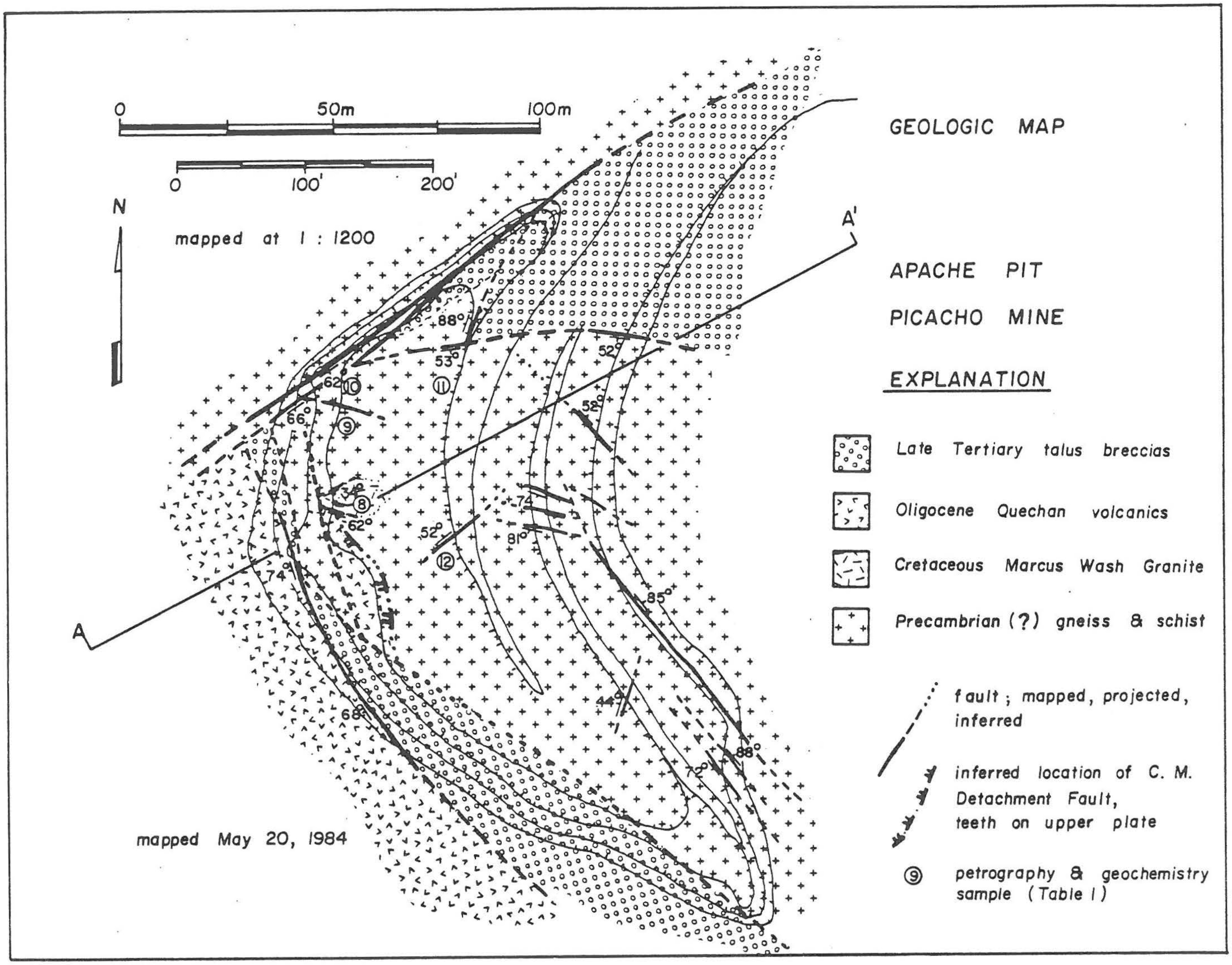
The paragenetic sequence of alteration and mineralization in the Dulcina orebody is: 1) brecciation, 2) gold and pyrite with rare silicification and hematite veining, 3) hematite as replacements of pyrite and biotite, 4) post-ore carbonate veinlets, 5) supergene redistribution of some gold, and supergene alteration of plagioclase to sericite and clay (Table 1).

Apache Orebody

The Apache orebody occurs on the southwest side of the mine complex (Fig. 1). The northern portion of the orebody has been mined out, but the southern extension is still being mined. The northern portion produced roughly 450,000 short tons grading .05 oz./ton (1.7 ppm) from a pit 155 m long, 60 m wide, and 25 m deep (Fig. 11).

The mined orebody was oriented approximately north-south and dipped 25° to the west, although its shape was somewhat irregular due to post-ore normal faults. An unknown, but significant, amount of gold was produced from a 25-30° west-dippping decline shaft and stopes during the turn-of-the-century operation. The workings are no longer accessible but were described by Van Nort and Harris (1984). They described the mineralization as a breccia of Precambrian(?) and Tertiary volcanic clasts in a red-brown matrix of cataclastic Precambrian(?) rock fragments and rock flour. They found the matrix to be cemented by Na-montmorillonite derived from volcanic ash. Their sampling showed both Precambrian(?) and volcanic clasts as well as the matrix to be mineralized with gold. Hence, they concluded that the age of the mineralization must be post-volcanic.

Mapping done in this study has shown that the CMDF occurs in the west side of the Apache Pit but has been completely cut by northnortheast-striking post-detachment normal faults. Like the Apache breccia, the CMDF dips westward here. Hence, we suggest



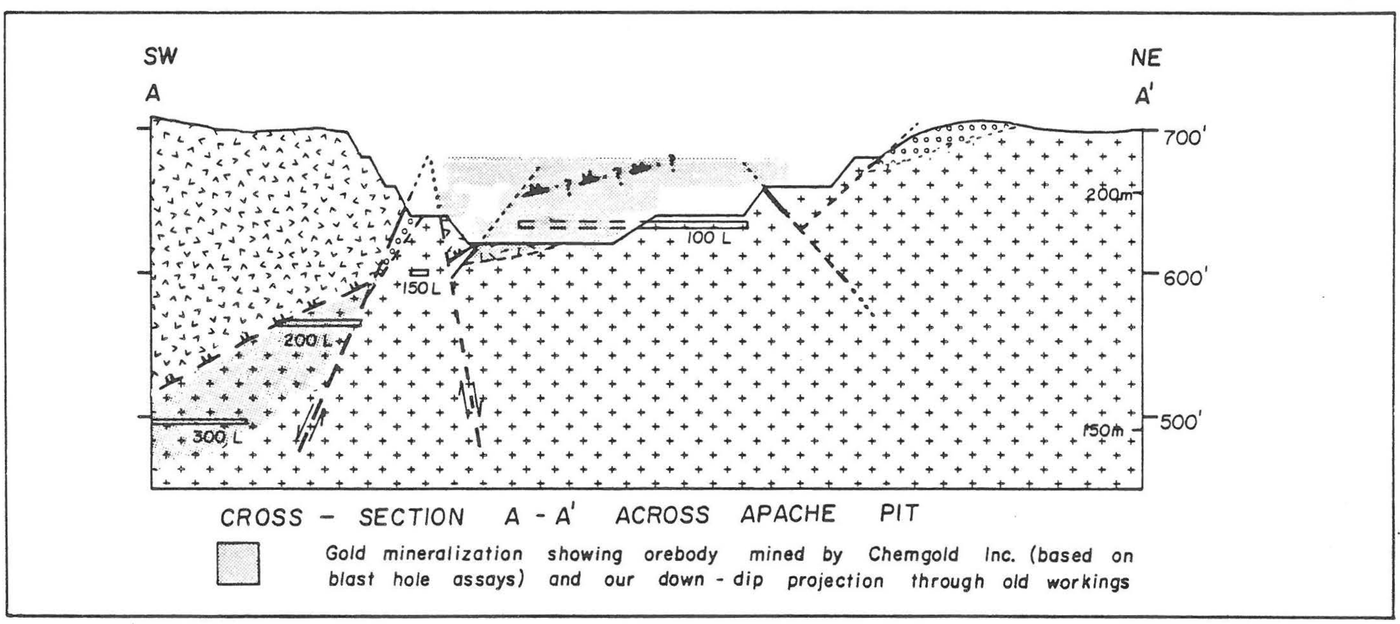


Figure 11. Geologic pit map and cross section from the Apache Pit. Much of the ore produced from Chemgold's operation was low-grade talus breccia. A fault sliver of higher-grade Marcus Wash Granite ore is exposed on the west wall of the pit (Sample 8).

that this mineralized rubble is the CMDF, although its mineralogy and coarse breccia texture are atypical of detachment faults. We have no ready explanation for the montmorillonite occurrence. This area may be one where the CMDF was very close to the surface during some of its motion or was strongly affected by later, near-surface normal faulting and weathering.

Timbers from the old decline are still visible on the west wall of the Apache pit. They follow a dike of silicified Marcus Wash Granite (Fig. 11). This dike has breccia fragments of Precambrian(?) gneiss included within it and is intensely fractured and moderately brecciated. It is well silicified and grades .170 oz./ton (see sample 8, Table 1). The metamorphic rocks surrounding the dike are only weakly mineralized and are less brecciated. A nearby sample of schist (#9 - see Figure 11) is only moderately brecciated, but significant strain was accommodated by bending, recrystallizing, and slippage along cleavage planes of biotite. The sample has no cataclastic rock flour. The breccia matrix is weakly mineralized with hematite but the sample only grades .010 oz./ton or .34 ppm (Table 1).

The contrast between these two nearby samples reiterates the importance that the host rock has in determining gold grades. The granite's style of strain was to shatter, forming excellent porosity for mineralizing solutions. Biotite in the schist allowed strain to occur with much less brecciation. The biotite also appears to have clogged pore spaces and hence, the schists and some gneisses were less receptive to mineralizing solutions. This relationship of more gold and more intense brecciation in the granite than the metamorphic rocks is evident from Table 1 (Marcus Wash is rarely waste in the mine).

Much of the Apache orebody that was mined by Chemgold was talus breccia that was shed off the large eastnortheast-striking normal fault on the north end of the pit (Fig. 11). The coherent hill of gneiss on the north and up-thrown side of the fault is typical of lower-plate metamorphic rocks below the CMDF zone. As this upthrown hill is surrounded by the four Picacho orebodies (Fig. 1), it appears that there probably was a hypogene orebody on this hill that has been eroded. Some of it was preserved as the talus-breccia ore. The hill on the east side of the Apache Pit where the old mill stands may also have had hypogene ore that contributed to the talus breccia ore. Thus, the Picacho Mines may well have been one continuous orebody before the post-ore faulting. This orebody would have had rough dimensions of 925 m by 550 m by 20 m, or roughly 27 million short tons.

San George Orebody

The San George orebody is located on the west side of the Picacho Mine and has not yet been developed (Figs. 1, 12). Chemgold, Inc., currently has plans for an open pit nearly circular in plan, with a diameter of approximately 250 m and a depth of 30 m. Only a few small underground workings are known to exist, and virtually all geologic information to date has been obtained through geologic mapping (Figs. 1 and 12) and through exploration drilling. The shape of the orebody is roughly circular in plan. The shape of the orebody in three dimensions is difficult to assess, because many of the drill holes bottom-out in either high-grade (0.03 oz./ton) or low-grade (0.008 to 0.03 oz./ton) ore.

Ore in the San George area occurs along and beneath the CMDF, which separates upper-plate Tertiary volcanic rocks from lower-plate pre-Tertiary metamorphic and plutonic rocks. The CMDF and the orebody have been offset by numerous northnorthwest-striking and northeast-striking high-angle faults. Numerous prospect pits exist in lower-plate rocks in proximity to the uppermost CMDF surface. This contact is roughly domal in shape and, in contrast with most other outcrops of the CMDF in the Picacho area, is strongly silicified, in addition to being intensely fractured and brecciated. These outcrops of silicified lower-plate rocks are easily recognized in the field, as they tend to form resistant, rubbly "knobs" (Fig. 13a). No talus-breccia ore has been found at the San George.

The character of the ore in the San George area is similar to that of the other Picacho orebodies in the respect that the rocks that act as hosts to mineralization have been subjected to intense brittle deformation, which served to structurally prepare the rocks for invasion by subsequent mineralizing fluids. Fracturing and brecciation have deformed the rocks to such a degree that positive identification of the protolith of this cataclasite is difficult. Most of the ore appears to have been Precambrian(?) felsic gneiss, but portions may have been Marcus Wash Granite.

Petrographic study of these rocks reveals the presence of quartz, plagioclase, microcline, zircon, minor biotite, and occasional sphene as orignial constituents of lower-plate rocks. Alteration and mineralization that followed brittle deformation have added varying quantities of hematite, pyrite, goethite, chlorite, quartz, calcite, and gold (Figs. 13b, 14). Hematite, which is one of the most abundant of these "added" minerals, occurs as veinlets of bladed and needle-like crystals, as anhedral masses in quartz-breccia matrix, as stringers along cleavage planes in biotite, and as pseudomorphs of pyrite in quartz veinlets and breccia filling. Hypogene gold was observed in two polished thin sections as grains in quartz-breccia matrix, and supergene gold was observed in late fractures.

FLUID INCLUSIONS

The overall shortage of hydrothermal gangue minerals in the Picacho orebodies has made fluid inclusion investigations difficult. Quartz veins present in some of the ore are believed to have formed either partly contemporaneously with or immediately preceeding gold deposition and were, therefore, selected for study. All samples analyzed were taken from the visible-gold bearing, hematite-stained outcrop in the west wall of the Apache pit.

While small (one micron) fluid inclusions exist in great numbers in most of the samples, inclusions of a size amenable to study are extremely scarce. All such inclusions that have been analyzed thus far range in size from 5 to 30 microns and contain two phases at room temperature --- liquid plus a small vapor bubble. No daughter minerals are present, and there is no indication of the presence of carbon dioxide. Preliminary heating/freezing data give homogenization temperatures ranging from 201 to 226° C and salinities of 0.5 to 0.7 wt. % NaCl equivalent (Liebler, 1986). Since mineralization at Picacho appears to have occurred within one kilometer of the surface, a very small (<30° C) correction may be added to homogenization temperatures to give tempera-

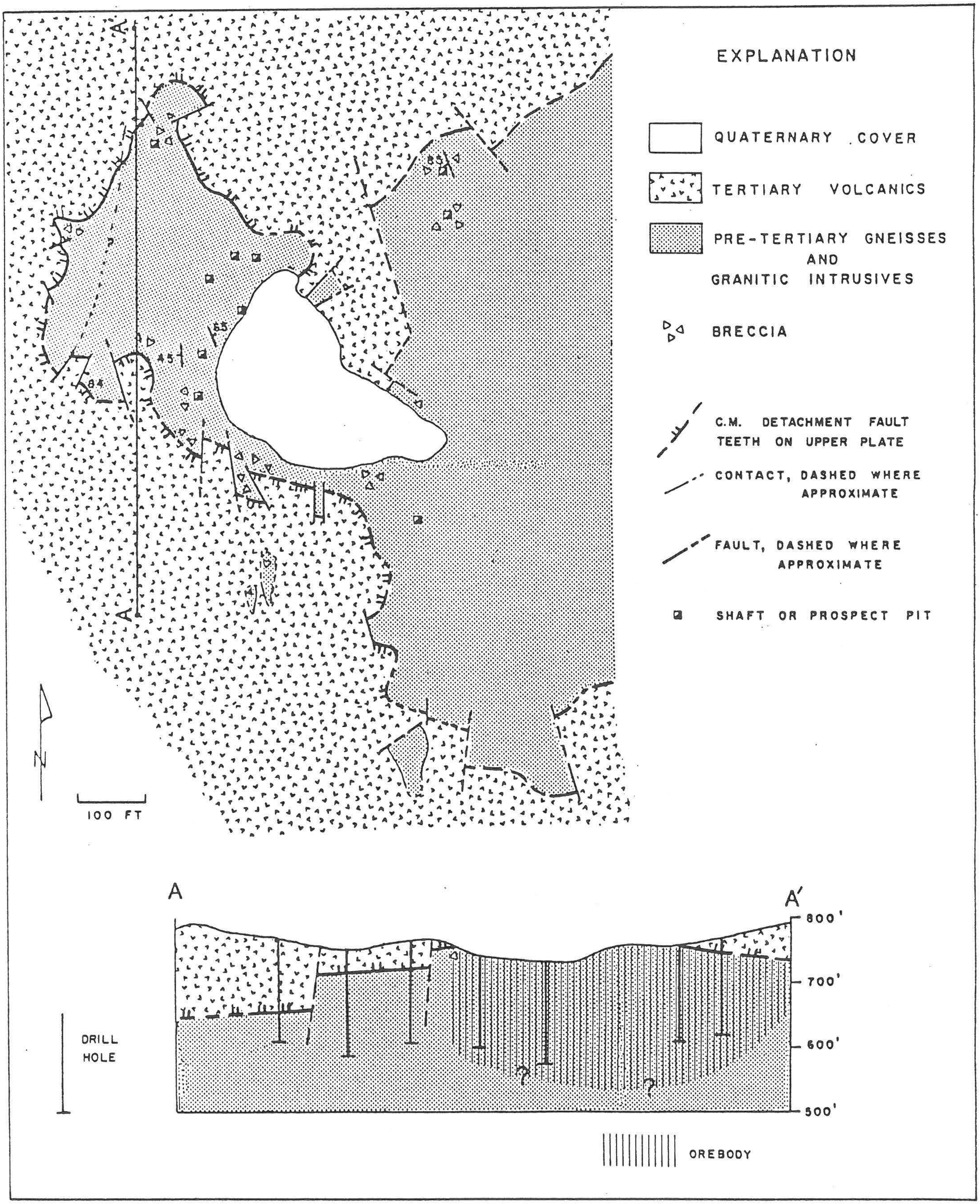


Figure 12. Geologic map and cross section of the San George orebody (From: Liebler, 1986).

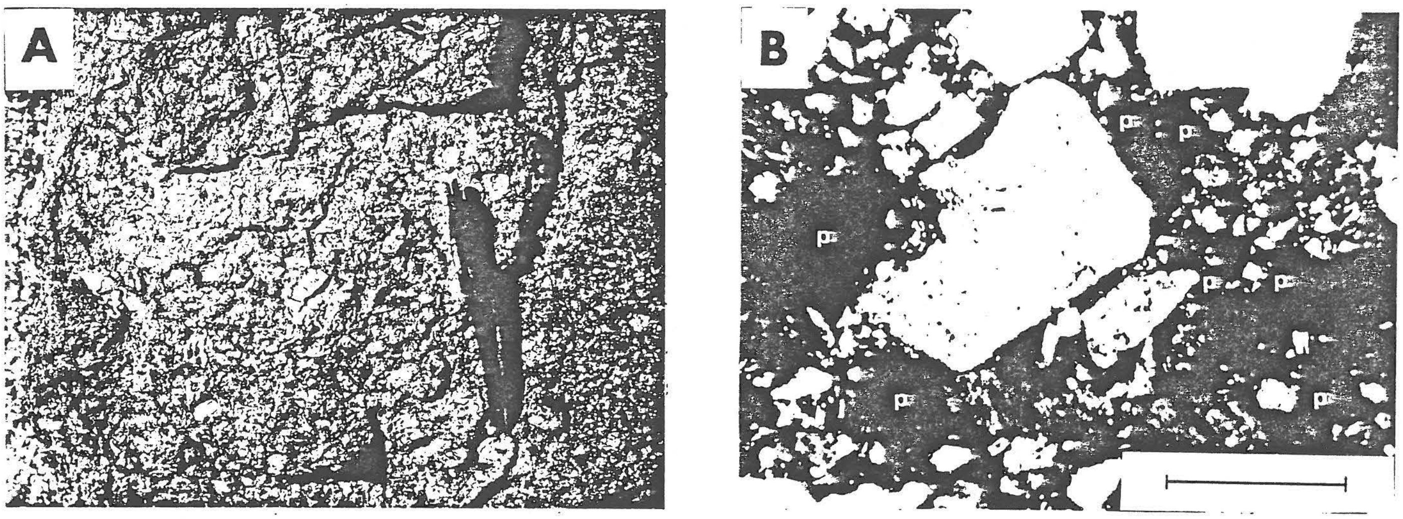


Figure 13a. Typical silicified breccia ore from the San George orebody.

13b. Photomicrograph, transmitted light, crossed nicols, bar scale = 0.5 mm. Opaque grains (p) in matrix were pyrite grains now oxidized to hematite + goethite. This is typical San George gold ore.

tures of formation.

GEOCHEMISTRY

A geochemical sampling program consisting of 164 rock chip samples was conducted in the Picacho Mine and surrounding areas. Of these 164 samples, 81 were collected within the mine while the remaining 83 were collected from surrounding areas. In the mine area, eleven samples were collected from the upper-plate Quechan volcanic rocks and 70 were chip samples of lower-plate crystalline rocks and crystalline rock breccias. Of the 83 samples collected in areas surrounding the mine, 14 were samples of hanging-wall Quechan volcanic rocks with the remaining 67 chip samples collected from footwall crystalline rocks. Thirty-nine of the overall sample suite were studied in thin section in addition to being analyzed geochemically (Table 1). Twenty-six samples (collected from the mine proper) were analyzed for Au and Ag only. Thirty-nine samples were analyzed for Au, Ag, As, Sb, Hg, and Mn. Ninety-eight samples were analyzed for Au, Ag, As, Sb, Hg, Mo, Pb, Cu, Tl, and Zn.

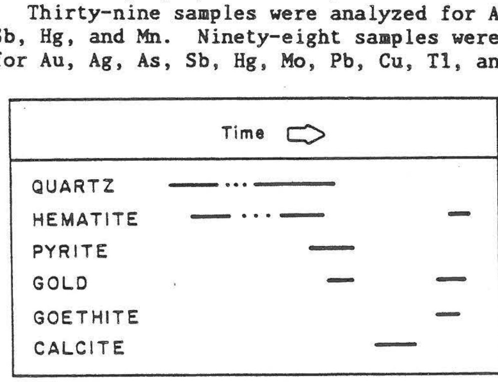


Figure 14. Paragenetic sequence of mineralization at the Picacho Mine. (From: Liebler, 1986).

The litho-geochemical sampling program conducted in the mine proper and in surrounding areas has resulted in the following observations:

1. Of the elements analyzed, only Au, As, and Sb proved to be important indicators of mineralization (Fig. 15).

2. The important elements Au, As, and Sb are strongly controlled by the CMDF breccia zones and rarely by high-angle fracture zones in the lower-plate crystalline rocks (Fig. 15). The regionally developed CMDF shows elevated concentrations of As, Sb, and Au covering many square kilometers around the Picacho Mine.

3. Au (0.30 to 1.03 ppm) is found only very rarely in the upper-plate volcanic rocks and is only present in association with high-angle faults.

4. R-mode factor analysis reveals a strong positive correlation between As and Au.

5. Eleven samples from the upper-plate Quechan volcanic rocks overlying known ore zones reveal a significant leakage of As above the CMDF. Eight samples of fresh volcanic rocks within 10 m of the CMDF and overlying the San George ore zone averaged 10.1 ppm As (range = 6.0 to 29.6 ppm) while three samples collected 15 m or more above the ore zone averaged only 2.1 ppm As (range = 1.3 to 2.6 ppm).

6. Antimony forms the most widespread halo along the CMDF around ore-grade Au mineralization at the Picacho Mine. Samples collected along the detachment at Little Picacho Wash 1/2 mile north of the mine range from 2 to 214 ppm Sb --- essentially comparable with Sb concentra-

PICACHO PETROGRAPHY SUMMARY

	SAMPLE	ROCK TYPE	PRIMARY MINERALS: PLAGIOCLASE	QUARTZ	K - SPAR	BIOTITE	SPHENE	PYROXENE	GARNET	SECONDARY MINERALS: SERICITE	CLAYS	CHLORITE	QUARTZ	CARBONATE	PYRITE	HEMATITE	LIMONITE	BIOTITE	TEXTURE: CATACLASIS	BRECCIATION	FRACTURING	AU o/T	AS ppm
ORE SAMPLES	7	mw	■	■	■					•	•		◩			◩	◩		■	■	■	.210	80
	8	mw	■	■	■					•						•	◩		■	■	■	.170	240
	13	mw?	■	■	■	•			•	◩	■					■	•		■	■	■	.045	380
	15	p€?	■	■	■	◩			•	◩						■	◩	•	■	■	■	.170	420
	20	p€	■	■	■	•				■	•	•				◩	◩		■	■	■	.045	380
	22	p€	■	■	■	■				■	◩					◩	◩	•	■	■	■	.195	470
	25	p€?	■	■	■	•				◩	•					◩	◩		■	■	■	.045	280
	29	mw	■	■	■	•			•	■			■			◩	◩		•	•	■	.105	190
	30	p€	■	■	■	■				◩	■					◩	◩		■	■	■	.105	140
	31	mw	■	■	■				•	◩			◩	•		◩	■	•	■	■	■	.125	210
WASTE SAMPLES	11	p€	■	■		■		•	•	◩	•					•						.005	80
	12	p€	■	■	■	•				◩	◩					•				•		.010	260
	16	p€	■	■	■	◩			•	■	•			•		■	◩					.010	230
	26	p€	■	■	■	•			•	■	•					■	◩		■	■	■	.005	200
	32	p€	■	■		■	•	•	•	◩		■			•							--	70
	33	p€	■	■		■		•		•	■			•		•					■	--	100
	34	p€	■	■	■					■	•			•		◩	◩			•	■	--	100

■ +10%   ◩ +2%   • tr   (primary minerals)

■ strong   ◩ moderate   • weak   (secondary minerals and texture)

Table 1. Summary of mineralogy, textures, and geochemistry of ore versus waste samples from the Picacho Mine. Note the contrast in cataclasis and FeO content of ore versus waste. Much of the hematite occurs as pseudomorphic replacements of pyrite subhedra.

tions within the ore zones. Samples collected as indicators of background well beneath the CMDF show Sb on the order of 1-3 ppm. Although there is a strong Sb anomaly in Little Picacho Wash, only one sample showed weakly anomalous Au (0.170 ppm).

7. Arsenic is highly anomalous in the Au ore zones. Arsenic values in the mine vary from 50 to 470 ppm. Within the ore zones many samples show in excess of 300 ppm As. Arsenic forms a much more restricted halo around the ore bodies than Sb. Arsenic concentrations in Little Picacho Wash, which gave a strong Sb anomaly are only weakly anomalous in As (10 to 60 ppm). Samples collected as representing background beneath the CMDF breccias show As concentrations of less than 10 ppm. Only one sample collected outside the mine area showed highly anomalous As (+180 ppm) --- a select sample of the cataclasite ledge formed at the CMDF in Arastra Wash northeast of the mine (Fig. 9a, 9b).

8. Silver:gold ratios are generally very low. Nearly all the samples collected were below the 0.2 ppm detection limit for Ag.

As a practical guide to exploration in the region, the geochemical survey at the Picacho Mine shows that trace-element geochemistry is of limited use in defining specific drill targets along the CMDF in areas of more than 15 m of volcanic cover. Trace-element geochemistry is, however, extremely helpful in defining proximity to mineralization underneath the Tertiary volcanic cover once drill samples of the CMDF breccias are obtained. The mean of 203 ppm As in the gold ore zones at the Picacho Mine is highly anomalous and characteristic of proximity to ore with or without ore-grade gold values. Along the CMDF this high As anomaly appears to drop off rapidly (within 1/3 to 1/2 km) from the ore zones to a moderate 10-60 ppm anomaly. Areas such as Little Picacho Wash show weak to moderate As and strong Sb anomalies, but almost no Au. If blind drilling indicates a strong As anomaly (numerous intervals of +60 ppm) in the CMDF breccias, it is indicative of proximity to a potential gold-bearing zone.

CONCLUSIONS AND GENETIC MODEL

The Picacho Mine region has suffered an extended history of deformation including Jurassic and/or Cretaceous thrusting, metamorphism and plutonism; Oligocene-Miocene volcanism and detachment faulting; and Miocene and perhaps Pliocene normal faulting.

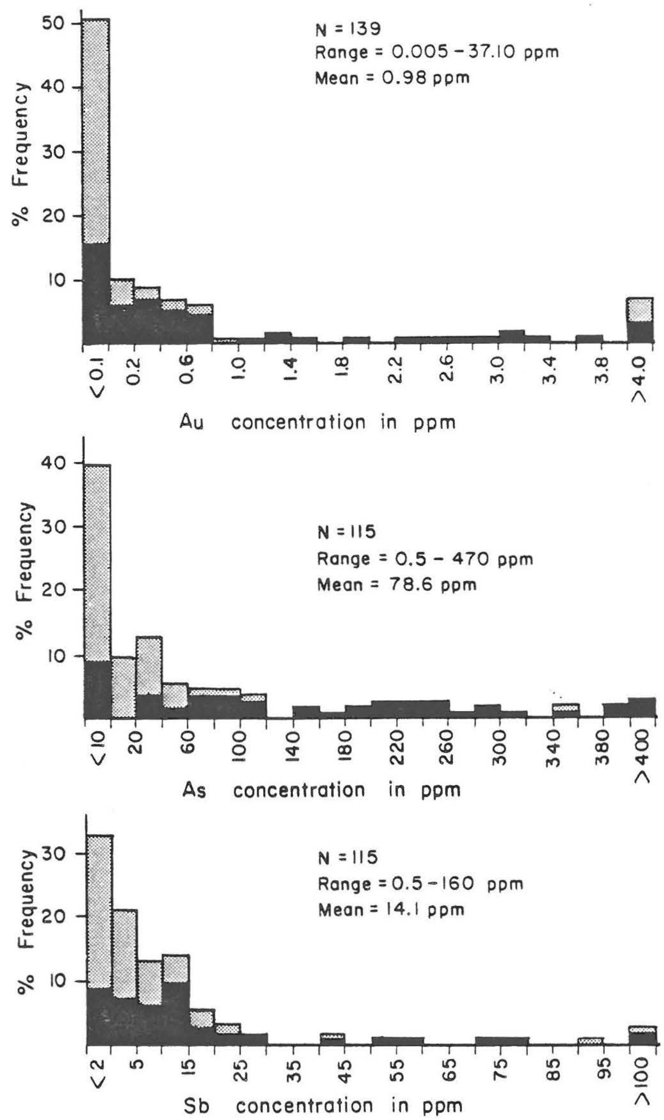


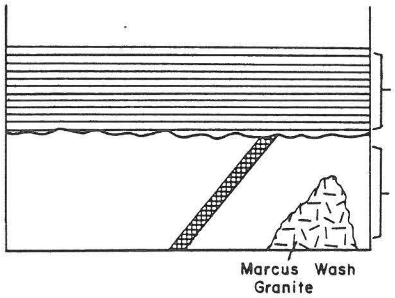
Figure 15. Percent frequency histograms of Au, As, and Sb concentration in samples collected from the Picacho Mine and vicinity. All samples shown on the histograms were collected from lower-plate rocks along and adjacent to the CMDF. The shaded portions of the graph represent samples collected outside the Picacho Mine. It should be emphasized that the population represented on these histograms is from the CMDF and do not reflect Au, As, and Sb concentrations generally present in the poorly broken lower-plate rock beneath the CMDF breccia zone.

This study of the Chocolate Mountains Detachment System has found it to be a very shallow feature, as documented by stratigraphic constraints, the open-space forming brecciation, lack of associated mylonitization, and lack of mineral recrystallization. The detachment fault in the Picacho Mine area appears to have formed at very shallow crustal levels, on the order of 1 km. The fault probably continued to significant depth, but the upper levels of the fault form the current exposures. Many of the other detachment complexes in the Cordillera expose much deeper crustal levels, which may be an important difference between them and the Picacho Mine region.

At this shallow level of formation and exposure, the mineralogy and texture of the rocks in the fault zone are critical in determining the character and thickness of the fault zone. When detachment faults form at greater depths, temperature and pressure become more effective in determining the character and thickness of the fault zone than lithology. The CMDF is generally thickest and most intensely cataclasized where non-foliated rocks host the fault zone. Foliated schist and gneiss allowed some deformation to take place as microfaulting within and along the sides of biotite grain boundaries, rather than as brittle cataclasis.

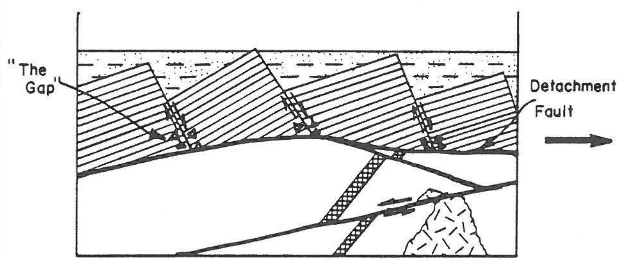
Mapping of the CMDF into the Picacho Mine, as well as the similar macroscopic appearance, petrographic textures, and trace-element geochemistry of the CMDF and the ore all indicate that the Picacho orebodies are portions of the CMDF. Regional sampling indicates that Au-As-Sb mineralization is common within the CMDF system. The hypogene ore occurs as highly brecciated Precambrian(?) felsic gneiss, Marcus Wash Granite, and Precambrian biotite gneiss and schist. The interfingering of these three rock types

SCHEMATIC GENETIC MODEL FOR DETACHMENT - HOSTED GOLD DEPOSITS, SW USA

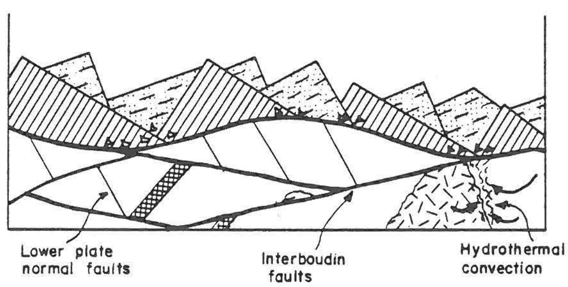


Tertiary volcanic and sedimentary rocks; Mesozoic metasedimentary and metavolcanic rocks (Winterhaven Fm. in Picacho region)

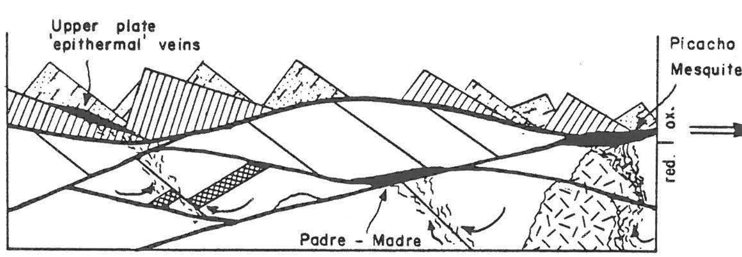
Precambrian granitoids, gneisses, schists; Jurassic intrusives, gneisses, metasedimentary and metavolcanic rocks (Orocopia Schist in Picacho region); Laramide granitoids (Marcus Wash Granite in Picacho region); Tertiary dikes and hypabyssal intrusives



Extension via step faults in Upper plate but by low-angle faults in the Lower plate; Upper plate in Picacho region .8 - 1. km thick;
Continued volcanism and sedimentation in fault-controlled basins
Note "the gap" where cross-section cannot be restored - this is zone of chaotic brecciation and open space, providing favorable mineralization sites



Continued extension, development of Detachment Fault and boudin shaped bodies bounded by low-angle interboudin faults. Intraboudin normal faults develop within boudin bodies.
Brecciation greatest at intersection of interboudin faults and Detachment Fault, and in synforms in Detachment Fault.
High heat flow due to volcanism and crustal thinning causes hydrothermal convection of sulfurous waters.



Continued extension, brecciation, volcanism.
Gold and pyrite precipitate in favorable structural sites (at Picacho, the C.M. Detachment Fault) when mineralizing waters encounter more oxidized waters.

Holocene mammals dig large holes in ground.

Adapted in part from Hillemeyer (1985) and Adams et al. (1983)

Figure 16. Structural model for development of Picacho-type orebodies.

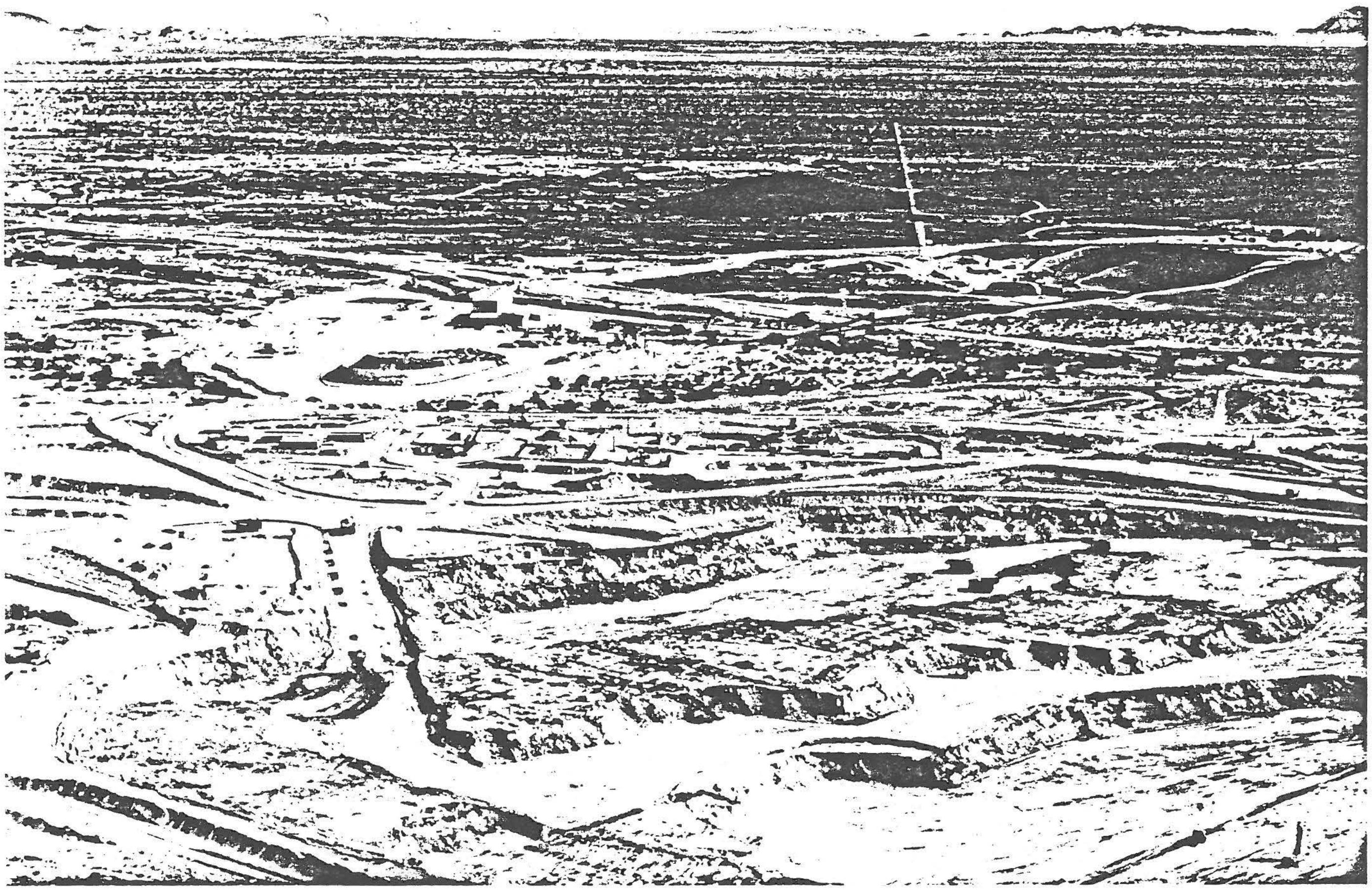


Figure 17. Air view of the Mesquite deposit on the southwestern flank of the Chocolate Mountains antiform with Picacho Peak on the skyline (dark mass). Open desert between Picacho and Mesquite deposits probably hides other major deposits and is being explored by Goldfields. Similar areas (low, covered areas on the flanks of ranges involved in detachment faulting) offer the possibility of finding other such deposits (including deposits on the west side of the San Andreas).

probably led to more complex deformation in the mine area than in surrounding areas where one rock type forms the CMDF zone. The best grades of ore are associated with the most intense brecciation, which produced the most porous rock at the time of mineralization. Mineralization introduced pyrite, hematite, quartz and gold during the main episode. Carbonate veining was a late feature. In much of the ore, especially in the Dulcina orebody, pyrite and lesser hematite were the only major minerals that were introduced. The pyrite occurs as euhedral grains in the cataclasite matrix and has now been oxidized to hematite. The gold occurs in, or is associated with the oxidized pyrite. The unfractured and non-cataclasized texture of the oxidized pyrite indicate that ore stage mineralization occurred after brecciation produced by detachment faulting. The trace-element geochemistry and fluid inclusion homogenization temperatures are typical of epithermal mineralization.

Wilkins (1984a, b) noted that the origin of the gold at Picacho was a hotly debated issue. Although much room for research and study remains, this study in concert with the pioneering work of Van Nort and Harris (1984), Dillon (1975), Haxel (1977), and Crowe (1973a, b, 1978) has produced a cogent explanation for the gold occurrence.

Tosdal and others (1985) have suggested a genetic link between the regional gold mineralization and Jurassic intrusive rocks. Keith and others (1984) and Wilt and Keith (1984) have presented geochemical evidence that suggests a genetic relationship between the Cretaceous(?) Marcus Wash Granite and the gold mineralization. This study indicates that neither of these events formed the present orebody although they may well have produced earlier gold mineralization in the mine area. Thus, it is possible that the Picacho area had pre-ore gold enrichment, an important feature in regional exploration.

Development of the shallow CMDF created huge zones of porosity within 1 km of the surface in

Oligocene-Miocene time (Fig. 16). Although the fault zone is irregular in porosity and thickness, it would have been a somewhat continuous, low-dipping feature. Hence, it was probably an excellent fresh-water aquifer. During and after detachment faulting, intense regional volcanism must have created a high heat flow in the crust, developing irregular volumes of hydrothermal convection in the lower plate. The Picacho Peak plug (Fig. 2) in Marcus Wash, 1500 m west of the mine, would probably have had convecting cells developed around its margin. These convecting hydrothermal solutions must have leached gold from enclosing lower-plate rocks, whether the rocks were pre-enriched or not. The association of the gold with euhedral pyrite (now oxidized to hematite), the low salinities observed in the fluid inclusions, and the lack of hypogene acidic alteration indicate that these leaching solutions had nearly neutral pH and that bisulfide complexes probably dissolved the gold (Romberger, 1986). Romberger (1986) shows that the solubilities of gold bisulfide complexes under reducing conditions exceeds gold abundances in typical rocks. Hence, given enough time, all the gold could be dissolved from the source rocks (unless the local pre-enrichment episode had formed some very high concentrations of gold). The Orocopia Schist, which lies at an unknown, but probably very shallow, depth below the mine, was a ready source of sulfur as it commonly contains disseminated pyrite. The thickness of the Orocopia Schist in this region (6-9 km) as judged from seismic sections (Morris and Frost, 1985; Morris and Okaya, 1986; Morris and others, 1986), would be an enormous source of sulphur as it was leached by circulating fluids.

These convecting hydrothermal fluids would tend to follow lower-plate faults, brecciated dikes of Marcus Wash Granite and contacts between lower-plate rocks. The convecting cells would have an upper cap formed by the detachment fault (Figure 16). Here the relatively hot solutions (210 to 250° C) would mix with the cooler, and well oxidized waters of the aquifer. Romberger (1986) has shown that oxidation is the most effective mechanism for destroying gold-bisulfide complexes, forcing gold out of solution to be coprecipitated with pyrite or adsorbed onto pyrite grains. The association of the gold with pyrite and hematite indicates that oxygen activity was fluctuating at the time of mineralization---good evidence for episodic mixing of solutions. Thus the formation of the Picacho orebody within the CMDF is due both to the porosity of the fault zone and to its being a redox boundary (Fig. 16). This conclusion is consistent with the observation that the upper-plate rocks of most detachment faults in the southwestern U.S. are strikingly more oxidized than their associated lower-plate rocks. The redox mechanism was obviously very thorough in that almost no mineralization moved upwards into the volcanic rocks. As shown by the trace-element geochemistry, only arsenic appears to have bled into the upper-plate Quechan Volcanics.

Supergene alteration and redistribution of the gold has taken place in the Picacho Mine area. Observation of native gold coating late fractures and local ore-grade samples in post-hypogene mineralization faults indicate that the deposit was somewhat enriched. The occurrence of good gold grades in unoxidized material deep below the leach pads (Stannus, per. commun., 1983) indicates that enrichment was not necessary to form ore grades.

The documentation of gold mineralization in a detachment fault at Picacho led to an exploration rush on detachment faults in the southwestern U.S. from 1982 to the present. Limited reconnaissance and comparison between Picacho and the Mesquite gold deposit, 35 km to the west along the same flank of the Chocolate Mountains antiform (Figure 17), suggest that this large gold reserve may also be localized by the CMDF system. The Padre-Madre deposit in the Cargo Muchacho Mountains (15 km southwest of Picacho) appears to be localized along a lower-plate interboudin fault that is very similar to the upper CMDF (Fig. 16). Several other gold deposits associated with detachment faults were noted by Wilkins (1984a). Dozens of non-economic gold prospects have been documented as detachment hosted in the 1982 to present exploration rush. Hence there is a large family of Picacho-type gold deposits. Many such deposits are probably also buried beneath the alluvium around ranges that are involved in detachment faulting. The brecciated character of the fault zones is conducive to rapid weathering, leaving the less brecciated rock standing as the exposed range. Placer deposits around a range involved in detachment faulting can thus be a direct guide to major buried gold deposits. Districts that are known to be high in As and Sb would also be keys to finding other Picacho-type deposits.

Comparison of Picacho to many other deposits in the region indicates the structural model of Figure 16 is applicable to most of these deposits. However, our geochemical conclusions about Picacho may only be applicable to some areas of detachment faulting. Detachment faults host many different types of ore deposits in the southwestern U.S. Wilkins and others (1986) have noted that many detachment-hosted deposits have much higher salinities than Picacho---on the order of 12-20 wt.% NaCl equivalent. Hence these solutions must be very different. Silver deposits (Garner and others, 1982), Cu-Fe-Au deposits (Schuiling, 1978; Heidrick and Wilkins, 1980; Wilkins and Heidrick, 1982), and manganese deposits (Lasky and Webber, 1944; Berg and others, 1982) have all been documented in detachment settings. Clearly these would each involve different hydrothermal fluid systems. However, they probably all involve basically the same structural setting; all are localized along different components of the mid-Tertiary detachment fault system.

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REFERENCES

Adams, M. A., Hillemeyer, F. L., and Frost, E. G., 1983, Anastomosing shear zones---A geometric explanation for mid-Tertiary crustal extension in the detachment terrane of the Colorado River region, California, Arizona, and Nevada: Geological Society of America Abstracts with Programs, v. 15, no. 7., p. 375.

Anderson, J. L., 1983, Proterozoic anorogenic granite plutonism of North America: Geologic Society of America Memoir 161, p. 133-154.

Anderson, J. L., Podruski, J. A., and Rowley, M. C., 1979, Petrological studies in the "suprastructural" and "infrastructural" crystalline rocks of the Whipple Mountains of southeastern California: Geological Society of America Abstracts with Programs, v. 11, no. 3. p. 66.

Anderson, T. H., Silver, L. T., and Salas, G. A., 1980, Distribution and U-Pb isotope ages of some lineated plutons, northwestern Mexico, in, Crittenden M. D., Jr., Coney, P. J., and Davis, G. H., eds., Tectonic significance of metamorphic core complexes of the North American Cordillera: Geological Society of America Memoir 153, p. 269-283.

Berg, L., Leveille, G., and Geis, P., 1982, Mid-Tertiary detachment faulting and manganese mineralization in the Midway Mountains, Imperial County, California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River Region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 298-312.

Carr, W. J., 1981, Tectonic history of the Vidal-Parker region, California and Arizona, in Howard, K. A., Carr, M. D., and Miller, D. M., eds., Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U. S. Geological Survey, Open-file Report 81-503, p. 18-20.

Carr, W. J., and Dickey, D. D., 1980, Geologic map of the Vidal, California and Parker SW, California and Arizona, quadrangles: U. S. Geological Survey Map I-1125.

Costello, S. C., 1985, A paleomagnetic investigation of mid-Tertiary volcanic rocks in the lower Colorado River area, Arizona and California: Master's thesis, San Diego State University.

Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., 1980, Tectonic significance of metamorphic core complexes of the North American Cordillera: Geological Society of America Memoir 153, 490 p.

Crowe, B. M., 1973a, Tertiary volcanism east of the San Andreas fault, southeastern California, in Kovach, R. L., and Nur, A., eds., Proceedings of the conference on tectonic problems of the San Andreas fault system: Stanford University Publications, p. p. 334-338.

Crowe, B. M., 1973b, Cenozoic volcanic geology of the southeastern Chocolate Mountains, California: University of California, Santa Barbara Ph.D. dissertation, 117p.

Crowe, B. M., 1978, Cenozoic volcanic geology and probable age of inception of basin-range faulting in the southeasternmost Chocolate Mountains, California: Geologic Society of America Bulletin, v. 89, p. 251-264.

Crowe, B. M., Crowell, J. C., and Krummenacher, D., 1979, Regional stratigraphy, K-Ar ages, and tectonic implications of Cenozoic volcanic rocks, southeastern California: American Journal of Science, v.279, p. 186-216.

Crowell, J. C., 1981, An outline of the tectonic history of southeastern California, in Ernst, W. G., ed., The geotectonic development of California (Rubey Volume I): Englewood Cliffs, New Jersey, Prentice-Hall, p. 583-600.

Dahm, J. B., 1983, Geometry and timing of Tertiary deformation of the Dome Rock Mountains, Yuma County, Arizona: Master's thesis, San Diego State University, 132p.

Dahm, J. B., and Hankins, D. D., 1982, Preliminary geology of a portion of the southern Kofa Mountains, Yuma County, Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River Region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 459-469.

Davis, G. A., Anderson, J. L., Frost, E. G., and Shackelford, T. J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona, in, Crittenden M. D., Jr., Coney, P. J., and Davis, G. H., eds., Tectonic significance of metamorphic core complexes of the North American Cordillera: Geological Society of America Memoir 153, p. 79-129.

Davis, G. H., 1980, Characteristics of metamorphic core complexes, southern Arizona, in Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., Tectonic significance of metamorphic core complexes of the North American Cordillera: Geological Society of America Memoir 153, p. 35-77.

Davis, G. H., and Coney, P. J., 1979, Geologic development of the Cordilleran metamorphic core complexes: Geology, v. 7, p. 120-124.

Dillon, J. T., 1975, Geology of the Chocolate and Cargo Muchacho Mountains, southernmost California (Ph.D. dissert.): Santa Barbara, California, University of California, 575 p.

Eberly, L. D., and Stanley, T. B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921-940.

Ellis, J., 1982, Structural analysis of the Big Maria Mountains, Riverside County, California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 222-234.

Ehlig, P. L., 1958, Geology of the Mount Baldy region of the San Gabriel Mountains, California (Ph.D. dissert.): Los Angeles, California, University of California, 195 p.

Ehlig, P. L., 1968, Causes of distribution of Pelona, Rand, and Orocopia Schists along the San Andreas and Garlock faults, in Dickinson, W. R., and Grantz, A., eds.: Proceedings of the conference on geologic problems of the San Andreas fault system: Stanford University Publications in Geologic Sciences.

Ehlig, P. L., Davis, T. E., and Conrad, R. L., 1975, Tectonic implications of the cooling age of the Pelona Schist: Geologic Society of America Abstracts with Programs, v. 7, no. 3, p. 314.

Ehlig, P. L., 1981, Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges, in Ernst, W. G., ed., The geotectonic development of California (Rubey Volume I): Englewood Cliffs, New Jersey, Prentice Hall, p. 253-283.

English, D. J., 1984, Regional structural analysis of the Santa Rosa Mountains, San Diego and Riverside Counties, California: Implications for the geologic history of southern California: Master's thesis, San Diego State University, 170 p.

English, D. J., Engel, A. E., and Shackelford, T. J., 1983, Mid-Tertiary detachment faulting west of the San Andreas in the Santa Rosa Mountains area of southern California: Geological Society of America Abstracts with Programs, v. 15, no. 8, p. 567.

Frost, E. G., Cameron, T. E., Krummenacher, D., and Martin, D. L., 1981, Possible regional interaction of mid-Tertiary detachment faulting with the San Andreas fault and the Vincent-Orocopia thrust system, Arizona and California: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 455.

Frost, E. G., Martin, D. L., and Krummenacher, D., 1982, Mid-Tertiary detachment faulting in southwestern California and its overprint on the Vincent-Orocopia thrust system: Geological Society of America Abstracts with Programs, v. 14, n. 4, p. 164.

Frost, E. G., and Martin, D. L., 1982a, Comparison of Mesozoic compressional tectonics with mid-Tertiary detachment faulting in the Colorado River area, California, Arizona and Nevada, in Cooper, J. D., Compiler, Geologic excursions in the California Desert: Geological Society of America Volume and Guidebook, Cordilleran Section, p. 113-159.

Frost, E. G., and Martin, D. L., 1982b, eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, 608 p.

Frost, E. G., and Martin, D. L., 1983a, The Orocopia Schist and Chocolate Mountians thrust system of southeastern California and western Arizona: New insights from removing the overprint of Tertiary detachment faulting and folding: AAPG-SEPM Pacific section meeting Abstracts with Programs, p. 86-87.

Frost, E. G., and Martin, D. L., 1983b, Overprint of Tertiary detachment deformation on the Mesozoic Orocopia Schist and Chocolate Mountains thrust: Geological Society of America Abstracts with Programs, v. 15, no. 8, p. 577.

Graham, G. C., and England, P. C., 1976, Thermal regimes and regional metamorphism in the vicinity of an overthrust fault---An example of shear heating and inverted metamorphic zonation from southern California: Earth and Planet. Sci. Letters, v. 31, p 142-152.

Garner, W. E., Frost, E. G., Tanges, S. E., and Germinario, M. P., 1982, Mid-Tertiary detachment faulting and mineralization in the Trigo Mountains, Yuma County, Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 158-172.

Gross, W. W., and Hillemeyer, F. L., 1982, Geometrical analysis of upper-plate fault patterns in the Whipple-Buckskin detachment terrane, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the

Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 256-266.

Gutmann, J. T., 1982, Geology and regional setting of the Castle Dome Mountains, southwestern Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 117-122.

Hamilton, W., 1982, Structural evolution of the Big Maria Mountains, northeastern Riverside County, southeastern California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 1-28.

Hankins, D. D., 1984, Geologic setting of precious metal mineralization, King of Arizona District, Kofa Mountains, Yuma County, Arizona: Master's thesis, San Diego State University, 135 p.

Harding, L., 1980, Petrology and tectonic setting of the Livingston Hills Formation, Yuma County, Arizona, in, Jenny, J. P., and Stone, C., eds., Studies in Western Arizona: Arizona Geological Society Digest, v. 12, p. 135-145.

Harding, L. E., Butler, R. F., and Coney, P. J., 1982, Stratigraphy, sedimentary petrology, structure, and paleomagnetism of the McCoy Mountains-Livingston Hills Formation, southeastern California and southwestern Arizona: Geological Society of America Abstracts with Programs, v. 14, p. 170.

Harding, L. E., Butler, R. F., and Coney, P. J., 1983, Paleomagnetic evidence for Jurassic deformation of the McCoy Mountains Formation, southeastern California and southwestern Arizona: Earth and Planet. Science Letters, v. 62, p. 104-114.

Harris, M., and Van Nort, S. B., 1975, Geology and mineralization of the Picacho gold prospect: Presentation to AIME Annual meeting.

Haxel, G. B., 1975, Relationship between the Orocopia Schist and the Chocolate Mountains thrust in the Picacho district, southeastern California: Geological Society of America Abstracts with Programs, v. 7, p. 612.

Haxel, G. B., 1977, The Orocopia Schist and the Chocolate Mountain thrust, Picacho-Peter Kane Mountains area, southeasternmost California (Ph.D. dissert.): Santa Barbara, California, University of California, 277 p.

Haxel, G., and Dillon, J. T., 1978, The Pelona-Orocopia Schist and Vincent-Chocolate Mountain thrust system, southern California, in Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 453-469.

Haxel, G., Mueller, K. J., Frost, E. G., and Silver, L. T., 1982, Mid-Tertiary detachment faulting in the northernmost Mohawk Mountains, southwestern Arizona: Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 171.

Haxel, G. B., Tosdal, R. M., Dillon, J. T., in press, Tectonic setting and lithology of the Winterhaven Formation, a new Mesozoic stratigraphic unit in southeasternmost California and southwestern Arizona: U. S. Geological Survey Bulletin, 26p.

Heidrick, T. L., and Wilkins, J., 1980, Field guide to the geology and ore deposits of the Buckskin Mountains, Arizona: Arizona Geological Society 1980 Spring field trip guide, p. 31-51.

Hillemeyer, F. L., 1984, Geometric and kinematic analysis of high- and low-angle normal faults within the Mojave and Sonoran detachment terrane: Master's thesis, San Diego State University, 209p.

Jacobson, C. E., 1980, Deformation and metamorphism of the Pelona Schist beneath the Vincent thrust, San Gabriel Mountains, California (Ph.D. dissert.): Los Angeles, California, University of California, 231 p.

Jacobson, C., 1983, Structural geology of the Pelona Schist and Vincent thrust, San Gabriel Mountains, California: Geologic Society of America Bulletin, v. 94, p. 753-767.

Jorgensen, M. R., Natenstedt, C. J., and Trumbly, P. N., 1982, Possible relationship between Miocene crustal extension/detachment faulting and the deposition of the Tolbard Fanglomerate in the Midway and western Palo Verde Mountains, Imperial County, California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 313-316.

Keith, S. B., Swan, M. M., Wilt, J. C., 1984, Regional gold exploration models for the Mojave region: Geologic Society of America Abstracts with Programs, v. 16, no. 6, p.697.

Lasky, S. G., and Webber, B. N., 1944, Manganese deposits in the Artillery Mountains region, Mohave County, Arizona: U. S. Geological Survey Bulletin 936-R, p. 417-448.

LeVeille, G. P., 1984, Geology of El Capitan, Sonora: Master's thesis, San Diego State University, 122 p.

LeVeille, G., and Frost, E. G., 1984, Deformed Upper Paleozoic-Lower Mesozoic cratonic strata, El Capitan, Sonora, Mexico: Geologic Society of America Abstracts with Programs, v. 16, no. 6, p. 575.

Leeman, W. P., 1974, Late Cenozoic alkalic basalt from the western Grand Canyon area, Utah and Arizona: Isotopic composition of strontium: Geological Society of America Bulletin, v. 82, p. 1691-1696.

Leeman, W. P., 1979, A tectonic interpretation of strontium isotope variations in late Cenozoic lavas--western U. S.: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 464.

Liebler, G. S., 1986, Master's thesis, University of Arizona, in preparation.

Logan, R. E., and Hirsch, D. D., 1982, Geometry of detachment faulting and dike emplacement in the southwestern Castle Dome Mountains, Yuma County, Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 598-607.

Lucchitta, I., and Suneson, N., 1982, Relationship of core complexes, Cenozoic extensional tectonism, and the stable craton near the Colorado Plateau margin in western Arizona: Geological Society of America Abstracts with Programs, v. 14, no. 3, p. 182.

Lyle, J. H., 1982, Interrelationship of late Mesozoic thrust faulting and mid-Tertiary detachment faulting in the Riverside Mountains, southeastern California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 470-492.

Mathis, R. S., 1982, Mid-Tertiary detachment faulting in the southeastern Newberry Mountains, Clark County, Nevada, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 326-340.

McDowell, M., 1986, Geometry of detachment-related deformation and its overprint on the Winterhaven Formation in the Gavilan Hills area, southeastern Chocolate Mountains, California: Master's thesis, San Diego State University.

Morris, R. S., and Frost, E. G., 1985, Geometry of Mid-Tertiary detachment faulting overpinted on the Chocolate Mountains Thrust System from seismic-reflection profiles in the Milpitas Wash region of southeastern California: EOS, American Geophysical Union Abstracts with Programs, December Meeting.

Morris, R. S., and Okaya, D. A., 1986, Crustal geometry of detachment faulting---Structural analysis of seismic-reflection data in SE California: Geologic Society of America Abstracts with Programs, Cordillean Section.

Morris, R. S., Okaya, D. A., Frost, E. G., and Malin, P. E., 1986, Base of the Orocopia Schist as imaged on seismic reflection data in the Chocolate and Cargo Muchacho Mtns. region of SE Calif., and the Sierra Pelona Region near Palmdale, Calif.: Geologic Society of America Abstracts with Programs, Cordilleran Section.

Mueller, K. J., Frost, E. G., and Haxel, G., 1982, Mid-Tertiary detachment faulting in the Mohawk Mountains of southwestern Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 448-458.

Otton, J. K., 1981a, Structural geology of the Date Creek Basin area, west-central Arizona, in Howard, K. A., Carr, M. D., and Miller, D. M., eds., Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona: U. S. Geological Survey Open-File Report 81-503, p. 82-84.

Otton, J. K., 1981b, Complex Oligocene-Miocene extensional and strike-slip tectonics in west-central Arizona: Geological Society of America Abstracts with Programs, v. 13, no. 2, p. 99.

Otton, J. K., 1982, Tertiary extensional tectonics and associated volcanism in west-central Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 143-157.

Pelka, G. J., 1973, Geology of the McCoy and Palen Mountains, southeastern California (Ph.D. dissert.): Santa Barbara, California, University of California, 162 p.

Pridmore, C. L., 1983, The genetic association of mid-Tertiary sedimentation, detachment-fault deformation and antiformal uplift in the Baker Peaks-Copper Mountains area of southwestern Arizona: Master's thesis, San Diego State University.

Pridmore, C. L., and Craig, C., 1982, Upper-plate structure and sedimentation of the Baker Peaks area, Yuma County, Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 356-376.

Pridmore, C. L., Craig, C., and Frost, E. G., 1983, Mid-Tertiary detachment faulting and its relationship to sedimentation in the Baker Peaks-Copper Mountains area of southwestern Arizona and northern Sonora: Geological Society of America Abstracts with Programs, v. 15, no. 7, p. 425.

Pridmore, C. L., and Frost, E. G., 1985, Basin development as a product of detachment-related extension, a reinterpretation of seismic reflection data across the Gila Trough, southwestern Arizona: EOS Transactions of the American Geophysical Union, December meeting.

Pridmore, C. L., Frost, E. G., and Okaya, D. A., Mid-Tertiary basin structure of the Harquahala Valley in west-central Arizona from seismic reflection data: Geologic Society of America Abstracts with Programs, Cordilleran Section.

Proffett, J. M., 1977, Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247-266.

Rehrig, W. A., and Reynolds, S. J., 1980, Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic complexes in southern Arizona, in Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., Tectonic significance of metamorphic core complexes of the North American Cordillera: Geological Society of America Memoir 153, p. 131-175.

Reynolds, S. J., 1980, Geologic framework of west-central Arizona, in Jenney, J. P., and Stone, C., eds., Studies in western Arizona: Arizona Geological Society Digest Volume 12, p. 1-16.

Reynolds, S. J., and Rehrig, W. A., 1980, Mid-Tertiary plutonism and mylonitization, South Mountains, central Arizona, in Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., Tectonic significance of North American metamorphic core complexes: Geologic Society of America Memoir 153, p. 159-176.

Romberger, S. B., 1986, The solution chemistry of gold applied to the origin of hydrothermal deposits: Canadian Inst. Min. Special Vol., in press.

Schuiling, W. T., 1978, The environment of formation of Cu + Ag-bearing calcite veins, Sacramento Mountains, California (Master´s thesis): Tucson, Arizona, University of Arizona, 60 p.

Shackelford, T. J., 1976, Structural geology of the Rawhide Mountains, Mohave County, Arizona (Ph.D. dissert.): Los Angeles, California, University of Southern California, 175 p.

Shackelford, T. J., 1980, Tertiary tectonic denudation of a Mesozoic-Early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona: Geology, v. 8, no. 5, p. 190-194.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S. J., Rehrig, W. A., and Raymond, R. H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 201-259.

Sibson, R. H., in press, Brecciation processes in fault zones: Inferences from Earthquake rupturing: Journal of Geophysical Research.

Silver, L. T., Bickford, M. E., Van Schmus, W. R., Anderson, J. L., Anderson, T. H., and Medaris, L. G., Jr., 1977, The 1.4-1.5 b.y. transcontinental anorogenic plutonic perforation of North America: Geologic Society of America Abstracts with Programs, v. 9, no. 7, p. 1176-1177.

Stone, P., Howard, K. A., and Hamilton, W., 1983, Correlation of metamorphosed Paleozoic strata of the southeast Mojave desert region, California and Arizona: Geologic Society of Amlerica Bulletin, v. 94, p. 1135-1147.

Suneson, N. H., 1980, The origin of bimodal volcanism, west-central Arizona (Ph.D. dissert.): Santa Barbara, California, University of California, 282 p.

Teel, D. B., 1982, Sedimentology and tectonic significance of the Copper Basin Formation in the eastern Whipple Mountains, San Bernardino County, California (Master´s thesis): San Diego, California, San Diego State University, 111 p.

Teel, D. B., and Frost, E. G., 1982, Synorogenic evolution of the Copper Basin Formation in the eastern Whipple Mountains, San Bernardino County, California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 275-285.

Teel, D., Pridmore, C. Jorgensen, M., and Frost, E., 1983, Regional control of mid-Tertiary sedimentation by detachment faulting and folding in western Arizona, southern California, and northern Sonora: AAPG-SEPM Pacific section Abstracts with Programs, p. 141.

Tosdal, R. M., 1982, The Mule Mountains Thrust in the Mule Mountains, California, and its probable extension in the southern Dome Rock Mountains Arizona: A preliminary report, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 55-60.

Tosdal, R. M., Haxel, G. B., Dillon, J. T., 1985, Lithologic associations of gold deposits, southeastern California and southwestern Arizona: Geologic Society of America Abstracts with Programs, v. 17, no. 6, p. 414.

Van Nort, S., and Harris, M., 1984, Geology and mineralization of the Picacho gold prospect, Imperial County, California: Arizona Geologic Society Digest, v. 15, p. 175-183.

Wallace, R. D., 1982, Evaluation of possible detachment faulting west of the San Andreas fault, southern Santa Rosa Mountains, California (Master´s thesis): San Diego, California, San Diego State University, 75 p.

Wallace, R. D., and English, D. J., 1982, Evaluation of possible detachment faulting west of the San Andreas, southern Santa Rosa Mountains, California, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 502-510.

Wallace, R. D., Engel, A. E., Shackelford, T. J., English, D. J., Clark, K., and Frost, E. G., 1983, Mid-Tertiary detachment faulting west of the San Andreas fault in the Santa Rosa Mountains and its regional implications: AAPG-SEPM Pacific section Abstracts with Programs, p. 143.

Wasserburg, G. L. F., and Lanphere, M. A., 1965, Age determinations in the Precambrian of Arizona and Nevada: Geological Society of America Bulletin, v. 76, p. 735-758.

Wilkins, J., Jr., 1984a, The distribution of gold- and silver-bearing deposits in the Basin and Range Province, western United States: Arizona Geologic Society Digest, v. 15, p. 1-27.

Wilkins, J., Jr., 1984b, Editor´s note: Picacho Mine update: Arizona Geologic Society Digest, v. 15, p. 182-183.

Wilkins, J., Jr., and Heidrick, T. L., 1982, Base and precious metal mineralization related to low-angle tectonic features in the Whipple Mountains, California, and Buckskin Mountains, Arizona: in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada (Anderson-Hamilton volume): San Diego, California, Cordilleran Publishers, p. 182-204.

Wilkins, J., Jr., Heidrick, T. L., and Beane, R., 1986, Mineralization in detachment faults---A model: Arizona Geologic Society Digest, v. 16 (this volume).

Wilt, J. C., and Keith, S. B., 1984, Metallogeny of Arizona lode gold production: Geologic Society of America Abstracts with Programs, v. 16, no. 6, p. 697.

Geology and Mineralization of the Picacho Gold Prospect Imperial County, California

Steven D. Van Nort
Lowell Mineral Exploration
5115 N. Oracle Road
Tucson, Arizona 85704

Michael Harris
BP Minerals International Ltd.
Lower William St.
Northam Southampton
Hants SO1 1QE England

ABSTRACT

The Picacho gold mining district is in southeastern Imperial County, California, approximately 35 km north of Yuma, Arizona. Early mining activities during the period 1860-1910 produced 600,000 tons of ore averaging .25 oz/t Au. The principal Picacho ore bodies were the Dulcina-Mars-Venus, Apache, San George, and Diablo, in decreasing order of importance. The property was extensively drilled in the late 1930's after the price of gold was raised from $20 to $35 an ounce, but no ore was mined.

The Picacho deposit is in a topographically low Precambrian window surrounded by Tertiary volcanic rocks and Quaternary sediments. The Precambrian sequence is composed of biotite schist, augen gneiss, and intensely fractured and altered quartzo-feldspathic cataclasite. Pegmatite and quartz breccia dikes and sills cut both fresh and altered Precambrian rocks. The altered rocks are characterized by an abundance of iron oxides with carbonate veining and cementing. These rocks are the host for most of the gold mineralization in the Dulcina-Mars-Venus area. The relatively fresh schist and gneiss do not, in general, contain economic quantities of gold. However, they are typically anomalous in gold when compared to the accepted gold background value for this type of rock. Exceptions to this generality are small areas of fresh pyritic schist which contain substantial gold. Silver has not been found in economically interesting levels.

Gold of economic interest occurs in a variety of environments. Mineralization at the Dulcina-Mars-Venus is in a breccia zone consisting entirely of Precambrian clasts in a fine-grained, red-brown matrix. The Dulcina open cut is bound by major faults and these are postulated to have been the agents of brecciation. The Apache ore zone is again in a breccia but fragments consist of Precambrian and Tertiary components. The San George-Diablo zones are localized along fragmental, tabular, siliceous zones at the Precambrian-Tertiary volcanic contact. These siliceous zones are typically 0.3 to 3 m thick and can sometimes be followed for a few hundred meters.

Several theories on the origin of the gold and alteration agents exist. We feel that a thorough understanding of the Picacho ore genesis and a comprehensive knowledge of its characteristics are invaluable exploration tools for the discovery of similar deposits in the metamorphosed Precambrian, Paleozoic, and Mesozoic rocks of the Southwest.

The following text was prepared as a talk which was delivered at a Silver City, New Mexico meeting in mid-1975.

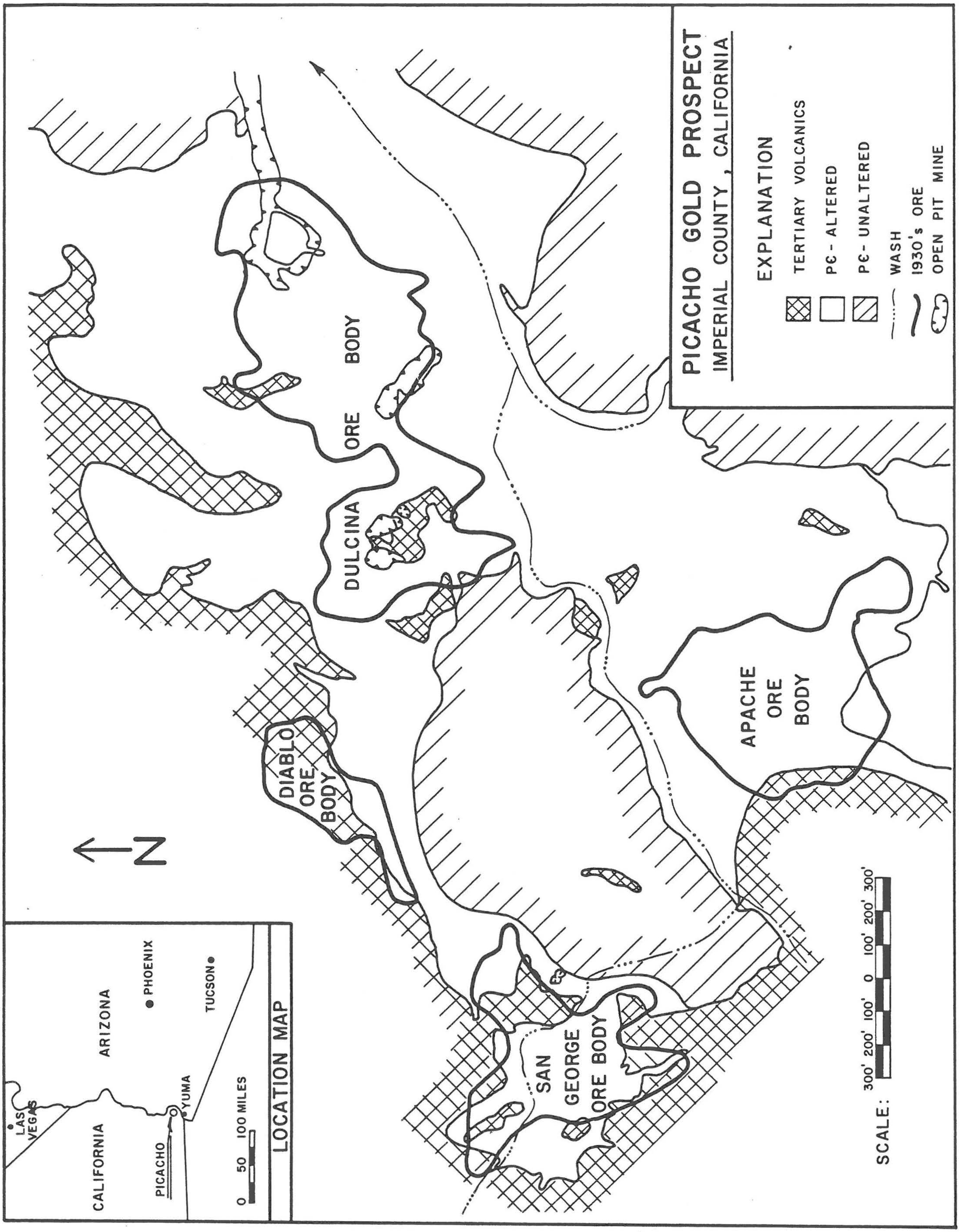
The Picacho gold prospect is in eastern most Imperial County, California; about 35 kilometers north of Yuma, Arizona and 6 kilometers south of the Colorado River.

Mining activities from 1904 to 1911 yielded 150,000 ounces of gold from ore that averaged a quarter of an ounce per ton. There was a town of 2500 people with about 700 miners working the several ore bodies. The ore was initially taken by rail to a cyanide plant on the Colorado River but in 1905 a stamp mill was built on the property and water was pumped to it from the river.

In the late 1930's, after gold had climbed from 20 to 35 dollars an ounce, the Picacho Gold Mining Company of Toronto put down almost 500 shallow holes that delineated 2.5 million tons averaging 0.057 ounces of gold per ton. The advent of the Second World War forced these companies to abandon the property and it received little attention until the recent jump in the price of gold.

The mine is in a Precambrian(?) window surrounded by Tertiary volcanics and Quaternary sediments. The mineralized areas form topographic lows while the unaltered and gold-barren Precambrian(?) schists and gneisses are expressed as hills. The ore bodies outlined by the dashes on the map are the ones blocked out by the drilling in the 1930's.

The metamorphic rocks range from very fresh biotite schists, gneisses, and augen gneisses, shown with black hashes, to strongly deformed and altered, iron oxide-rich cataclasites and mylonites which are the uncolored area on the map. Pegmatites, quartz breccia dikes, and a fine-grained intrusive-appearing phase are present and have all been tentatively classified as Precambrian(?).


PICACHO GOLD PROSPECT
IMPERIAL COUNTY, CALIFORNIA
EXPLANATION
TERTIARY VOLCANICS
PЄ - ALTERED
PЄ - UNALTERED
WASH
1930's ORE
OPEN PIT MINE
DULCINA ORE BODY
APACHE ORE BODY
DIABLO ORE BODY
SAN GEORGE ORE BODY
N
SCALE: 300' 200' 100' 0 100' 200' 300'
LOCATION MAP
CALIFORNIA
ARIZONA
LAS VEGAS
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TUCSON
YUMA
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0 50 100 MILES

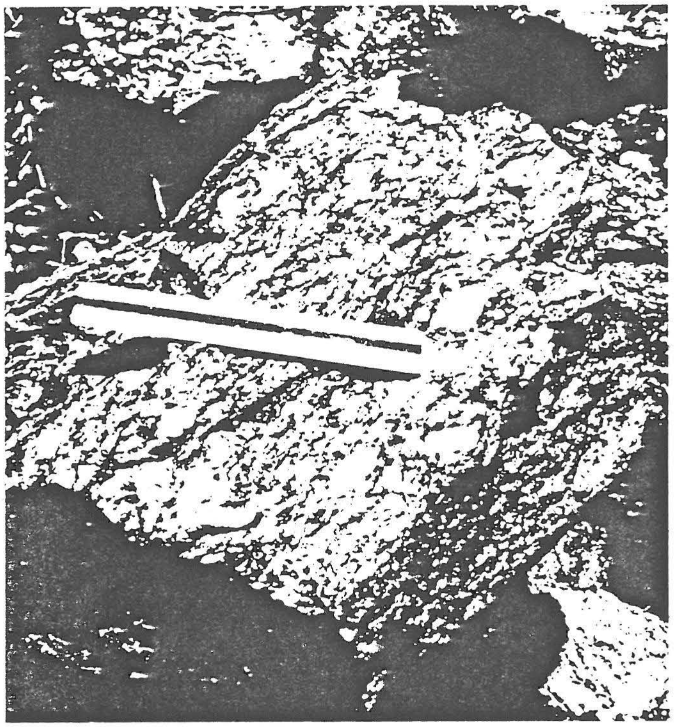

Figure 2. Unaltered gneiss.

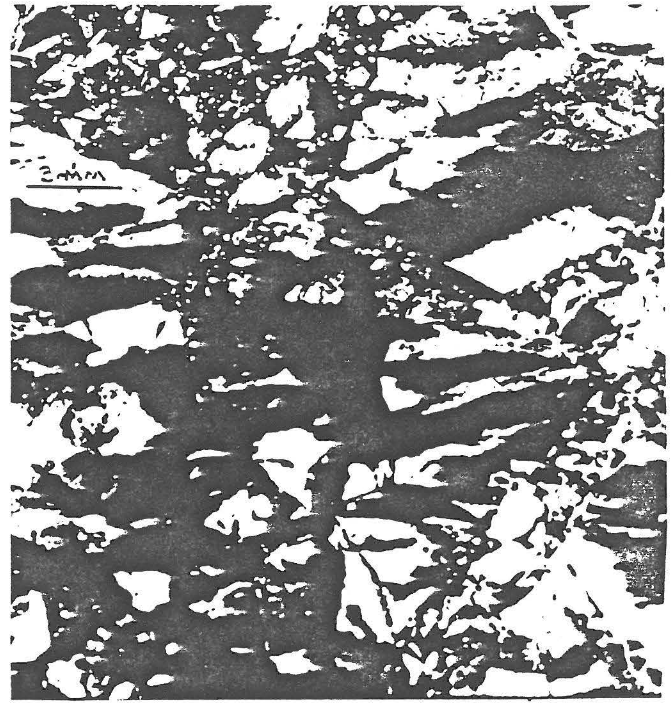

Figure 3. Photo-micrograph, unaltered gneiss.

The unaltered schist and gneiss are composed of aligned biotite surrounded by feldspar and quartz. The augens are of quartz and K-spar. Biotite in surface samples is usually partially altered to chlorite and/or oxidized to various shades of yellow and brown. These rocks may contain minor amounts of clay derived from the decomposition of feldspar. Their relatively low iron oxide content is expressed primarily as thin limonitic coatings on fracture plane and is associated with the weathering of the mafic materials. Hematite is rare. The unaltered metamorphics are normally barren and out of the ore areas. Only locally, where pyrite has been observed, is there any appreciable amount of gold. The pyrite cubes have faces measuring up to 2 millimeters and have only been found in the Dulcina area at depths of roughly 30 to 40 meters. We concentrated and assayed the pyrite and it proved to be responsible for all, or nearly all, of the gold. Electron microprobe traverses and high power microscopy has so far not found discrete particles of gold on pyrite surfaces although a 20 micron grain of sphalerite was detected with the probe in a fracture. We have never seen sulfides on the surface.

Microscopically, the unaltered schists and gneisses consist of lepidoblastic biotite and chlorite accompanied by low albite, K-spar, quartz, and minor amphibole and proxene - normally hornblende and diopside. There are usually scattered grains of almandine, sphene, and rutile. Hornblende has largely altered to biotite and chlorite, the feldspars are generally somewhat argillized/sericitized and the quartz is strained exhibiting a mottled extinction that resemble microcline twinning. There is a rough alignment of the quartz "a" axes parallel to the schistosity. Biotite and chlorite occur in roughly equal amounts, but in general, the fresher the rock, the greater is the ratio of biotite to chlorite. There is almost always carbonate present either as coatings around grains or as veinlets. It seems most probably that these quartzo-feldspathic schists and gneisses were derived from arenaceous sediments.

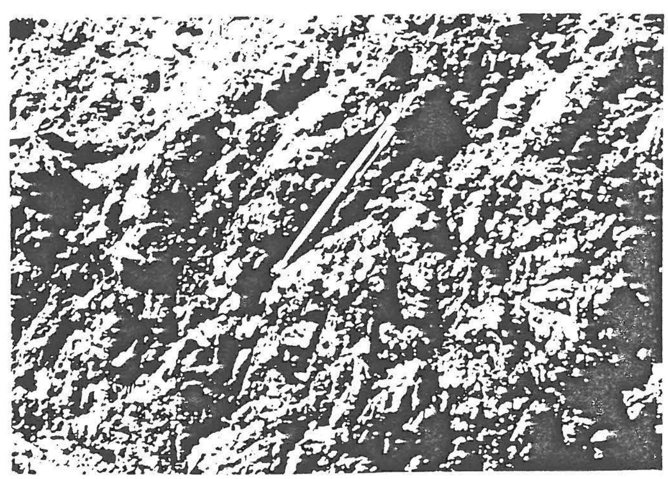

Figure 4. Altered gneiss.

The altered Precambrian(?) rocks, which are the host for most of the gold at Picacho, are easily recognized by their red to brown colors and absence of obvious metamorphic lineations. They contain an abundance of iron oxides, a lot of clays, and it is rare to find many feldspars or any micas. Some areas have been significantly silicified, but in general, the altered rocks are quite friable due to the large clay content and their intensely fractured nature. The altered zone invariably occurs above the fresh gneiss with a sharp to gradational contact separating them.

Figure 5. Photo-micrograph, altered gneiss.

In thin section these altered rocks find the original schist or gneiss reduced to a highly fractured and brecciated quartz-feldspar cataclasite containing large amounts of carbonate and iron oxides, especially hematite. The original metamorphic lineations have been completely destroyed and the fracturing, brecciation, and carbonate veining do not follow a discernible pattern.

In summary, the Precambrian(?) metamorphic rocks vary in alteration roughly according to the following graph. Micas are rarely found in the most altered rocks but are very common in the unaltered schists and gneisses; metamorphic lineations follow the same pattern; the ratio of hematite to limonite decreases proportionately with the alteration as does the total amount of iron oxides; pyrite is only present at depth in very fresh rocks; and this is the most

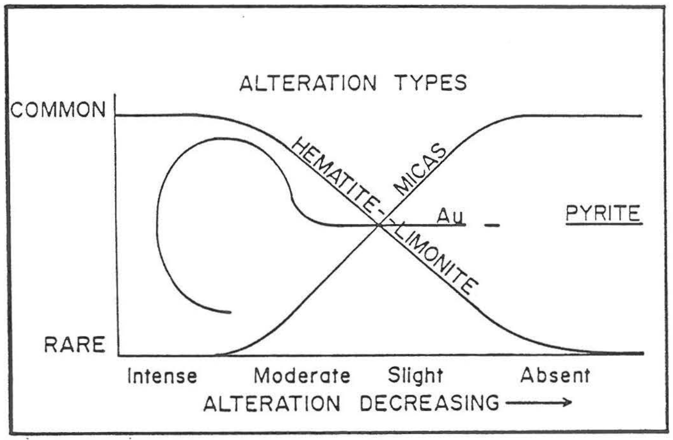

Figure 6. Alteration graph.

sense we can make of the gold distribution except to say that you have a better chance of finding gold in an altered rock.

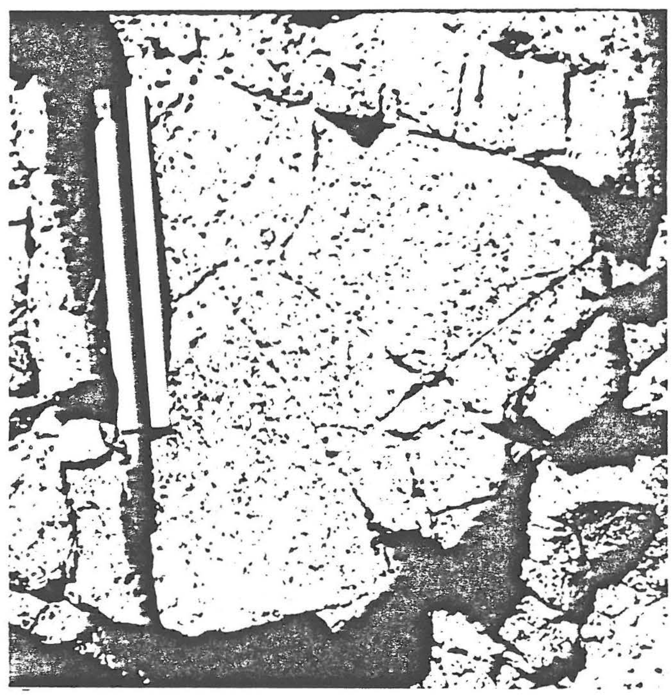

Figure 7. Intrusive.

There is an intrusive appearing rock that is in sharp contact with the metamorphics near the Apache. It is a fine-grained, dense, fresh-looking rock with a typical alignment of the micas. It has not been found to carry gold and drifts driven into it were invariably stopped. Microscopically, one can see equigranular quartz and feldspar scattered small grains of apatite, sphene and hornblende; opaques suggestive of being pyrite pseudomorphs; and a 70:30 ratio of biotite to chlorite plus muscovite. The quartz and feldspar are very fresh compared to the other Precambrian(?) rocks and it is yet to be decided whether the minerals were aligned by metamorphic processes or during magmatic crystallization. Young intrusives are known elsewhere in the area and an age date of this rock would be helpful.

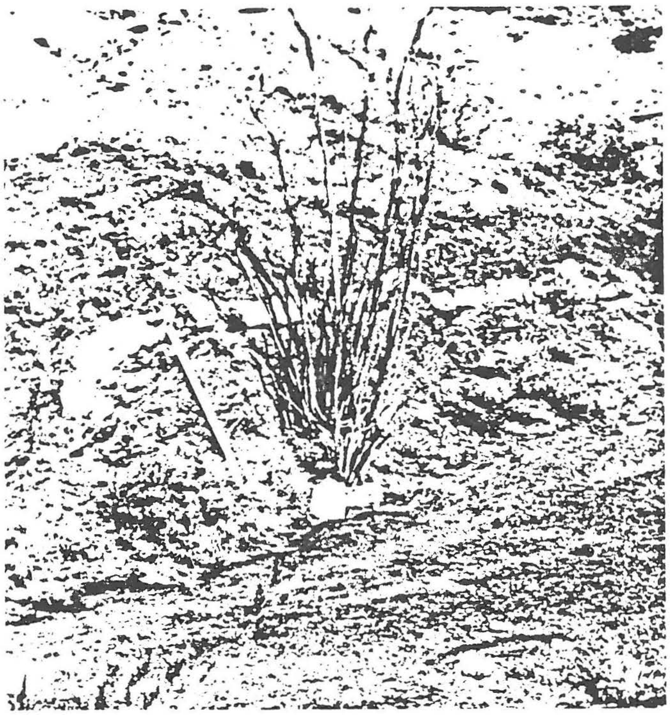

Figure 8. Pegmatitic dikes.

There are two kinds of pegmatites at Picacho. One type forms dikes and sills which are typically several decimeters to a meter thick and up to 20 to 30 meters long. They may be conformable to, or transgress the schistosity and their contacts with the schists are abrupt and commonly mylonized suggesting an intrusive origin or later faulting along the contact. The other kinds occur as metamorphic segregations that merge into a gneiss which contains a much greater concentration of mafic minerals than is normal. Both forms are similar mineralogically, being composed of up to 10 millimeter long crystals of quartz and feldspar which are typically altered and strained. We have seen a few large books of muscovite but this is not very common.

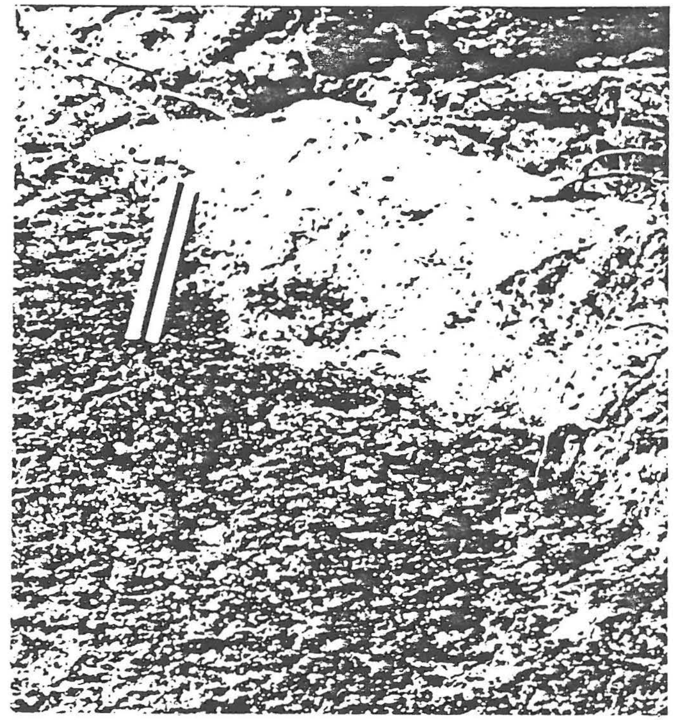

Figure 9. Pegmatitic segregation.

There are also quartz breccia dikes composed of angular to subrounded, milky white quartz fragments cemented by a ferruginous silica and carbonate matrix. These

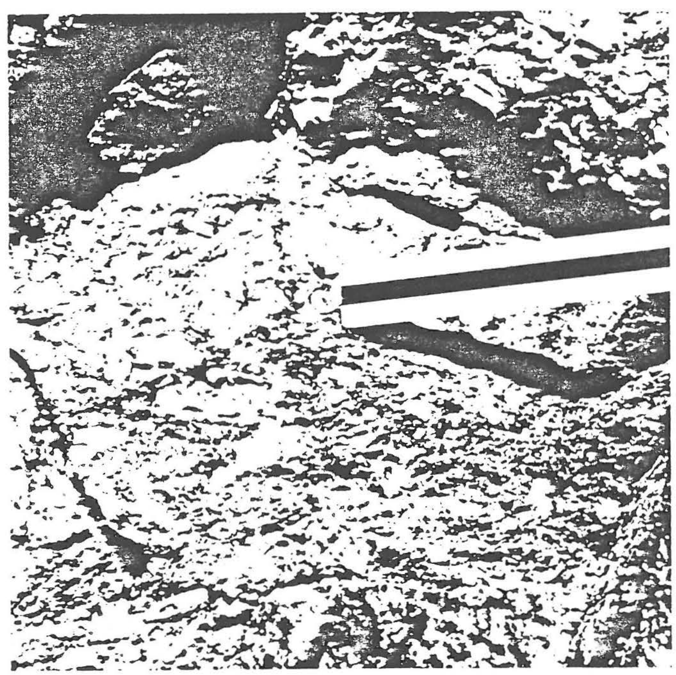

Figure 10. Quartz breccia dike.

dikes are one to several decimeters thick and typically less than a few meters long. Their highly fragmental and strained nature is best appreciated under crossed nichols.

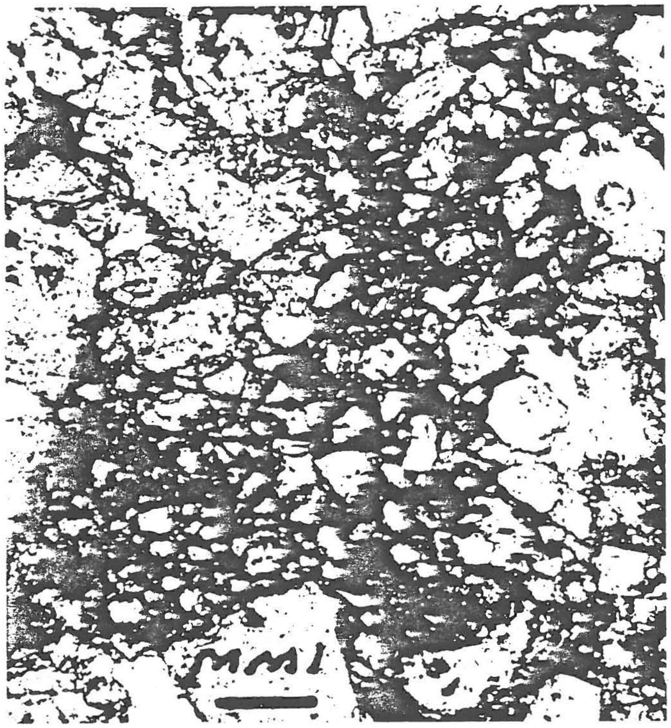

Figure 11. Photomicrograph quartz breccia dike.

The quartz grains are fairly well aligned optically and fine lamellae of dust inclusions were probably incorporated during fracturing.

Both pegmatite types and the quartz breccia dikes occur in altered and unaltered Precambrian(?) rocks but not in the volcanics. X-ray analyses of the pegmatites and breccias did not find any elements that are not in the metamorphics and neither run any gold. The pegmatites are most probably related to the Precambrian(?) metamorphism but the nature of the quartz breccia dikes is more uncertain. It seems unlikely that they are brecciated pegmatites, as the two have been found in sharp contact, the breccias are devoid of the feldspars which typify the pegmatites, and there is a rough alignment of the quartz optic axes in the breccia. This evidence suggests to us that they were intruded as a quartz breccia dike rather than having been brecciated following emplacement.

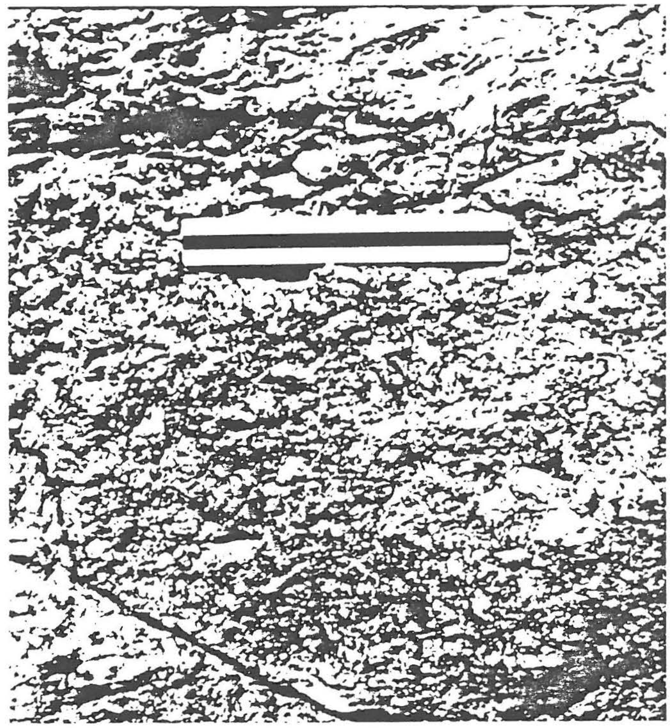

Figure 12. Rubble.

A gold-rich silicified "rubble" zone is present along the volcanic-gneiss contact at the San George and Diablo ore bodies, and this is what the early miners went after in those areas. This zone is typically less than a few meters thick but is fairly continuous over more than 100 meters along the contact. It is composed of quartz fragments in a silica cement and an attempt to relate its trace elements geochemistry to that of either the metamorphics or the volcanics failed. Its origin is not fully understood, or at least agreed upon, and I will return to this question later.

The Tertiary volcanic rocks, colored with wide stripes on the map, do not carry ore grade mineralization although a few do contain anomalous amounts of gold. We are not sure why or how this happens but presume that either a lava gobbled up a mineralized Precambrian(?) boulder, gold has been subsequently faulted in, or there is some young mineralizing activity around. The volcanics lie in both fault and normal depositional contact with the Precambrian rocks. Bruce Crowe of U.C. Santa Barbara has divided the regional volcanic stratigraphy into the three main units and has assigned them a Miocene-Oligocene age. We have not intimately studied the volcanics and they are considered only as a nuisance covering up ore.

A mineralized breccia containing various sizes of Precambrian(?) and Tertiary fragments is present in the Apache underground workings. Some of the clasts are up to one-half of a meter in length, all appear to be randomly oriented, their degree of alteration is variable, and they may be angular to rounded. Precambrian(?) components are dominant over the volcanic fraction especially near the breccia's contact with the country rock. The clasts are cemented by a fine-grained, red to brown matrix and the unit is so well lithified that timbering was rarely needed. An X-ray diffraction study of the matrix showed it to consist mainly of Precambrian(?) rock fragments varying in size from one centimeter down to minus 10 microns. This material is well cemented with significant amounts of sodium-montmorillonite derived from the alteration of Tertiary volcanic ash. Petrographic work on the matrix did not discover shards or any evidence indicating a normal volcanic origin. We sampled the Precambrian(?) clasts, Tertiary clasts, and the matrix separately and all three carry gold. There is a similar mineralized breccia in the underground Dulcina workings but we haven't found any volcanic fragments in it yet.

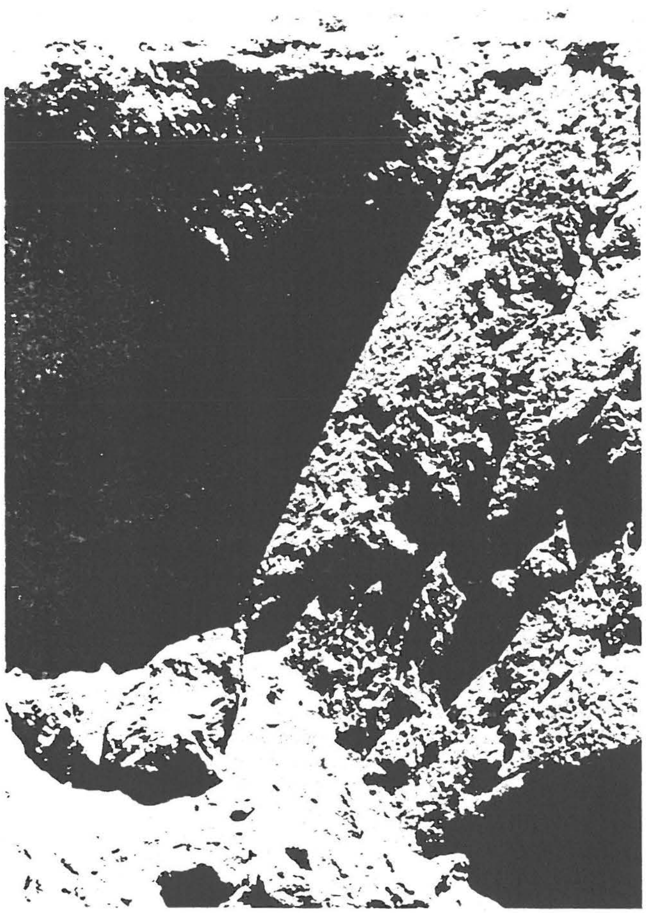

Figure 13. Faulting at the Dulcina Pit.

Faulting is extremely common in both the Precambrian(?) and Tertiary sequences. There is widespread evidence of recent tectonism in the immediate area and the Salton Sea and San Andreas are not far away. Detailed underground and surface mapping showed that most faults are not continuous over extended distances but the main washes are probably major geologic structures as they commonly separate intensely altered areas from fresh schist and have exotic volcanics rafted along them.

The genesis of the Picacho deposit is a hotly debated but still unresolved question and various theories have gone in and out of vogue. Consequently, we feel it best to list what facts we do know about the mineralization, try to explain some of them, and then present a few possibilities for your consideration.

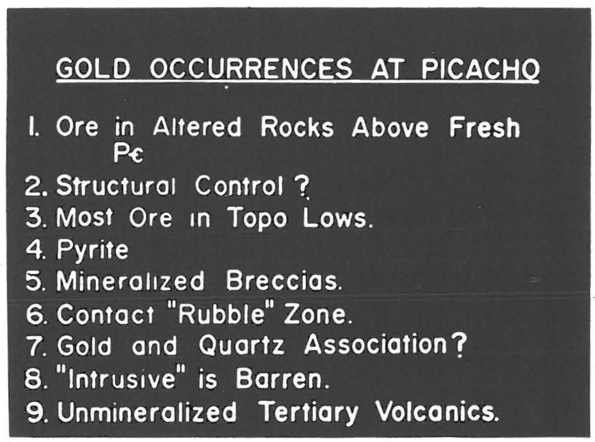

Figure 14. Gold occurrence chart.

First, we must note that most of the ore is in very altered Precambrian(?) rocks that are above unaltered, and as a rule, uneconomic schists and gneisses. We are referring now principally to the Dulcina area. The most precise one could be in using the alteration as a guide to ore is to assume that there may be gold if the rock is altered, but this is far from a sure bet as we have not found the degree of alteration to be indicative of the degree of gold mineralization. A lot of the iron oxides must have been derived from the weathering of the mafic constituents as drilling into the fresh rock has not found sufficient pyrite to have so thoroughly coated such an area. It is interesting to note that the altered rocks contain slightly less or an equal amount of total iron compared to the fresh non-pyritic rocks making it possible for most, or all, of the iron oxides in the mafic-free altered rocks to have been derived from iron-rich silicates without any contribution from pyrite. It has been suggested that the ore horizon represents a relic auriferous and pyritic Precambrian(?) strata, but we could not find any supporting evidence for this and schistosity is so chaotic in the area that it seems unlikely a bed would have retained a continuous stratigrahic position.

Second, the altered rocks are invariably intensely shattered and are bounded by inferred and observed tectonic structures which abruptly separate them from unaltered country rock or volcanics.

Third, the ore areas are topographic lows. This may be due to their more erodeable nature but the association with major faults suggests that this is not the only factor responsible. In any case, this geomorphological feature has been observed in a similar deposit from the general area and could prove to be a valuable exploration tool.

Fourth, on the basis of negative evidence, we are tentatively assuming that the gold was originally in solid solution with pyrite.

Fifth, the Apache breccia is a real problem. Certainly it is either a fault breccia, a collapse breccia, a volcanic phenomenon, or some combination of these. Somehow, one must account for a mineralized volcanic clast. The breccia in the Dulcina open cut is clearly bounded by at least two major faults and projection of the faults mapped underground at Apache often delimit the breccia.

Sixth, there is a silicified "rubble" zone in places among the volcanic-gneiss contact that can be quite rich in gold.

Seventh, we panned some of the mineralized rocks and in several cases found gold coating quartz veins. We also found visible gold in a fractured quartz vein on the 150 foot level of the Apache mine. The question is: are these quartz veins the feeders for all the gold at Picacho? We think not, as the veins exposed at the surface are barren and the rest of the mineralization does not have any discernable spatial relationship to them.

Eighth, the role and nature of the intrusive phase is not clear but it does not constitute ore.

Lastly, as a general rule, the Tertiary volcanics are unmineralized.

We believe there are several types of ore bodies and that the largest is the finely disseminated gold in the altered metamorphics. We propose that the area was racked by major faults which are expressed today as washes but are also vividly exposed in the Venus and Dulcina pits, and in several other places. The gold was introduced as auriferous pyrite into tectonically prepared ground and subsequent meteoric action oxidized the pyrite, destroyed the other rock constituents, and freed the gold. This event was triggered by plutonic activity prior to the effusion of the Tertiary volcanics.

The second kind of ore body is the contact silicious zone that we think is the remnant of a mechanically concentrated gold-rich layer lying on the pre-volcanic surface. This horizon was silicified by solutions that accompanied and followed the volcanics and was later shattered by contact faulting which is common in this area.

The last type are the breccias that we feel are collapsed structures caused by tectonic stress during the late Tertiary; but the possibilities for them are so wide that it seems rather unfair to speculate any farther.

Editors Note: Picacho Mine Update

Mine Developments

The Picacho mine is operated by Chemgold, Inc., a wholly owned subsidiary of Glamis Gold, Ltd., Chester Miller, President. Production is currently running at 6,000 to 7,000 tons per day with a 1 to 0.7 ore to waste ratio. The ore is heap leached, and 45 to 55 ounces of gold are recovered each day. Planned production for 1985 is in the 24,000-ounce range. The dore runs about 89% Au and 6%-7% Ag. Ore reserves now total 10,000,000 tons grading 0.04 oz/ton Au or 18,000,000 tons grading 0.03 oz/ton Au if a cutoff grade of 0.007 oz/ton is used (Stannus, 1983).

Genesis of the Ore Deposit

In Harris and Van Nort's excellent description of the Picacho gold deposit, which is published essentially as presented at the Base and Precious Metals Symposium at Silver City, New Mexico, on May 22-25, 1975, the authors stated that ". . . the genesis of the Picacho deposit is a hotly debated . . ." issue. In 1984, the origin of the gold at Picacho is still a hotly debated issue. At least three interpretations concerning gold have been widely circulated by (1) Stanley Keith of Magmachem, (2) Eric Frost and his students at San Diego State University, and (3) Joe Wilkins and Tom L. Heidrick.

Keith's concept is that the gold is hydrothermal and derived from a magmatic source related to the pegmatite dikes and intrusive rocks described by Harris and Van Nort: specifically a two-mica, peraluminous granite. An extensive geochemical data set, which includes multi-element analyses from a number of samples at Picacho, is consistent with the two-mica magma chemistry model (Keith, 1984, personal commun.).

Several students at San Diego State University under the direction of Frost have completed maps and detailed analyses of veins, veinlets, fault veins, and unmineralized faults and fractures in and adjacent to the pit areas. They concluded that Picacho is a detachment fault-type deposit with gold mineralization deposited in listric normal fault breccias in an upper or middle plate; depositional loci consistent with the detachment-fault mineralization model proposed by Wilkins and Heidrick (1982).

Wilkins and Heidrick have investigated aspects of the Picacho deposit (at separate times) and both conclude that Picacho is detachment-fault related but the gold metallization occurs along the detachment fault surface and in the lower plate chlorite breccia. However, the mineralized lower plate rocks were subsequently cut and rotated by a second generation of detachment faulting, which also involved Crowe's (1978) Ferguson Wash ignimbrite and younger rocks. A conceptual cross section showing both generations of faulting is shown on figure 1. The two-generation concept is patterned after Dokka's (1980) model for the Newberry Mountain detachment faults.

In the two-detachment fault concept, the detachment fault exposed northwest of the mine (Frost, 1983, personal commun.) is a second-generation fault. In the pit area, Harris and Van Nort's "gold-rich rubble zone" is a rotated mineralized segment of the first detachment fault and the "mineralized breccia" represents rotated listric fault breccias. In support of this concept, Stannus (1983) stated that gold metallization decreases with increasing distance down and laterally away from 36- and 50-degree-dipping microbrecciated fault surfaces interpreted as rotated segments of the original detachment fault. These segments are (or were) exposed in the Apache and Dulcina pits.

All three interpretations are more or less consistent with the nine facts about mineralization presented by Harris and Van Nort.

REFERENCES

Crowe, B. M., 1978, Cenozoic volcanic geology and probable age of inception of basin-range faulting in the southwestern Chocolate Mountain, California: Geological Society of America Bulletin, v. 89, p. 251-264.

Dokka, R., 1980, Early Miocene detachment faulting in the central Mohave Desert, California, in Howard, K. A., Carr, M. D., and Miller, D. M., eds., Tectonic framework of the Mohave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, p. 29-31.

Frost, E. G., 1983, Personal communication: Professor of Geosciences, San Diego State University, California.

Keith, S. B., 1983, Personal communication: President, Magmachem Exploration, Inc., Phoenix, Arizona.

Stannus, B., 1983, Personal communication: Mine engineer, Picacho Mine, California.

Wilkins, Joe, Jr., and Heidrick, T. L., 1982, Base and precious metal mineralization related to low-angle tectonic features in the Whipple Mountains, California and Buckskin Mountains, Arizona, in Frost, E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 182-204.

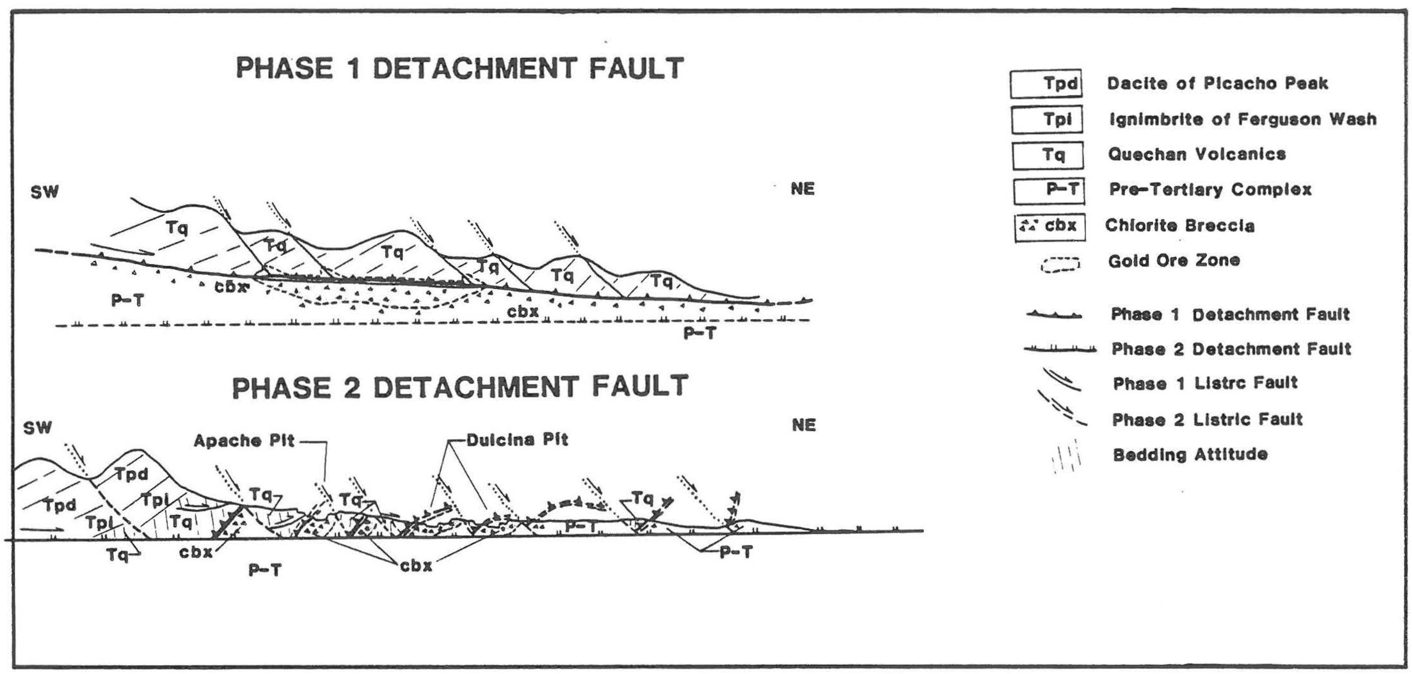

Figure 1. Conceptual cross sections at the Picacho mine, showing two generations of detachment faulting and associated gold mineralization

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MID-TERTIARY DETACHMENT FAULTING IN SOUTHWESTERN ARIZONA AND SOUTHEASTERN CALIFORNIA AND ITS OVERPRINT ON THE VINCENT THRUST SYSTEM

FROST, Eric G., MARTIN, Donna L., KRUMMENACHER, Daniel, Dept. of Geol. Sci., San Diego State University, San Diego, CA 92182

Nearly all the mountain ranges in southwestern Arizona and southeasternmost California record multiple phases of Mesozoic deformation overprinted by detachment-related deformation of mid-Tertiary age. On a regional basis, rocks record K-Ar resetting due to Jurassic arc magmatism (160-120 myBP), Late Mesozoic magmatism and tectonism (80-60 myBP), and Tertiary detachment faulting (27-12 myBP). Mesozoic deformation appears to have imparted a pronounced physical anisotropy to the crust, which later exerted a strong control on Tertiary detachment faulting. Pronounced antiformal-synformal folding of the detachment fault (DF) is largely responsible for the topographic form of the region and the large-scale distribution and exposure of rock units. Two sets of folds are present, one with NE- and one with NW-trending axes. In southwest Arizona, the NW folds are more prominent than the NE folds, which are so pronounced in the Parker-Needles area. Large-scale folding in the Pelona-Orocopia Schist terrane, as described in southern California by many workers, may also be detachment-related. DF contacts typically separate tilted Tertiary rocks from pre-Tertiary units, including the Pelona-Orocopia Schist in some areas. The Mesozoic Vincent-Chocolate Mountain thrust seems to be both cut and in part reactivated by the DF. Dating of this thrust in the southern Chocolate Mountains yields reset K-Ar ages of 22.6 ± 0.7 myBP (w/r) just below the fault, 37.4 ± 3.7 myBP (bio) at 30 cm below, and 53.6 ± 6.4 myBP (bio) at 100m below the fault. Such Tertiary overprinting of Mesozoic low-angle fabrics seems to characterize the geologic development of this region. The DF is offset by later normal faults and thus records only one phase of mid- to late-Tertiary regional crustal extension. This detachment phase, however, appears to be genetically linked to mid-Tertiary volcanism, sedimentation, and mineralization, all of which are intimately related to regional crustal extension.

A LATE JURASSIC MINIMUM AGE FOR THE PELONA-OROCOPIA SCHIST PROTOLITH, SOUTHERN CALIFORNIA

№ 45372

MUKASA, S.B., Department of Geological Sciences, University of California, Santa Barbara, CA 93106; DILLON, J.T. Alaska Geological Survey, College, AK 99701; and TOSDAL, R.M., Department of Geological Sciences, University of California, Santa Barbara, CA 93106.

The Pelona-Orocopia Schist is exposed in windows in the Vincent-Chocolate Mountains thrust throughout southern California and southwest Arizona. Concordant U-Pb zircon ages of 163.2 and 160.9 m.y. on two fractions (see Table 1) from a pre-metamorphic pyroxene-hornblende diorite dike provides a Late Jurassic minimum age for the protolith of the Pelona-Orocopia Schist. This diorite, which is exposed in the Mammoth Wash area, central Chocolate Mountains, southeast California, intruded the graywacke and basalt protolith prior to subsequent thrust-related metamorphism in late Mesozoic time.

The minimum age refutes several tectonic models which propose that the protolith of the Pelona-Orocopia Schist is younger than 160.9 to 163.2 m.y. old. Specifically, the origin of the protolith could not be related to a latest Cretaceous or early Tertiary dextral proto-San Andreas Fault, nor to a Cretaceous marginal or back-arc basin, nor to the upper Jurassic to Tertiary Franciscan Complex. Remaining models are those which relate the Pelona-Orocopia Schist protolith to pre-late Jurassic oceanic terranes of western California, or to the Jurassic magmatic arc which extends across southwestern North America, or to the Jurassic Mojave-Sonora Megashear.

Table 1: U-Pb Isotopic Data

Fraction	Total U (ppm)	Total *Pb (ppm)	$t(\frac{*206Pb}{238U})$m.y.	$t(\frac{*207Pb}{235U})$m.y.
>75 µm	95.5	2.79	163.1	163.4
<75 µm	133.7	3.82	160.3	161.4

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OVERPRINT OF TERTIARY DETACHMENT DEFORMATION ON THE MESOZOIC OROCOPIA SCHIST AND CHOCOLATE MTNS. THRUST

№ 2911

FROST, Eric G., Dept. of Geol. Sci., San Diego State Univ., San Diego, CA 92182; and MARTIN, Donna L., Dept. of Geol. Sci., Univ. of Calif. Santa Barbara, Santa Barbara, CA 93106

Well-developed Tertiary detachment faults and large-scale folds are present in the Trigo Mtns. of southwestern Arizona and the Picacho Pe and southern Chocolate Mtns. areas of southeastern California. A stacked sequence of detachment faults defining large-scale anastomosi faults, or fault lenses, is also exposed in the Cargo Muchacho Mtns., immediately adjacent to the San Andreas fault (Algodones fault). Detachment-related faulting and folding have overprinted the pre-existing structure in the area, principally the Orocopia Schist and Chocolate Mtns. Thrust System of Mesozoic age, as superbly defined by Dillon (1975) and Haxel (1977) in this region. Unravelling the Terti ary overprint suggests several possible modifications of previous models for the system. The late Triassic-early Jurassic Aztec Sandstone appears to be interbedded in the Winterhaven Fm., making the un older than previously thought. The Winterhaven and Orocopia also appear to be part of the same lithotectonic sequence, suggesting a Tria sic depositional age for the Orocopia. Intracontinental thrusting an nappe formation may be responsible for generating the Chocolate Mtns. Thrust in mid-Mesozoic time. K-Ar ages have been uniformly reset to about 60 myBP on all units, including the Marcus Wash granite, indica ing that this is largely an uplift age. Mid-Tertiary resetting is al present below detachment faults. The overall geologic history of thi region appears very similar to the Mesozoic compressional regimes exposed in most ranges to the north along the Colorado River and their subsequent overprint by Tertiary detachment-related deformation. Ter ranes offset from this region along the San Andreas probably record th same juxtaposition of Mesozoic and Cenozoic tectonic fabrics.

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PELONA-OROCOPIA SCHIST PROTOLITH: ACCUMULATION IN A MIDDLE JURASSIC INTRA-ARC BASIN

№ 4537

TOSDAL, R.M., Department of Geological Sciences, University of Cal fornia, Santa Barbara, CA 93106; DILLON, J.T., Alaska Geologica Survey, College, AK 99701; HAXEL, G.B., U.S. Geological Survey, Menlo Park, CA 94025; and MUKASA, S.B., Department of Geologica Sciences, University of California, Santa Barbara, CA 93106.

The protolith of the Pelona-Orocopia Schist of southern California an southwest Arizona was a continentally-derived graywacke and shale sequence with subordinant interlayers of basalt, chert, limestone, loca pods of ultramafic rocks, and rare diorite dikes. Concordant U-Pb zi con ages of 163.2 and 160.9 m.y. on two fractions from a diorite dike provide a Late Jurassic minimum age for the protolith (see Mukasa and others, this volume). Regional metamorphism of all protolith rocks c temporaneous with late Mesozoic thrusting produced this schist.

Some models propose that the upper plate of the thrust fault syste overlying the schist moved southwestward, but most structural evidenc indicates northeastward overthrusting. This interpretation is crucia since some of the rocks of the upper plate are very similar to rocks that occur within the intra-continental Jurassic magmatic arc of sout west North America. We suggest that the protolith accumulated in an intra-arc rift basin within the western part of the Jurassic magmatic arc. This tectonic setting accounts for both the oceanic depositiona environment and the continental provenance of the clastic rocks.

Although slightly older, the rift basin could have been part of th intra-arc rift system of Late Jurassic age that is recognized in the western Sierra Nevada and Klamath Mountains, California. The rift ba may have formed at the junction of the sinstral late Middle to Late Jurassic Mojave-Sonora Megashear and the continental margin along an obliquely-convergent plate boundary.

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LITHOLOGIC ASSOCIATIONS OF GOLD DEPOSITS, SOUTHEASTERN CALIFORNIA AND SOUTHWESTERN ARIZONA

№ 6129

TOSDAL, R.M., HAXEL, G.B., U.S. Geological Survey, 345 Middlefiel Road, Menlo Park, CA, 94025, and DILLON, J.T., Alaska Division c Geological and Geophysical Surveys, College, AK 99708

Disseminated gold deposits in the Chocolate and Cargo Muchacl Mountains, southeastern California, and other historically importa lode and related placer districts in the Dome Rock Mountain southwestern Arizona, share several lithologic associations. All a hosted largely or entirely by gneiss. For most of these deposits, tl protolith of the gneiss was one or both of two regionally extensi lithologic units of known or probable Jurassic age. These are 1) sil cic volcanic and volcaniclastic rocks and hypabyssal quartz porphyr intruded by 2) dioritic, granodioritic, and granitic plutonic rocks(tl slightly different gneiss at the Picacho Mine could be a higher gra equivalent of the metamorphosed Jurassic granitoids or an old gneiss).

Metasomatic rocks, now kyanite-quartz-white mica gneiss, are commo ly, but not invariably, spatially associated with mineralization. The rocks are exposed along contacts between and derived from both tl metavolcanic rocks and the granodioritic to granitic plutons. Fie and mineralogic evidence indicates metasomatism was related to granit plutonism and probably synchronous with amphibolite facies region metamorphism.

These observations suggest that the gold deposits are, at least part, genetically related to Jurassic igneous rocks. Although gold m well have been remobilized or further concentrated during late Mesozo and(or) Tertiary deformations and magmatism, it probably was initial introduced or concentrated during Jurassic plutonism and region metamorphism.

FIELD NOTES AND SKETCHES

[Original contains five sheets]