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JDS

MIDDLE TERTIARY MINERALIZATION RELATED TO METAMORPHIC CORE COMPLEXES AND DETACHMENT FAULTS IN ARIZONA AND CALIFORNIA

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Tucson, Arizona

For presentation at the SME Annual Meeting
Denver, Colorado - February 24-27, 1987

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INTRODUCTION

Cordilleran metamorphic core complexes in the southwestern United States are areas where middle to late Tertiary low-angle normal faulting has uncovered rocks that were at temperatures sufficient for mylonitization during the early part of Tertiary extensional faulting. Large-displacement low-angle normal faults that separate upper- and lower-plate rocks in metamorphic core complexes are termed detachment faults. The significance of Tertiary detachment faulting in the Basin and Range Province has only become apparent in the past 6-8 years, and the association of mineral deposits with detachment faults has only been recognized in the past few years as well.

Crystalline rocks below detachment faults have typically undergone chloritic alteration and brecciation over a distance of a few to a few hundred meters below the fault surface (Fig. 1). Chloritic alteration and brecciation overprinted mylonitic fabrics formed during earlier ductile shearing along the down-dip projection of detachment faults. Rocks that underwent pre-Tertiary ductile deformation and prograde metamorphism were subjected, in rapid succession, to middle to late Tertiary mylonitization, brecciation and chloritic alteration, microbrecciation immediately adjacent to the fault, and subaerial exposure. Lower-plate rocks thus experienced rapid decompression and cooling as a result of tectonic denudation and isostatic uplift (Wernicke, 1981; Davis, 1983; Davis et al., 1986).

Upper-plate rocks typically consist of highly fractured, faulted, and tilted pre-Tertiary rocks and their depositionally overlying cover of middle to upper Tertiary volcanic and sedimentary rocks. Normal faults commonly strike perpendicular to detachment-fault-displacement direction and lower-plate mylonitic lineation (Fig. 1). Distention of upper-plate rocks was accommodated downward by displacement on detachment faults, and this displacement increased laterally down the regional dip of the detachment fault.

Two distinct paragenetic mineral assemblages occur in many mineralized detachment-fault terranes. Sulfide-rich mineralization reflecting low $f(O_2)$ conditions generally occurred before mineralization reflecting more oxidizing conditions. Important sulfide mineral deposits are present at the Copper Basin deposit in the Whip-

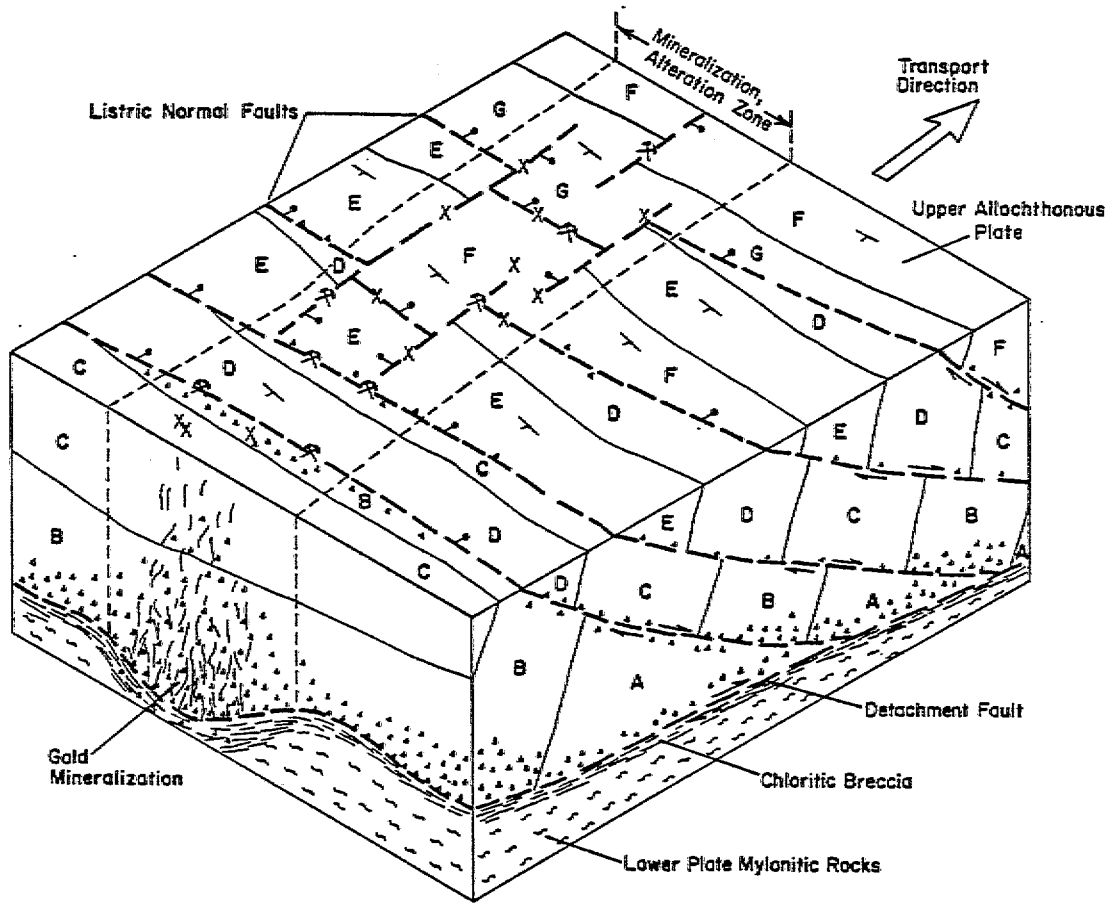

Figure 1. Block diagram slowing elements of metamorphic core complexes and precious-metal mineralization associated with low-angle faulting.

FIELD TRIP

ARIZONA – CALIFORNIA METAMORPHIC CORE COMPLEXES AND MINERALIZED DETACHMENT ZONES.

APPLIED GEOLOGIC STUDIES INC.

1985

ASARCO

Southwestern Exploration Division

February 20, 1985

To: J. D. Sell

From: H. G. Kreis

Field Trip
Detachment Zones
California-Arizona

During the week of February 3rd Tony Dalla Vista and I attended the metamorphic core complex and detachment zone field trip led by Bill Rehrig. The itinerary of the field trip is summarized on the first two pages of the accompanying field trip book.

The geology of nearly all the stops is well described in the accompanying book, but there are a few stops in need of additional description. In addition, some information of interest was obtained from field trip participants. All of this follows.

Madre-Padre Mine: Newmont's discovery, the Madre-Padre Mine is hardly described in the accompanying book, and it was the best field trip example of gold mineralization associated with low angle faulting.

The Madre-Padre is said to contain 300,000 ounces of gold in rock with an average grade of 0.05 to 0.07 oz./ton. This indicates a size of 5 million tons. Judging from the large area of drilling and what was said on the field trip, the gold mineralization is thin, possibly less than 100', excluding lenses of internal waste.

The gold is disseminated in narrow lenses of very strong shear foliation and chloritization that are separated by less intensely sheared and chloritized waste rock. The lenses of gold mineralization and shear foliation dip gently to the west at less than 20°.

The host rock is a fine to medium-grained, gneissic biotite diorite. To the east and apparently beneath the gold bearing diorite is a coarse-grained granite with moderately chloritized mafic minerals. In the area examined, the contact between the two rock types was covered. Shearing and strong brecciation in the outcrops closest to the contact indicate it is a fault contact. Judging from the outcrops that I saw, the gold bearing, brecciated diorite was faulted over the granite by a low angle fault.

Most of the mafic minerals in the diorite are chloritized, and locally epidote is found in the rock. In general, less than 5% quartz veining and less than 1% pyrite is present in the diorite. Sericitization and 6" thick quartz veining occurs in the old stopes of the Madre-Padre Mine.

American Girl Mine: Newmont's American Girl Mine lies about one mile north of the Madre-Padre Mine. Although not visited, this deposit is said to be geologically similar to the Madre-Padre deposit, and it is at least 300,000 ounces of gold in size.

Mesquite Deposit (not visited): The only information given about Goldfield's Mesquite deposit is that the deposit is sandwiched between two low angle fault structures.

Copperstone Deposit (not visited): AMOCO's Copperstone Deposit, near Parker, Arizona, consists of 10 million tons at 0.07 oz. gold per ton. Apparently, it has a silica zone and a hematite zone near some chlorite alteration. Its relationship to detachment faulting is not known, but it is above a detachment fault. However, it has a 50 million year old date which is much older than detachment faulting.

I was shown some samples of mineralization that were taken on strike, one mile from Copperstone. These samples consisted of quartz breccia fragments in a hematite-specularite matrix with barite crystals.

Clara Peak Prospect: The field trip visited the Clara Peak Prospect which is located just east of the Swansea Mine. Phelps Dodge staked on or about the prospect in October 1984. The prospect has gold mineralization in a 5' to 20' thick, shallow dipping fault zone. The gold values are very spotty and range up to 20 ppm.

The footwall rock is chloritized, augen gneiss, possibly after Precambrian granite or a Jurassic intrusive. The hanging wall rocks are southwesterly dipping andesitic volcanics and intervolcanic sediments (mostly brown sandstone).

The mineralization and alteration in the fault zone is strongly hematite stained, bleached, clay-sericite altered breccia. The mineralization, prior to oxidation, consisted of up to 2% total sulfides. Copper oxide staining suggests most of the former sulfides were chalcopyrite. Micro quartz veinlets are less than 2% of the mineralized breccia, and local barite is present. Weak specularite occurs in the chloritized footwall gneiss.

Bill Rehrig suggested the altered breccia of the fault zone is actually a rhyolite dike that intruded the shallow dipping fault zone, but the evidence for a rhyolite dike was not convincing.

Nickle Plate Prospect: The Nickle Plate prospect is in a Whipple Mountain wilderness study area, and its geology is almost identical to that of the Clara Peak prospect. A 5' to 10' thick, moderately dipping, fault zone contains up to 0.1 oz. gold per ton. The mineralized fault is in chloritzed quartz monzonite just below andesitic volcanics. The mineralization is $\leq$10% quartz veining and silicification in quartz monzonite that is clay-sericite altered. The rock is strongly hematite and copper oxide stained.

Copper Basin Deposit: The Copper Basin copper deposit, described in the accompanying book, was presented as an example of a detachment type, bulk tonnage mineral deposit (40 million tons of copper "ore"). Although no gold is associated with the copper mineralization, the large size of the deposit was used to justify the possibility of such tonnages of gold ore elsewhere in detachment structures.

The few outcrops that I examined gave strong evidence of a typical porphyry copper sulfide system dissected by post mineral, low angle faulting. So, someday it would be worthwhile examining the core from this deposit to resolve such differing interpretations.

Riverside Mountains: The west end of the Riverside Mountains hosts widespread siderite veining. Most of the siderite is oxidized to goethite. Locally, there are one foot thick quartz-siderite veins. We were told the siderite mineralization carries no precious metal values, and the significance of the siderite veining is not known. Texas Gulf Sulfur recently staked the entire area.

McCoy Gold Deposit: I learned from a Tenneco geologist that their McCoy deposit contains 3 million tons at 0.09 oz. gold per ton. The McCoy deposit is located 20 miles from Duval's Copper Canyon deposit.

The quoted reserve occurs in the oxidized equivalent of magnetite-pyrite-pyrrhotite mineralization. The oxide zone is enriched in gold, and the sulfide zone only contains 0.03 oz. gold per ton. The mineralization occurs in limestone at the contact of a quartzite bed where the contact is cut by a porphyry dike. The ore is 100' thick, and the 3 million tons is open pit mineable.

Vulture Mine: The Vulture Mine at Kingman is said to be open. For various reasons, no serious exploration work has been performed on the property in recent years. This property is worth an Asarco evaluation for open pit mineable ore.

American Mine: The American Mine in San Bernardino County, just east of the Chase Bagdad, is rumored to be an 80' thick zone and part of it has been downfaulted to a depth of about 200'. The reserves are rumored to be a few hundred thousand tons at 0.1 oz. gold per ton. This property should be evaluated by Asarco for open pit mineable ore.

Crescent Peak Mine: The Crescent Peak Mine area, near Crescent Peak, was drilled by Tenneco. At Crescent Peak Mine area, gold mineralization is hosted by a low angle fault zone in granitic rocks. The gold mineralization is up to 100' in thickness and averages a rather uniform 0.01 oz. gold per ton. The best intercept was 100' at 0.04 oz. gold.

Sterling Mine: The Sterling Mine at Burro Mountain in Beatty, Nevada is said to have 700,000 tons at 0.2 to 0.25 oz. gold per ton. The gold values are very erratic, and are hosted in a flat, thrust type fault where it is intersected by basin-range faults.

H. G. Kreis/mek

H. G. Kreis

HGK:mek
Accompaniment

Library

FIELD TRIP

ARIZONA – CALIFORNIA METAMORPHIC CORE COMPLEXES AND MINERALIZED DETACHMENT ZONES.

APPLIED GEOLOGIC STUDIES INC.

TENTATIVE SCHEDULE

Sunday, February 3

Evening seminar introducing and overviewing the metamorphic core complex detachment fault, precious metals story - Distribution of handout material and general RAP session.

Monday, February 4

Drive from Tuscon north on I-10 to the Red Rock exit. Proceed north on frontage road to dirt road leading into the southeast end of the Picacho Mountains where we will carefully examine excellent exposures of a lower-middle- and upper plate detachment zone package.

Return to Interstate and proceed to the South Mountain core complex just south of Phoenix where we'll briefly look at lower plate mylonitic rocks derived from a composite mid-Tertiary batholith.

Drive west from South Mountains to I-10, then north on gravel road to Vulture Mountains where multiple listric faults have rotated and repeated mid-Tertiary volcanic-volcaniclastic rocks perhaps in upper plate configurations with respect to some subsurface detachment discontinuity.

Intersect U.S. Highway 60 and drive east to Wickenburg - Rancho Grande Motel.

Tuesday, February 5

Drive west to small town of Salome and into the Harquahala Mountains to check out the Hercules thrust fault, a major Laramide low-angle structure which will be compared with Tertiary detachment faults.

Continue west through the Harcuvar metamorphic core complex to State Highway 72, northwest toward Bouse and then into the Granite Wash Mountains to the Yuma mine area to examine copper-gold mineralization localized by Mesozoic-Laramide stratigraphic and structural (thrust fault) factors. Return to route 72, then to Bouse and proceed northeast to visit the Swansea and Clara mineral districts in the Buckskin Mountains. The Swansea hematite-copper deposit will be compared with the Clara copper-gold occurrence, both of which are localized in the Buckskin detachment zone.

Drive out of Buckskins ending up at Parker - El Rancho Motel.

Wednesday, February 6

4-wheel drive traverse up Bowman Wash into the Whipple metamorphic core complex in California to examine detachment setting of the Copper Basin copper (minor gold) bulk tonnage deposit.

Drive south on U. S. 95 to the Riverside Mountains to inspect detachment fault (?) not related to lower plate mylonitic rocks.

Proceed south on 95 to Blyth - Comfort Motel.

Thursday, February 7

Drive south from Blyth on State Route 78 past the Mule and Palo Verde Mountains and then on dirt road into the Midway Mountains to check out the manganese mineralization localized in the so called Midway detachment fault.

Proceed south on 78 to the Ogleby cut off and then into the Cargo Muchaco Mountains to consider the structural-stratigraphic setting of gold mineralization in that area.

Drive to Yuma, Arizona, pass by the airport, and then onto Phoenix via Interstate 8.

H. KREIS
JOSell

HAND OUT MATERIAL

Field trip to Arizona-California metamorphic core complexes and mineralized detachment zones

TENTATIVE SCHEDULE

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Evening seminar introducing and overviewing the metamorphic core complex detachment fault, precious metals story - Distribution of handout material and general RAP session.

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Drive out of Buckskins ending up at Parker - El Rancho Motel.

Wednesday, February 6

4-wheel drive traverse up Bowman Wash into the Whipple metamorphic core complex in California to examine detachment setting of the Copper Basin copper (minor gold) bulk tonnage deposit.

Drive south on U. S. 95 to the Riverside Mountains to inspect detachment fault (?) not related to lower plate mylonitic rocks.

Proceed south on 95 to Blyth - Comfort Motel.

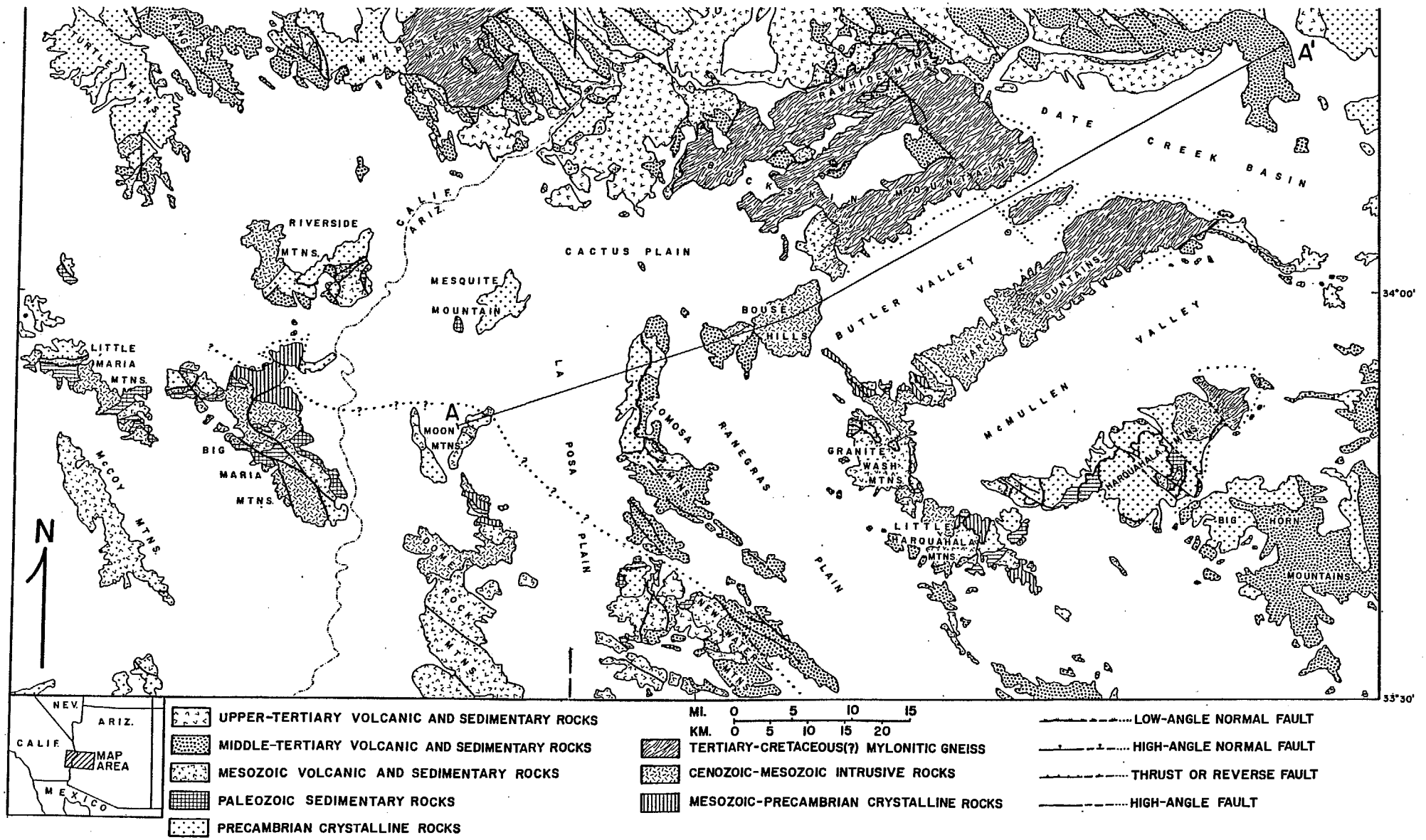
Thursday, February 7

Drive south from Blyth on State Route 78 past the Mule and Palo Verde Mountains and then on dirt road into the Midway Mountains to check out the manganese mineralization localized in the so called Midway detachment fault.

Proceed south on 78 to the Ogleby cut off and then into the Cargo Muchaco Mountains to consider the structural-stratigraphic setting of gold mineralization in that area.

Drive to Yuma, Arizona, pass by the airport, and then onto Phoenix via Interstate 8.

GENERAL


TURTLE MTNS.
WHIPPLE MTNS.
RAWHIDE MTNS.
BUCKSKIN MOUNTAINS
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ARIZ.
RIVERSIDE MTNS.
CACTUS PLAIN
MESQUITE MOUNTAIN
BOUSE HILLS
BUTLER VALLEY
HARQUAHALA MOUNTAINS
VALLEY
34°00'
LITTLE MARIA MTNS.
A
MOON MTNS.
LA POSA PLAIN
TOMOSA MTNS.
RANEGRAS PLAIN
McMULLEN
GRANITE WASH MTNS.
HARQUAHALA MTNS.
BIG MARIA MTNS.
McCOY MTNS.
LITTLE HARQUAHALA MTNS.
BIG HORN MOUNTAINS
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NEW WATER MTN.
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NEV.
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MAP AREA
MEXICO
UPPER-TERTIARY VOLCANIC AND SEDIMENTARY ROCKS
MIDDLE-TERTIARY VOLCANIC AND SEDIMENTARY ROCKS
MESOZOIC VOLCANIC AND SEDIMENTARY ROCKS
PALEOZOIC SEDIMENTARY ROCKS
PRECAMBRIAN CRYSTALLINE ROCKS
MI. 0 5 10 15
KM. 0 5 10 15 20
TERTIARY-CRETACEOUS(?) MYLONITIC GNEISS
CENOZOIC-MESOZOIC INTRUSIVE ROCKS
MESOZOIC-PRECAMBRIAN CRYSTALLINE ROCKS
LOW-ANGLE NORMAL FAULT
HIGH-ANGLE NORMAL FAULT
THRUST OR REVERSE FAULT
HIGH-ANGLE FAULT

TECTONIC SETTING OF THE

METAMORPHIC CORE COMPLEXES

The following is an abbreviated description of tectonic events leading up to and following Tertiary deformation in the Metamorphic Core Complexes of the Southwest. It will allow you to see the complexes within their Phanerozoic setting. The sequence below is from oldest to youngest.

PALEOZOIC

- Foreland, miogeoclinal sedimentation onto a beveled "basement" made up of a relatively thin sequence of late Precambrian Apache Group sediments and earlier crystalline/metamorphic rocks. Hiatus of Paleozoic sedimentation in the Silurian.
- Amagmatic without significant tectonic activity.

MESOZOIC

Triassic:

- Inception of volcanism, continental sedimentation (redbeds) in fault-bounded basins.
- Extensional(?) tectonism, faulting, uplift, and basic volcanism concentrated in southeast Arizona. Western Arizona experiencing volcanic activity and thick accumulations of coarse detritus in intercontinental basins. Few plutons known.

Jurassic:

- NW-trending, continental, volcanic arc through southwest Arizona resulting in volcanic and continental sedimentary accumulations. Numerous plutons of ~160 m.y. emplaced along with a porphyry copper deposit or two.
- Arc-related tectonism.

Cretaceous:

- Main contribution of Mesozoic sedimentation into the developing Sonoran embayment in SE Arizona from nonmarine lower Cretaceous to marine upper Cretaceous. Elsewhere, continental sedimentation of erratic thicknesses, some up to 20,000 ft.

- Extensive calc-alkaline plutonism and volcanism (Laramide Orogeny) from ~100 m.y. in west to 55 m.y. in southeasternmost Arizona. Main porphyry copper period. Major,deep thrusting involving basement in southwest Arizona; basement-cored uplifts (Rocky Mtn. style) in southeastern part of state. Extreme compression and crustal shortening. Areas of amphibolite-grade metamorphism and transposed, low-angle foliation. Reactivation of strike-slip movements on NNW-trending Texas "lineament" structures.

TERTIARY

Paleocene-Eocene:

- Continuation of Laramide Orogeny, culminating in the Eocene with the most intense compression (SW and NE-directed thrusting) & basement wedge uplifts (plus basin-fill). Deformation extends farthest eastward. As a result of maximum encroachment rates between Farallon and North American plates and extreme low-angle subduction, calc-alkaline arc magmatism is shut off for Arizona from about 55 to 35 m.y.B.P. Instead, crustal-derived, 2-mica, alkali(?) granites to quartz monzonites were emplaced commonly in sill-like form, especially within areas of low-angle metamorphic fabrics from about 55 to 40 m.y.B.P.

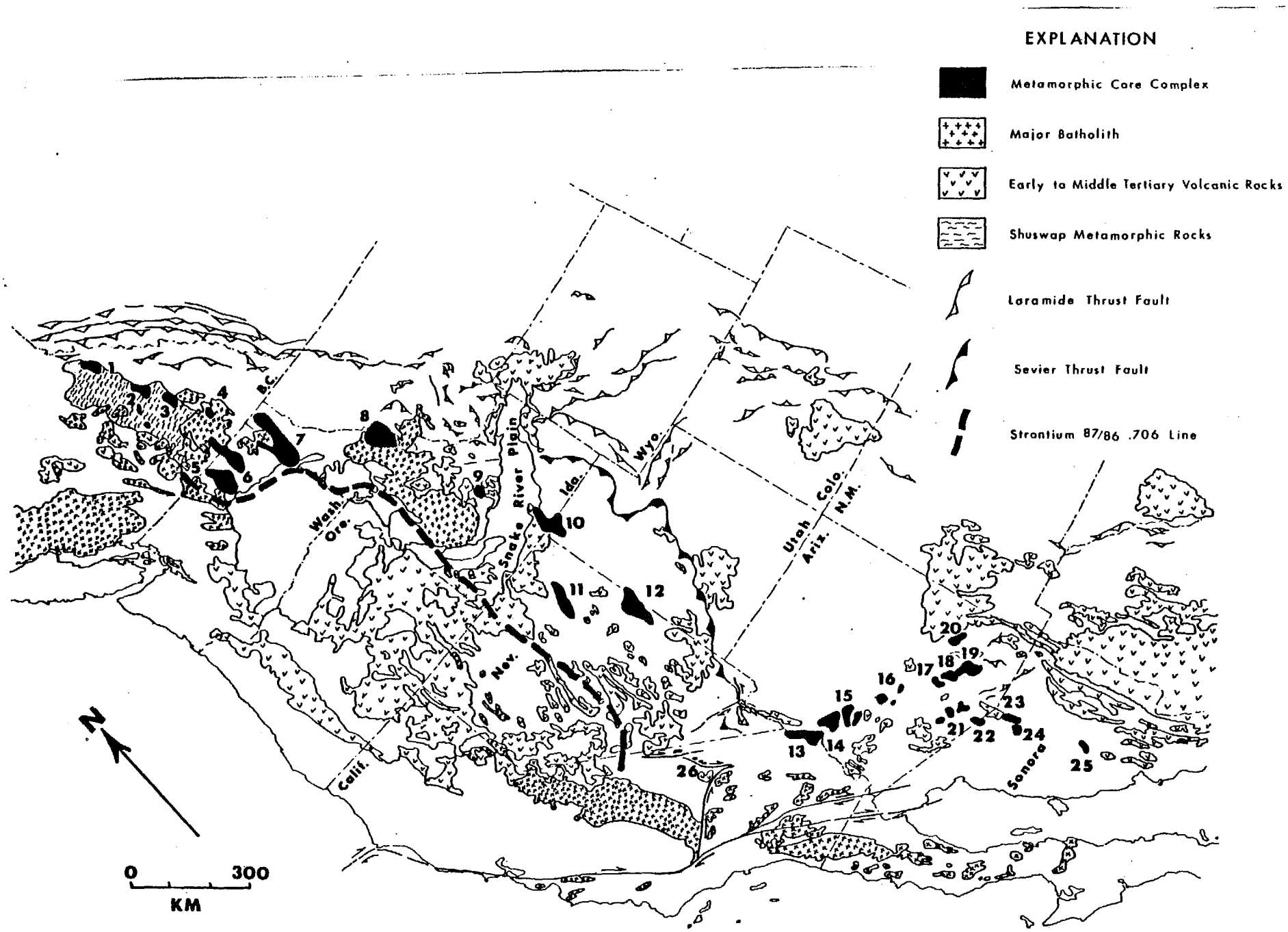
Oligocene:

- Sometime around 30-35 m.y.B.P., convergence rates between oceanic plates and North America decreased dramatically accompanied by the following tectonic effects.
  1. Change from NE compression to extension.
  2. Extension marked by widespread NNW-NW dike and pluton alignments, mylonite zones, detachment surfaces and a myriad of low-angle listric normal faults. Mylonite-detachment zones (Metamorphic Core Complexes) show preferential development in areas of low-angle, metamorphic & igneous fabrics inherited from the Laramide Orogeny.
  3. Majority of Tertiary horizontal extension (locally over 100%) in the Basin-Range Province occurred during this time period.

Extension was accompanied by widespread plutonism and volcanic activity ("ignimrite flare up") during the period 30-20 m.y. Magmas were generally calc-alkaline, similar to those of the Laramide Orogeny, but late stage differentiates of mid-Tertiary magmatic centers tended to be more alkali-rich and associated with Pb, Zn, and precious metals rather than copper. Along with the build-up of extensive volcanic fields and calderas, thick local accumulations of arkosic red beds, fanglomerates, lacustrine sediments and slope breccias filled listric fault-basins.

Miocene:

- Detachment and listric fault, extensional tectonism and calc-alkaline magmatism continue to about 15 m.y.B.P. From 14 m.y. to present, tectonics and magmatism changed as follows:
  1. High-angle normal faulting of more northerly trend typical of the physiographic Basin and Range.
  2. Switch to basaltic or bi-modal basalt-rhyolite magmatism. Basalts are sterile ore deposits-wise, but silicic rocks are associated with either lithophile elements (Be, Mo, V, Li, F) or precious metal deposits.


EXPLANATION
Metamorphic Core Complex
Major Batholith
Early to Middle Tertiary Volcanic Rocks
Shuswap Metamorphic Rocks
Laramide Thrust Fault
Sevier Thrust Fault
Strontium 87/86 .706 Line
B.C.
Wash.
Ore.
Calif.
Nev.
Idaho
Snake River Plain
Wyo.
Utah
Colo.
Ariz.
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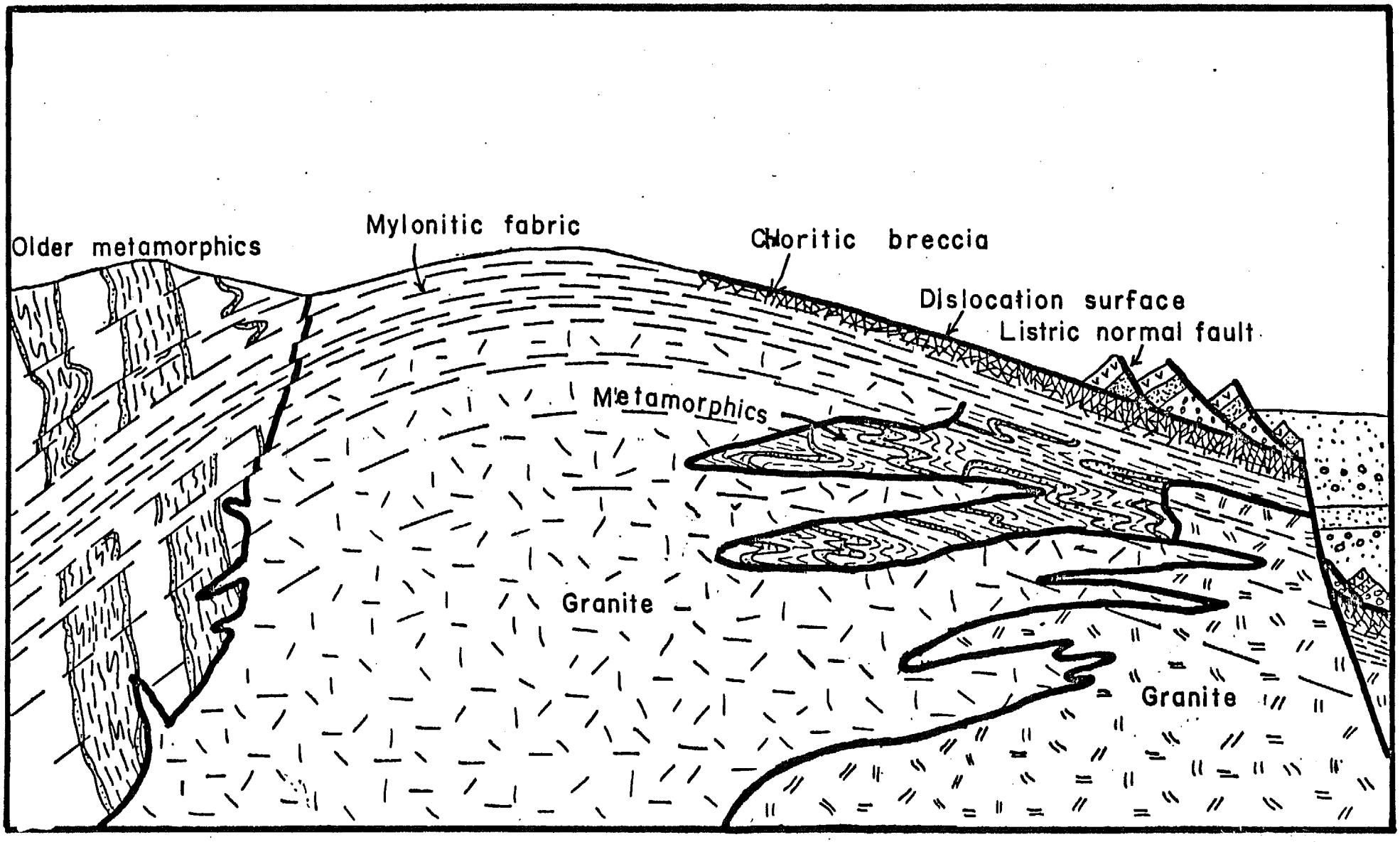

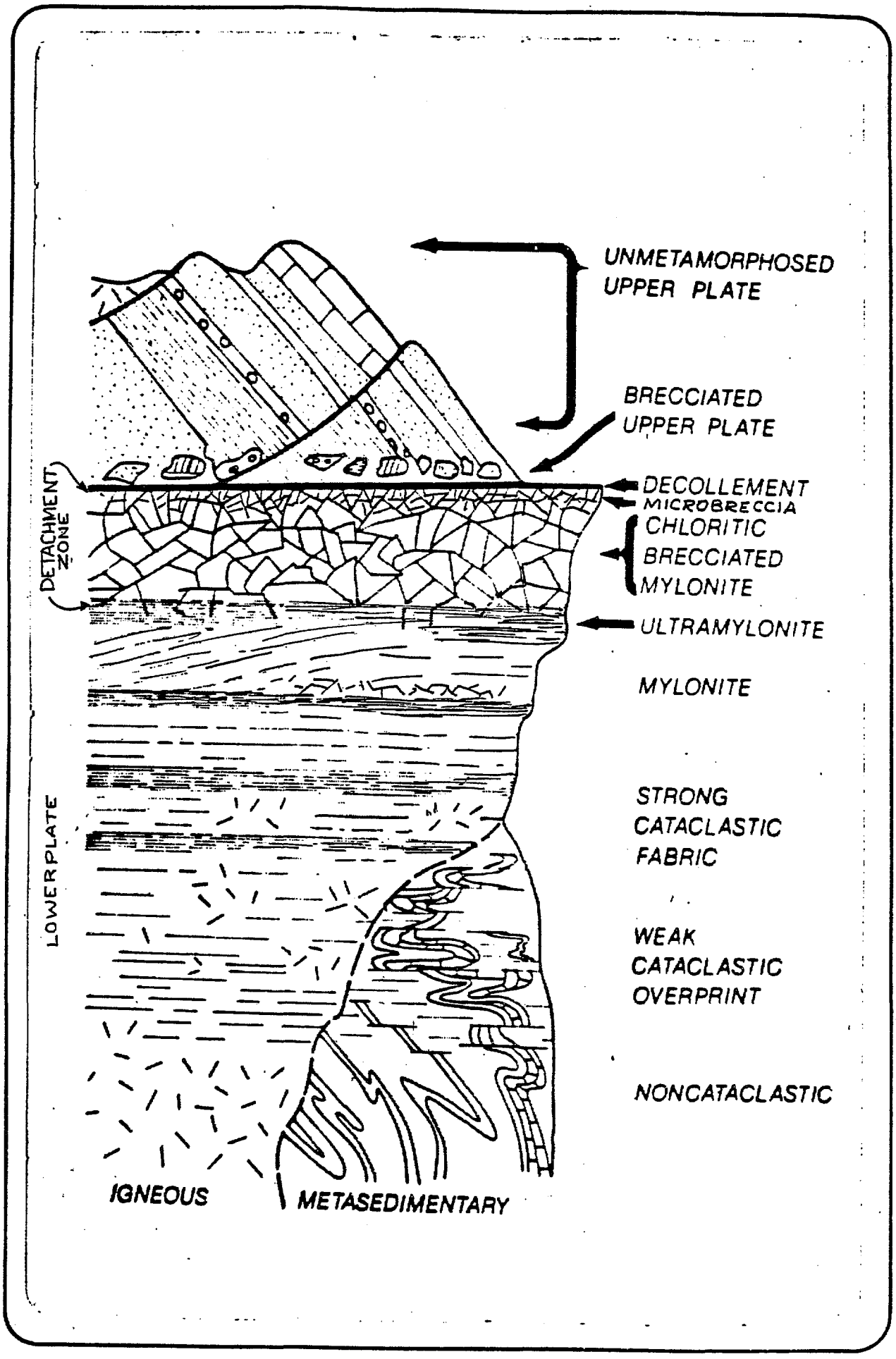
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BRECCIATED
UPPER PLATE
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MICROBRECCIA
CHLORITIC
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ULTRAMYLONITE
MYLONITE
STRONG
CATACLASTIC
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WEAK
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NONCATACLASTIC
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LOWER PLATE
IGNEOUS
METASEDIMENTARY

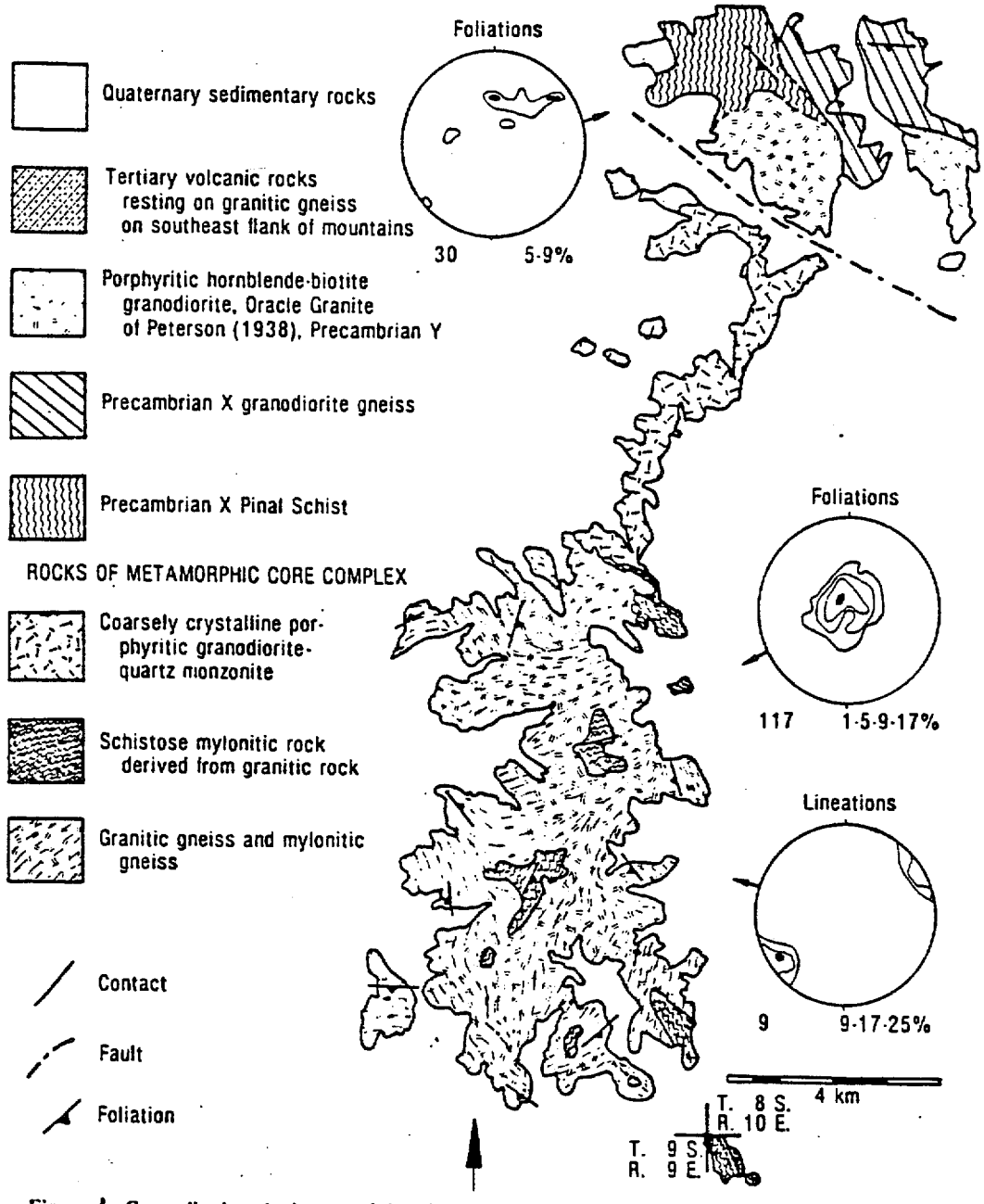
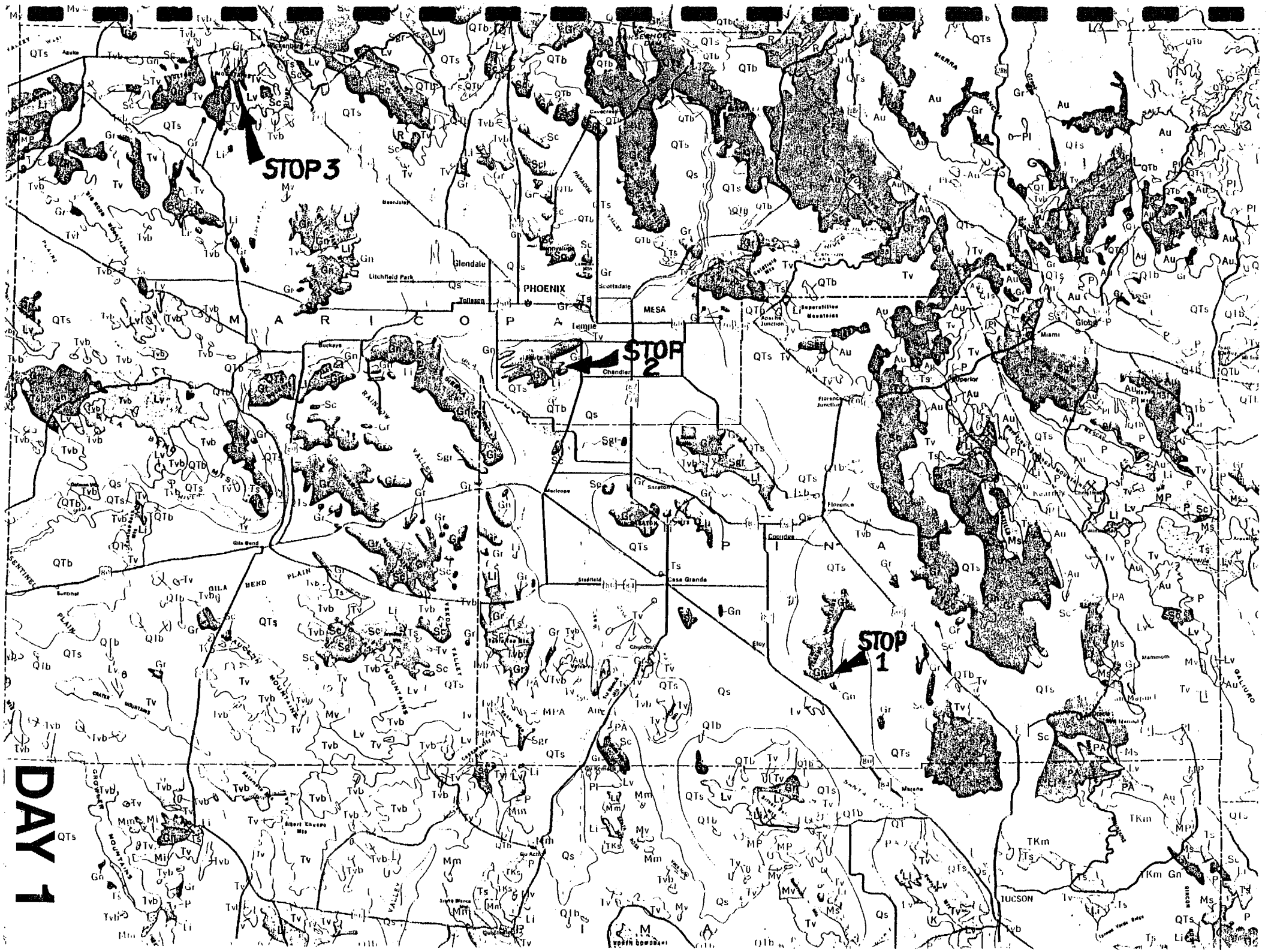


Figure 1. Generalized geologic map of the Picacho Mountains, Arizona (modified from Yeend, 1976), with lower-hemisphere equal-area net projections showing orientation of foliation in the northern Picacho Mountains and foliation and lineation in the southern Picacho Mountains (foliation and lineation data from Yeend, 1976). Contours are percent per one percent area.

From Banks (1980).

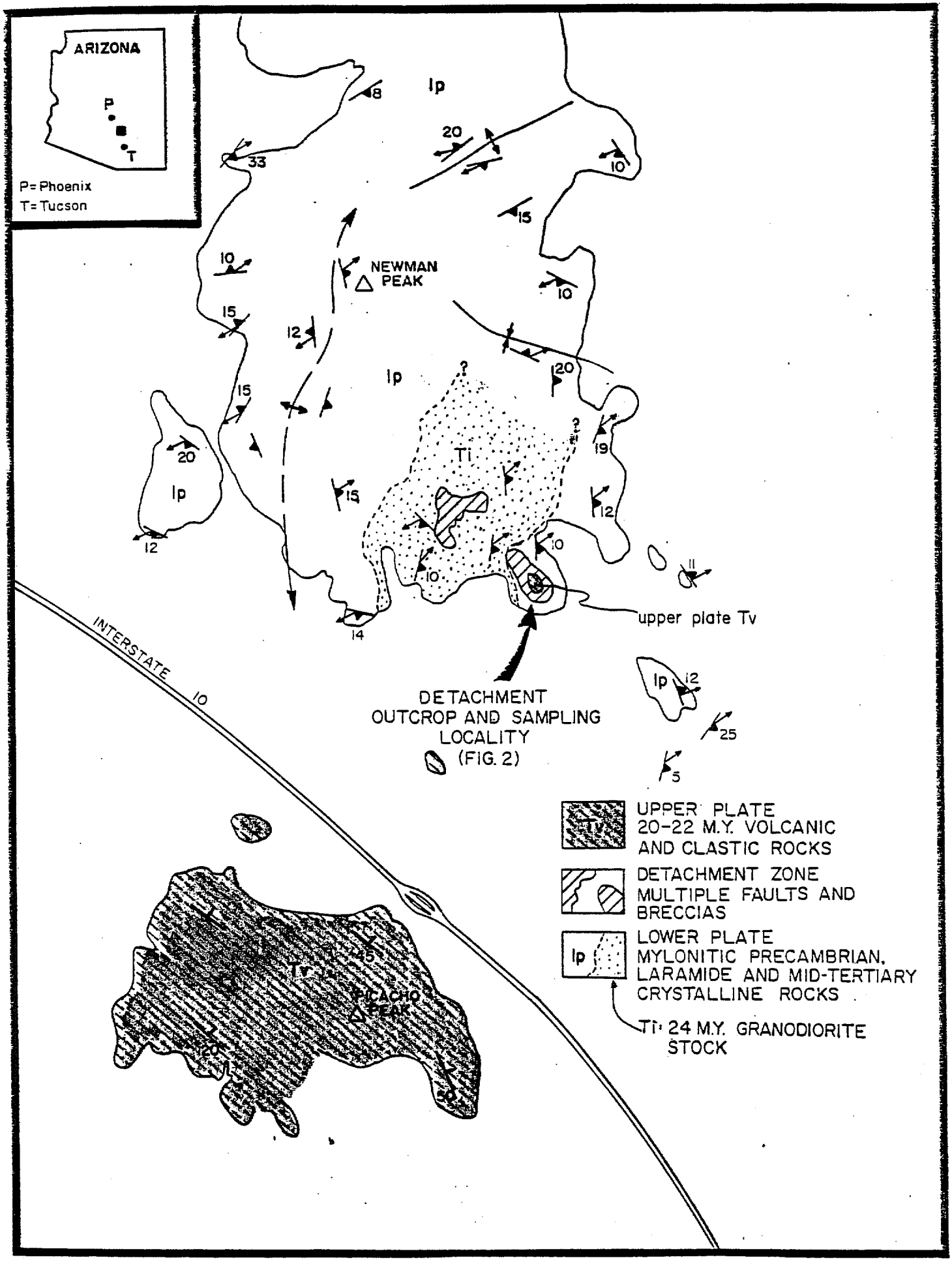

STOP 3
STOP 2
STOP 1
PHOENIX
MESA
Glendale
Scottsdale
Tempe
Chandler
Litchfield Park
Tolleson
Buckeye
Gila Bend
Maricopa
Casa Grande
Coolidge
Florence
Superior
Miami
Globe
Mammoth
Marana
TUCSON
M A R I C O P A
P I N A

DAY 1

SOUTHERN PICACHO MOUNTAINS MCC

The Picacho Mountains form a metamorphic core complex (MCC) with core rocks quite similar to the Catalina-Rincon MCC near Tucson. Most of the range consists of a foliated and variably lineated basement of Precambrian schist, gneiss and granitic rocks (Oracle granite) which has been well intruded by Laramide and mid-Tertiary plutonic rocks. Commonly these plutons are 2-mica, alkali-rich granites and pegmatites believed to be of 40-50 m.y., late Laramide age. Our goal is to examine a particularly well exposed detachment fault zone which is associated with the Picacho MCC at its south end. Here the detachment separates a lower plate of mylonitic Oracle granite and 24 m.y. granodiorite pluton from an upper plate of metasomatically altered 20-22 m.y. andesitic flow rocks. At the outcrop hill which we will climb, a middle plate of non-mylonitic, brecciated and propylitized Oracle granite(?) is sandwiched between upper and lower plates. The detachment sequence, intruded by high level felsic dikes and sills, together with results of geochemical and isotopic research indicate (1) that the entire ductile to brittle deformational package did not form at great depth and (2) that it developed insitu.

The Picacho stop will acquaint field trip participants with the basic elements of the metamorphic core complex-detachment environment, especially the middle plate which is the site of economic mineralization to be seen later on the trip. A few figures, maps, etc. on the Picacho area are included in the following pages.


ARIZONA
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T
P= Phoenix
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lp
NEWMAN PEAK
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INTERSTATE 10
DETACHMENT OUTCROP AND SAMPLING LOCALITY (FIG. 2)
Tv
PICACHO PEAK
UPPER PLATE 20-22 M.Y. VOLCANIC AND CLASTIC ROCKS
DETACHMENT ZONE MULTIPLE FAULTS AND BRECCIAS
LOWER PLATE MYLONITIC PRECAMBRIAN, LARAMIDE AND MID-TERTIARY CRYSTALLINE ROCKS
Ti: 24 M.Y. GRANODIORITE STOCK

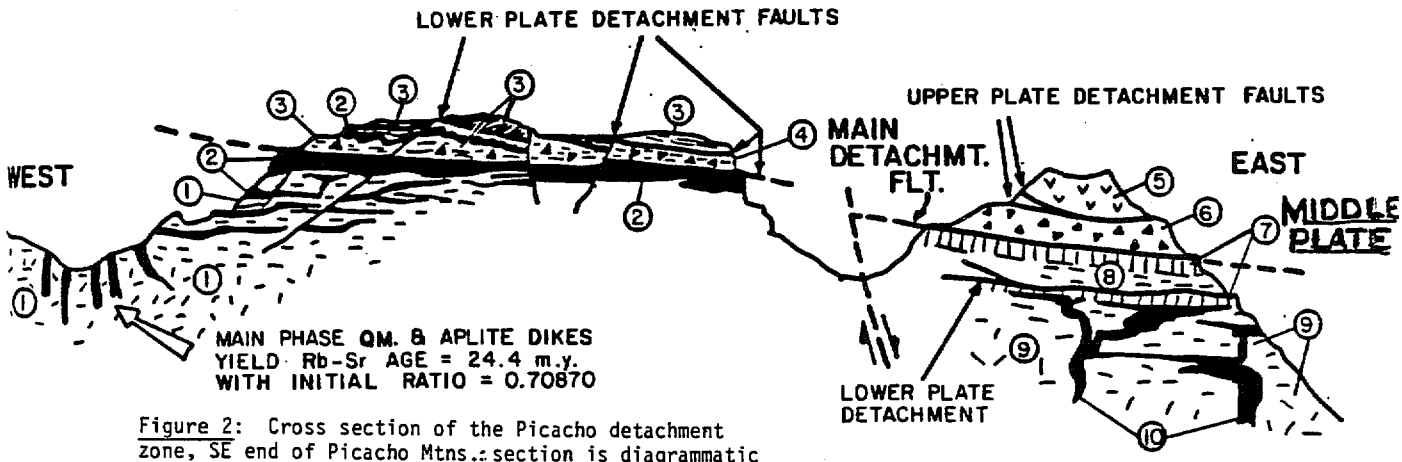
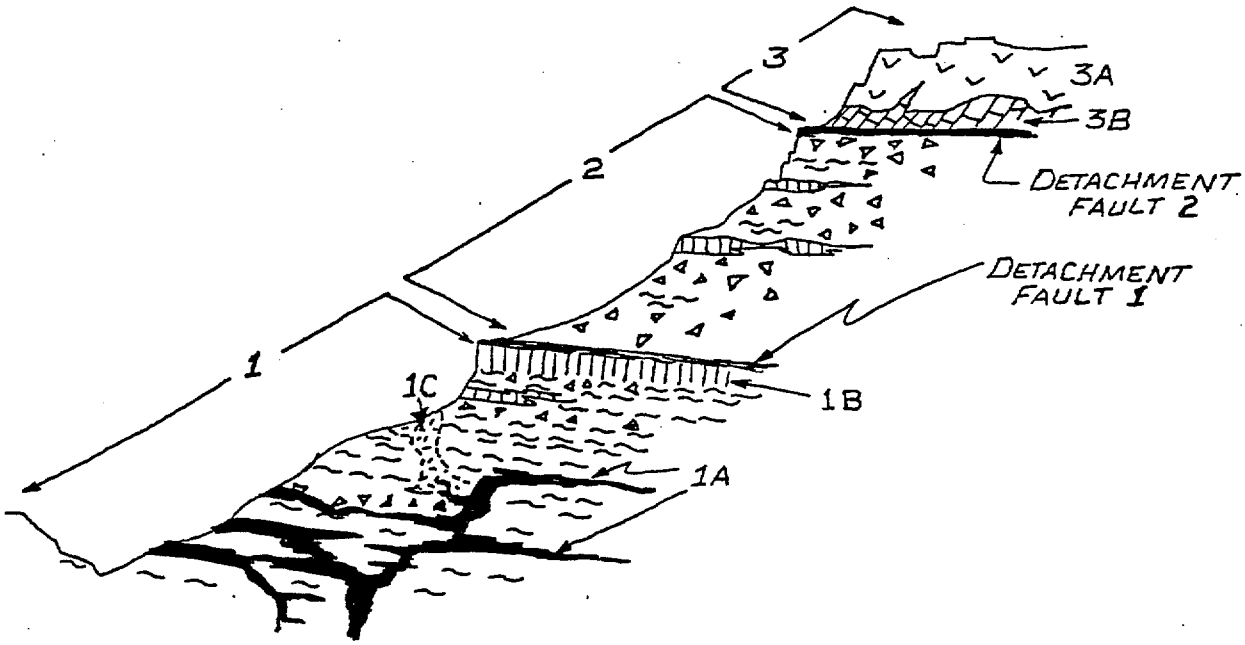


Figure 2: Cross section of the Picacho detachment zone, SE end of Picacho Mtns.: section is diagrammatic and not to exact scale. 1 = Equigranular, mylonitic, quartz monzonite, 24.4 m.y. age: deformation increasing upward, especially at contacts with flat felsic sills and quartz veins. 2 = Dense, very fine grained to aphanitic (partially porphyritic) rhyolite to aplite sills or low-angle dikes. Moderately to intensely mylonitized and microbrecciated near the top of the thick unit. Flat quartz veining common. 3 = dark colored, mylonite to ultramylonite gneiss and schist; unit is extremely contorted with common structural discordances, sheared out foliation and superimposed chloritic brecciation. Flat rhyolite dikes (mylonitic) are injected into the mylonite-breccia melange and have been torn apart by detachment faulting. 4 = chaotic mix of contorted, rotated slices and blocks of mylonite and chlorite breccia; mylonitic Oracle "granite" recognized as dismembered pieces. 5 = Rhyodacite (?) flow breccia, strongly iron stained and replaced by calcite in veins and irregular bodies; part of the Picacho Pk. upper-plate volcanic sequence. 6 = Approx. 35 m of chlorite, epidote-rich, brecciated Oracle (?) "granite" without mylonitic texture. 7 = Dense, greenish gray ultramylonite with partially superimposed microbrecciation. 8 = mylonitic Oracle "granite" with lenses of breccia and ultramylonite. 9 = lineated, mylonitic Oracle "granite" becoming less mechanically deformed lower in section. 10 = rhyolite porphyry dikes and sills; moderately mylonitic but intruding more intensely mylonite rocks; 25.9 m.y. age.

PICACHO DETACHMENT LOCALITY



1. LOWER PLATE: Mylonitic quartz monzonite porphyry. Protolith is 1.4 b.y. Oracle "granite" superimposed by mylonitic (lineated) deformational fabric which becomes more intense upward toward detachment fault 1.

1A. Dikes and sills of syn-deformational rhyolite. Rhyolite has mylonitic texture but discordantly intrudes more intensely mylonitized Oracle granite. Whole rock K-Ar date of 25.9 +/- 3.1 my.

1B. Dark, dense, aphanitic, chloritic microbreccia; nonlineated.

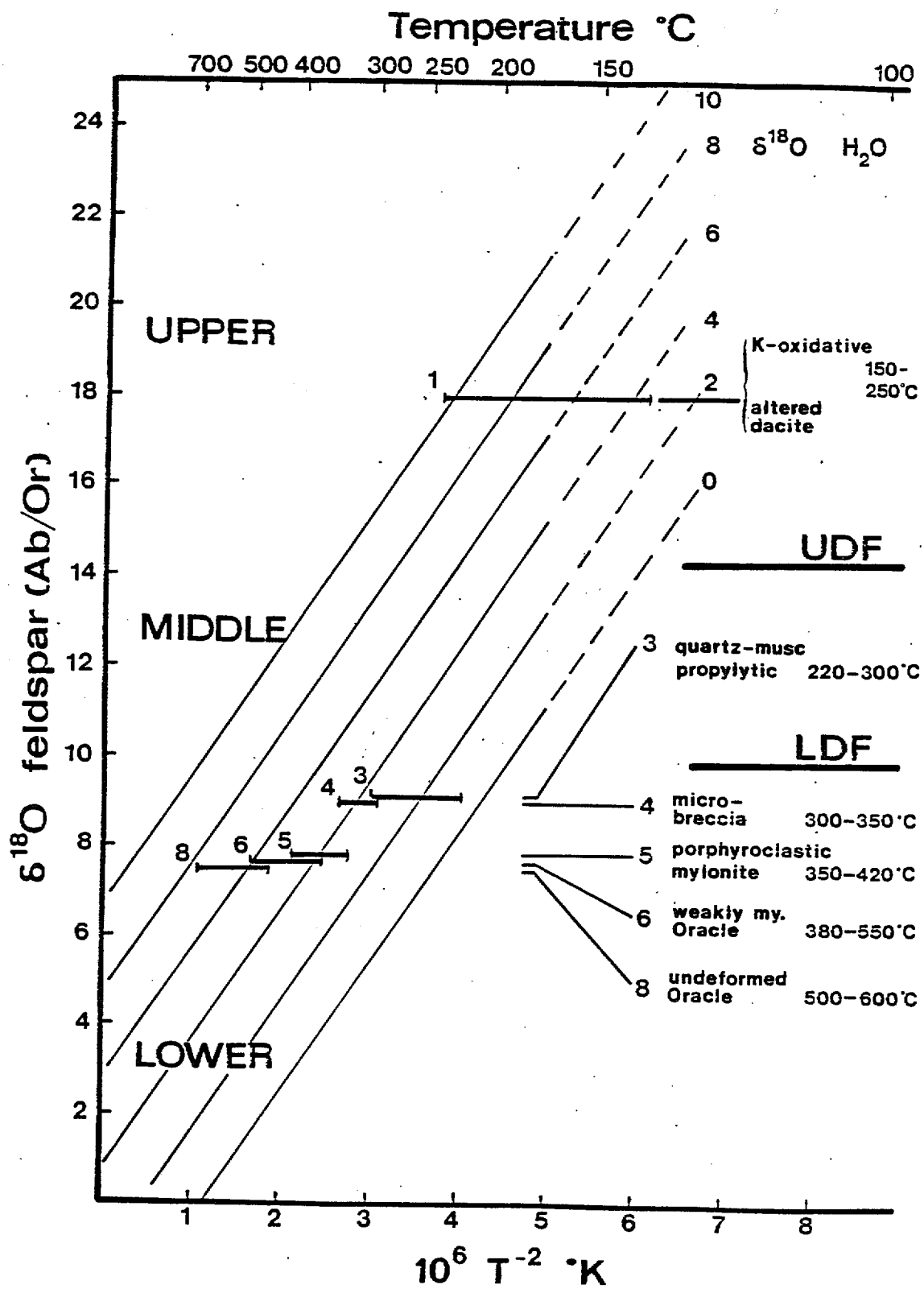
1C. Irregular, ill-defined patches of medium-grained granite cutting mylonite & ultramylonite. Granite is only weakly deformed but is altered with sercite and chlorite.

2. MIDDLE PLATE: Generally non-mylonitic (nonlineated) sequence of brecciated, coarse-grained granite (Oracle?) with rare, small zones showing mylonitic textures. Plate is pervasively altered (propylitic) and veined with quartz, chlorite, epidote and Kspar (adularia?). Sparce sulfides in irregular veinlets, small clots and disseminations occur throughout with rare copper oxide mineralization noted. Zone also contains thin, discontinuous lenses of dark, flinty ultramylonite or microbreccia (cataclasite) as 1B, below.

3. <u>UPPER PLATE</u>: Volcanic rocks resting on a polished, silicified detachment fault.

3A. Autobrecciated rhyodacite to andesite flow correlatable with the volcanics of Picacho Peak, west of I-10. Volcanic flows have suffered intense potash metasomatism & loss of sodium along with hematization.

3B. Travertine - like lense of carbonate and carbonate breccia replacing? and intruding upper plate volcanic rocks at the detachment surface. May be a hot springs product similar to what occurs more extensively in the Rawhide - Buckskin Mtns of western Arizona.


Temperature °C
700 500 400 300 250 200 150 100
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6
4
2
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UPPER
MIDDLE
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K-oxidative
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altered dacite
UDF
quartz-musc propylytic 220-300°C
LDF
micro-breccia 300-350°C
porphyroclastic mylonite 350-420°C
weakly my. Oracle 380-550°C
undeformed Oracle 500-600°C
δ18O feldspar (Ab/Or)
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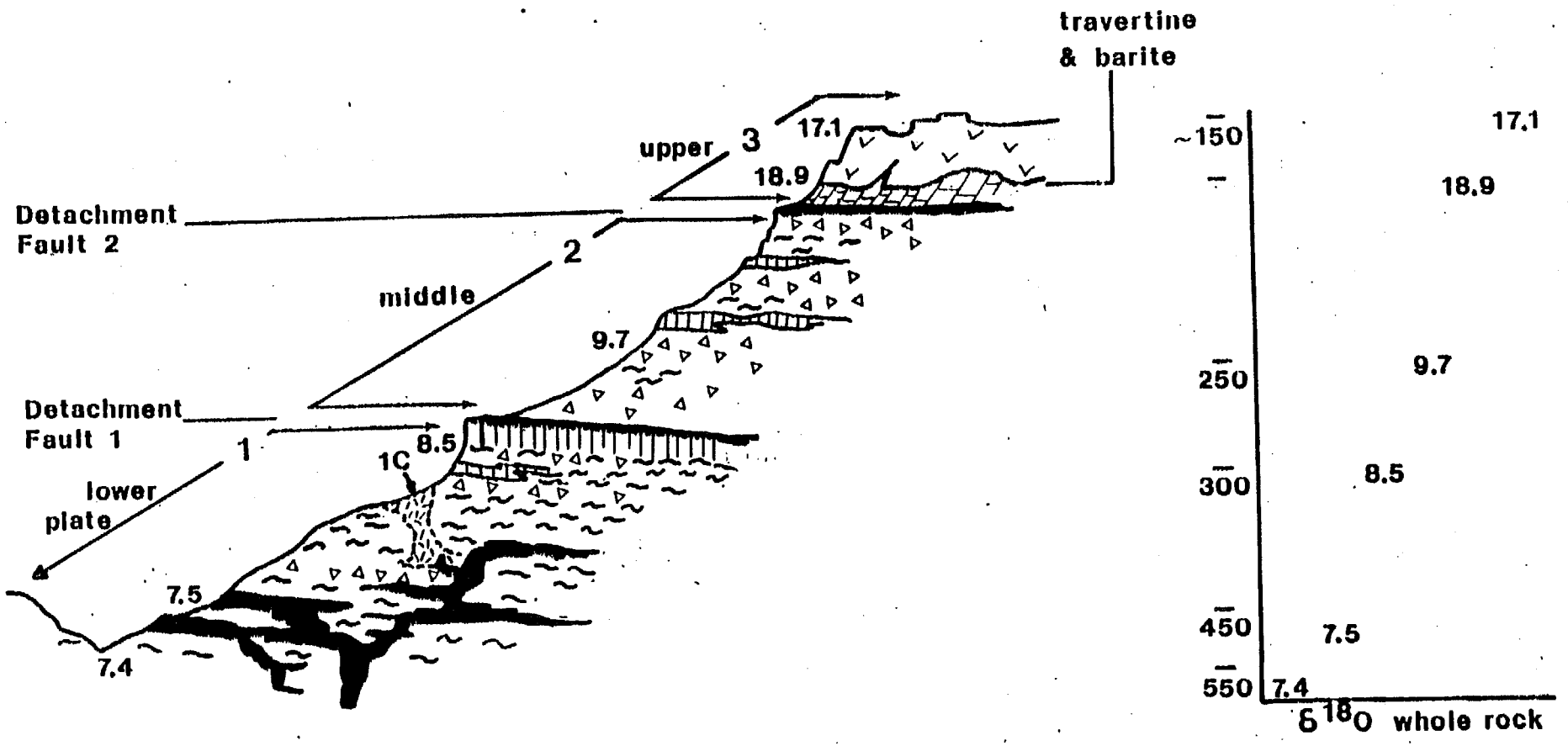
travertine
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SOUTH MOUNTAIN MCC

The South Mountain area just south of metropolitan Phoenix is quite typical of a Cordilleran metamorphic core complex. It is of special interest because of the lower-plate involvement of a large mid-Tertiary pluton which is variably mylonitized and thus has proved that this intense and penatrative ductile deformation is quite young. High level, porphyritic dikes are also mylonitic and indicate that deformation occurred at relatively shallow levels. The object of our visit will be to look at the deformational character of the lower plate and to see the intensity of NNW-trending diking which strikes perpendicular to the stretching lineation. Detachment fault-related chloritic breccia like that examined at Picacho occurs above the mylonitic rocks along the crest of the South Mountain foliation arch and along its southeast flank. We will examine these outcrops if time permits. The actual detachment fault is covered by overburden but is thought to wrap around the east end of the arch. The isolated Tertiary volcanic rocks of Tempe Butte and tilted conglomerates of Papago Park in the Phoenix Valley are undoubtedly detached pieces of an upper plate to the complex.

Excerpts from Reynolds and Rehrig (1980) and Reynolds (1981) follow.

GEOLOGICAL OVERVIEW OF THE SOUTH MOUNTAINS, CENTRAL ARIZONA

by Stephen J. Reynolds

Introduction:

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

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

General Geology: (Refer to figures 1 and 2)

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

Structural Relationships: (Refer to figures 2 and 3)

Most rocks in the range exhibit a gently dipping mylonitic foliation which contains a pervasive N60E-trending lineation. The foliation is defined by planar mineral aggregates and thin bands of intensely granulated and recrystallized rock. Mylonitically foliated rocks contain joints, quartz-filled tension fractures, and "ductile normal faults"

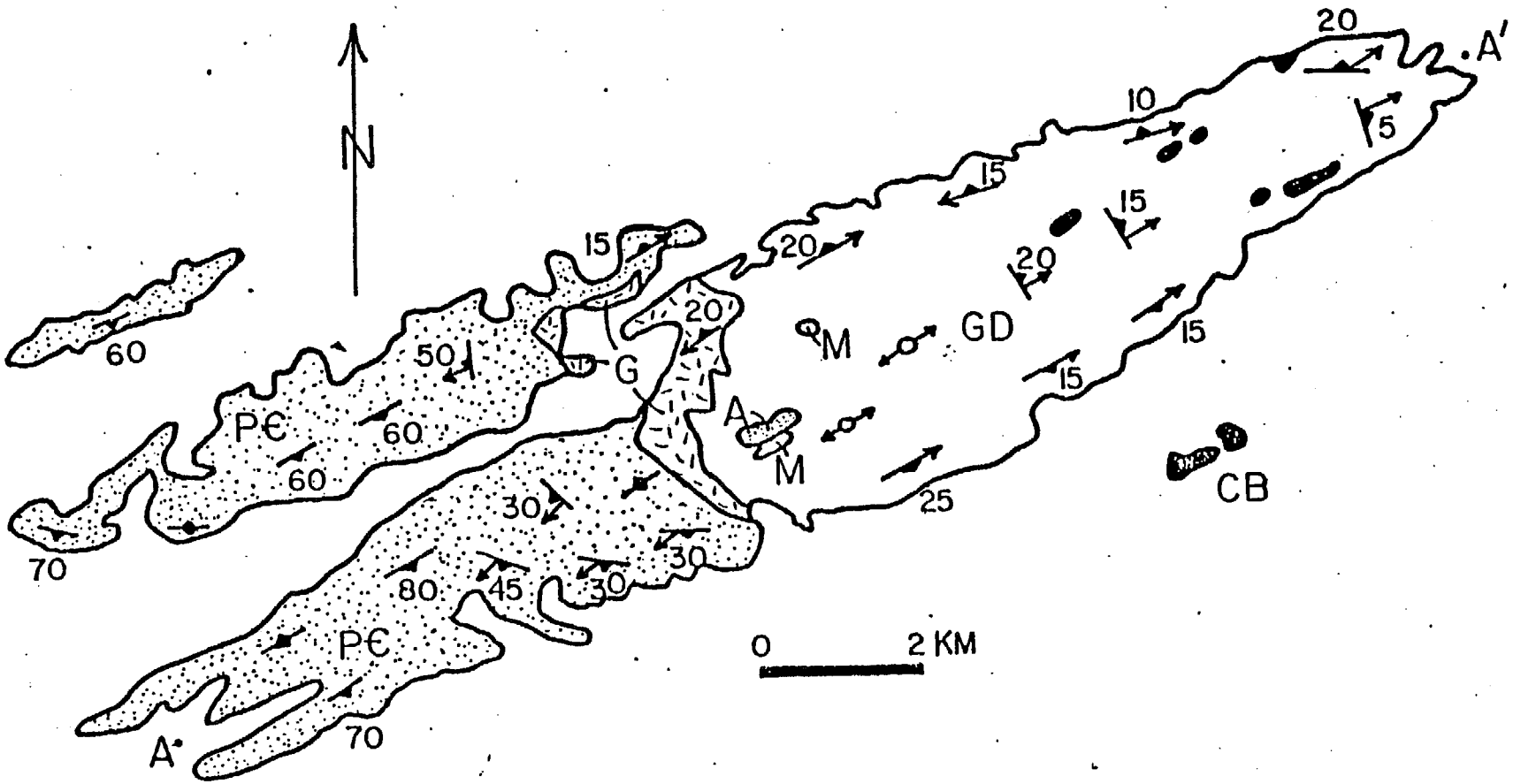
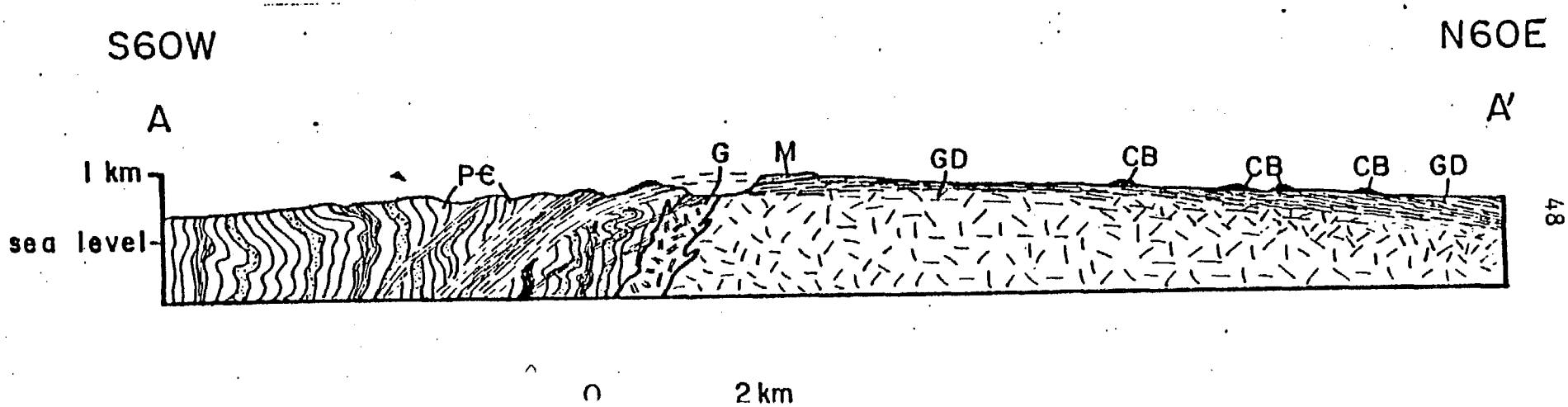


Figure 1. Generalized geologic map of the South Mountains, exclusive of the southern foothills. PG: Precambrian metamorphic and igneous rocks; GD: Oligocene granodiorite; G: Oligocene granite; A: Oligocene alaskite; M: mylonitic rocks; CB: chloritic breccia.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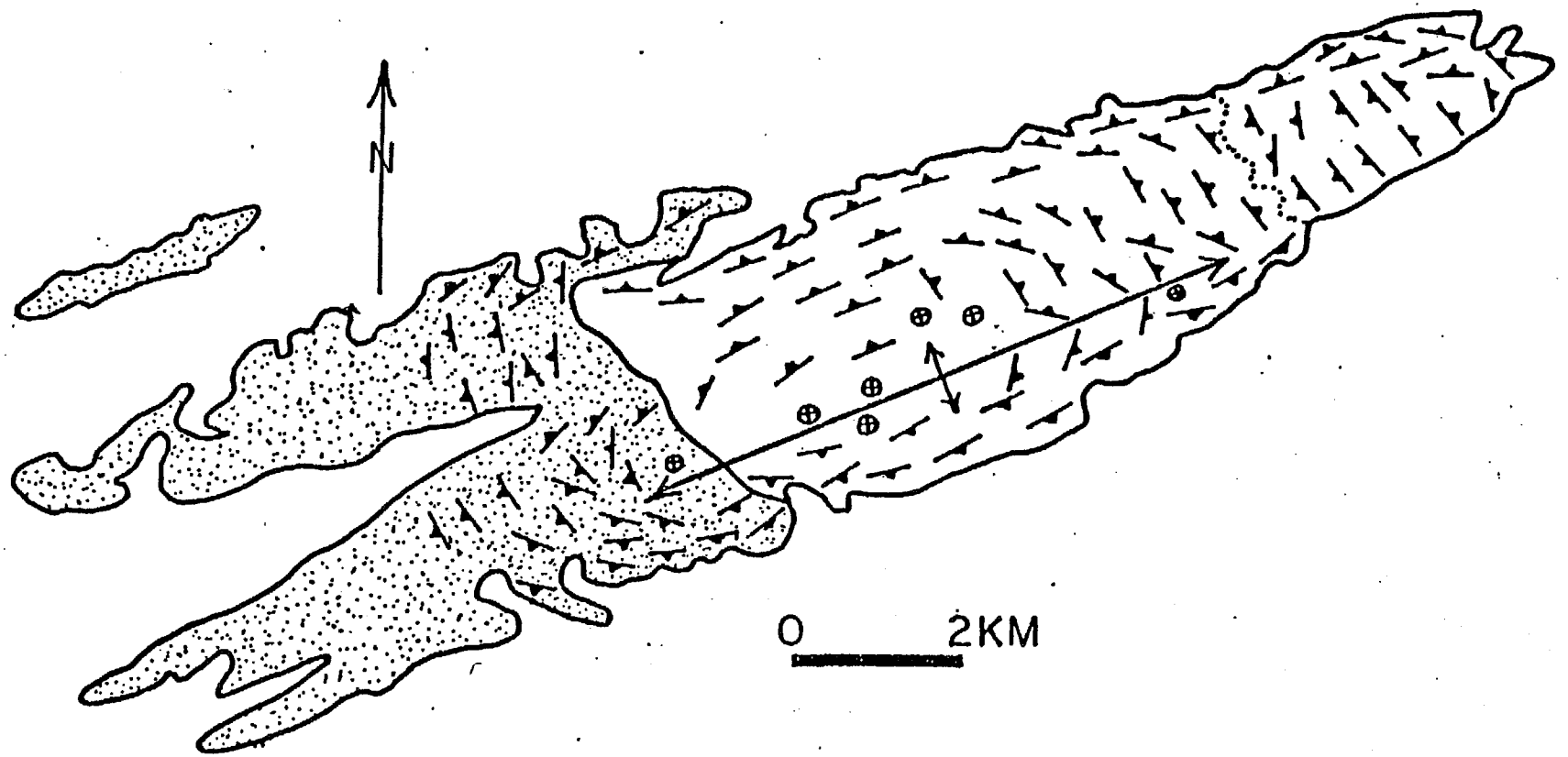


Figure 3. Orientation of mylonitic foliation where it is present in the South Mountains.

which mostly strike NNW, perpendicular to lineation. Inclusions in deformed plutonic rocks are elongated parallel to lineation and flattened perpendicular to foliation. Folds are rare in mylonitic plutonic rocks, but are more abundant in mylonitically deformed Precambrian amphibolite gneiss.

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

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

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

Another important lithological and structural transition is exposed along the northeast end of the range where mylonitic granodiorite grades upward into chloritic breccia. Structurally lowest exposures of the granodiorite in this area are noncholoritic and well foliated. Up section, chlorite and anastomosing, curvi-planar joints are present in the granodiorite. The rocks are progressively more jointed and brecciated higher in the section where they ultimately grade into chloritic breccia. Remnants of mylonitic foliation in the granodiorite are preserved in the breccia. Relict mylonitic foliation in the breccia generally dips to the southwest, indicating that total disorientation

and random rotation of the foliation did not occur, except locally. Joints, breccia zones, and normal faults (northeast side down) have variable northwest strikes. Slicken sides in the breccia have scattered, but dominantly northeast trends. In the southern foothills of the range, the chloritic breccia is overlain by a dislocation surface which dips gently to the northeast. Upper plate rocks above the dislocation surface are Precambrian metamorphic rocks which locally have a mylonitic fabric.

Geological Evolution:

Reynolds and Rehrig (1980) have discussed geological evolution of the South Mountains. Around 1.7 b.y. ago Precambrian sediments and volcanics were deposited and subsequently metamorphosed and deformed into a steep northeast-striking foliation. Granitic rocks in the westernmost parts of the range may be representatives of the 1.65 b.y. old suite of granites which are common in Arizona. There are no Paleozoic or Mesozoic rocks in the range. Around 25 m.y. ago, the Precambrian rocks were successively intruded by the granodiorite and granite. At this time, the plutons and the Precambrian metamorphics were subjected to deformation which formed a low-angle mylonitic foliation containing a northeast-trending lineation. NNW-striking dikes were intruded both during and after mylonitization. Strain indicators in the mylonitic rocks require that during mylonitization, the rocks were vertically flattened and extended parallel to the lineation. After mylonitization, the chloritic breccia was formed in the response to northeast movement of rocks above the dislocation surface. Normal, dip-slip movement is suggested by structures in the upper plate rocks and underlying chlorite breccia. Arching of the mylonitic foliation and chloritic breccia is probably one of the last events in the range. It was followed by the Basin and Range disturbance in which steep normal faults down-dropped the adjacent Phoenix basin around 14 to 8 m.y. ago. Since 8 m.y., the area has been tectonically quiet and geological developments have been dominated by erosion and deposition.

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

The central notch is underlain by easily eroded, Oligocene granite. Along its western contact, the granite intrudes the Precambrian metamorphic rocks. Along its eastern contact, the granite grades into and locally intrudes an Oligocene granodiorite (25 m.y. old) which occupies most of the range east of the notch. The television and radio towers are built upon a subhorizontal tabular body of alaskite which overlies and intrudes the granodiorite. The pronounced gentle topographic profile

SUMMARY AND SOME SPECULATIONS ABOUT THE SOUTH MOUNTAINS CRYSTALLINE COMPLEX (from Reynolds and Rehrig, 1980).

Summary:

Some of the more important observations should be summarized before inferences and speculations can be discussed.

(1) The complex is asymmetrical: gently dipping mylonitic granodiorite is overlain by chlorite breccia in the northeast half of the range, whereas no chlorite breccia is associated with moderately dipping mylonitic amphibolite gneiss on its southwest side.

(2) Mylonitization in the amphibolite gneiss, plutons, and dikes increases in intensity upward from the nonmylonitic core of the arch.

(3) Mylonitic fabric cuts a broad zone through the Precambrian amphibolite gneiss. Rocks above and below the zone are lithologically identical, and most retain their Precambrian structure.

(4) Fabrics in all rock types indicate that mylonitization resulted from extension parallel to lineation and flattening perpendicular to foliation. Lineation contained within the foliation trends N60°E, orthogonal to dikes, joints, quartz veins, "ductile normal faults," and other extensional features in the mylonitic rocks. Dikes in particular are perpendicular to lineation, are essentially the same age as mylonitic deformation, and are almost totally confined to positions either within or below the zone of mylonitization. They presumably represent fillings of tensional features that formed as rocks extended parallel to lineation.

(5) The chlorite breccia deforms and postdates the mylonitic fabric. Mylonitization took place under conditions of biotite stability. Mylonitization resulted in recrystallization and flow of quartz and formed a well-defined foliation and lineation. The deformation that formed the breccia occurred under chlorite-stable conditions

and was accompanied by very minor recrystallization of quartz. It destroyed the earlier mylonitic fabric and generally formed no foliation. The chlorite breccia is not present everywhere that mylonitic rocks are. The two clearly are drastically different in structural style and are at least partly different in relative age.

(6) Mylonitization is of mid-Tertiary (late Oligocene to early Miocene) age and is exposed in a range characterized by abundant evidence of mid-Tertiary plutonism. Mylonization is only slightly later in age than the plutonism and is not a protoclastic phenomenon from the fact that the mylonitic fabric is superimposed across cooling joints, dikes, aplites, and quartz veins which postdate solidification of the plutons.

(7) Foliation in the Precambrian amphibolite gneiss was apparently little affected by Mesozoic and Laramide tectonics. It maintained its steep, northeast-striking orientation from its formation 1.7 b.y. ago until mid-Tertiary time, when the plutons were intruded discordantly across it.

Speculations:

Some speculations regarding origin of the complex can be made after considering the foregoing observations and inferences. The spatial and temporal association of mylonitization and the mid-Tertiary plutons implies a genetic relationship. However, because mylonitic fabric cuts through the amphibolite gneiss, the event is not strictly a case of "granite tectonics." Perhaps mylonitization was facilitated by heat that the pluton brought into upper levels of the crust. As the rocks were heated or while they were still hot, they extended parallel to the east-northeast-trending lineation and were flattened perpendicular to the subhorizontal foliation. This was possibly in response to the regional mid-Tertiary stress field of σ_1 (maximum compression) vertical, σ_2 north-northwest, and σ_3 (minimum compression) east-northeast that was proposed by Rehrig and Heidrick (1976). Davis and others (1975) have documented similar orientations for strain and possible stress axes for mylonitic rocks in the Tortolita Mountains near Tucson, Arizona.

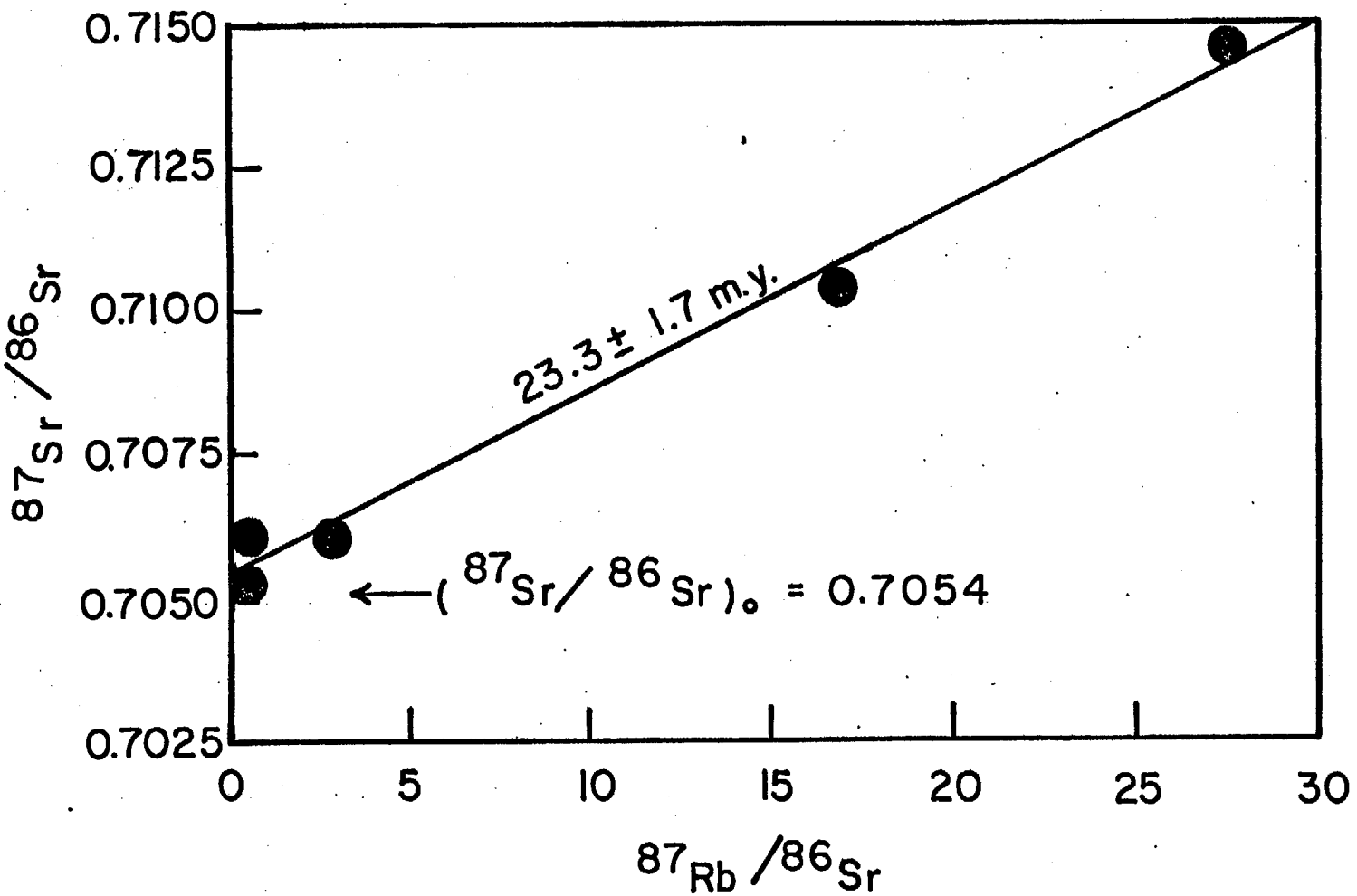
All evidence indicates that east-northeast-directed extension slightly predated, was synchronous with, and slightly postdated development of the mylonitic fabric. Hydrothermally altered and mineralized fractures in the mid-Tertiary plutons, when interpreted in the manner suggested by Rehrig and Heidrick (1972, 1976) indicate that σ_3 was east-northeast during late magmatic to postmagmatic cooling and fracturing of the plutons. North-northwest-trending dikes the <u>same age</u> as mylonitization indicate east-northeast-west-southwest extension. Mid-Tertiary dikes outside the complex also trend north-northwest and thus indicate that this is a <u>regional</u> extension (Rehrig and Heidrick, 1976) and not one related to <u>local</u> strains accompanying mylonitization! Dikes that postdate mylonitization in the complex also strike north-northwest and imply that east-northeast-west-southwest extension existed after mylonitization. In addition, fabrics in the chloritic breccia imply that some form of northeast-southwest extension continued after mylonitization ceased.

It is important to emphasize that the mylonitization is not believed to be a part of classic Basin and Range deformation. Mylonitic rocks evidently occur both in the present-day ranges and the bottoms of the basins. Mylonitization clearly predates essentially all faulting within the past 14 m.y. which formed the present basins and ranges (Eberly and Stanley, 1978; Peirce, 1976; Shafiqullah and others, 1976). Therefore, mylonitization is believed to be a manifestation of a poorly understood Oligocene to early Miocene flattening and extensional event that took place along low-angle surfaces and zones. Mylonitic fabric of this type and orientation in southern Arizona is unrelated to Laramide thrusting, as has been hypothesized by some workers.

Exact temperatures of mylonitization are not known, but several observations provide some constraints. Temperature and fluid content must have been sufficient so that, for the strain rates involved, quartz and some biotite could recrystallize while plagioclase and most K-feldspar deformed brittlely. Silica must have been mobile because quartz veins are more abundant where the rock is mylonitic than in non-mylonitic rocks.

Confining pressure during deformation cannot have been excessive. Plutons slightly predating mylonitization are not deep-level stocks but are instead hydrothermally altered and fractured in a fashion suggestive of fairly low confining pressure. Dikes that are the same age as mylonitization are generally aphanitic; again this situation indicates fast cooling at shallow depths. These dikes and plutons appear to be the only satisfactory way to convey sufficient heat to these high crustal levels.

If the complex is analogous to similar complexes in southern and western Arizona, the chloritic breccia was formed in association with an overlying dislocation surface, above which would lie highly extended rocks as young as early to middle Miocene. In the South Mountains, slickensides, observed displacements of low-angle normal faults in the breccia, and antithetic rotation of mylonitic foliation in the granodiorite all indicate relative transport related to the chloritic breccia as being dominantly to the northeast. The chloritic breccia and overlying dislocation surface are well exposed in the southern foothills of the South Mountains. In this area, upper-plate rocks above the dislocation surface are faulted and brecciated amphibolite gneisses. Relict mylonitic foliation in the gneisses dips southwest and is cut by northeast-dipping normal faults. Additional possible upper-place rocks are brecciated mid-Tertiary volcanic units, tilted and faulted mid-Tertiary sedimentary and volcanic units, and deformed Precambrian (?) granites locally exposed near Tempe (3 to 10 km northeast of the northeasternmost outcrops of mylonitic rocks in the South Mountains). The sedimentary and volcanic units dip moderately to the southwest; this is consistent with antithetic rotation that would have accompanied southwest-to-northeast transport along low-angle, listric normal faults.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$^{87}Sr/^{86}Sr$
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THE VULTURE MOUNTAINS

The Vulture Mountains is made up of a highly listric faulted terrane of mid-Tertiary volcanic rocks depositionally on top of a crystalline basement composed of Precambrian mafic schist, quartzo-feldspathic gneisses and a major, NE-trending, Laramide granodioritic batholith. Volcanics and basement are severely tilted on a series of NNW-striking, shallowly west-dipping listric normal faults. There are no shallow-dipping mylonitic rocks noted in the Vulture Mtns. such as might be expected in such areas of tilting. Such brittle, rotational tectonism may however be accomodated by ductile rock behavior at depth in a mylonitic plate which is not exposed.

Mineralization in the Vulture range is mainly associated with the Laramide batholith as numerous copper showings and prospects. The famous Vulture mine at the south end of the range appears related to bull quartz veins cutting mafic schists and gneisses, and may be of Precambrian age. There are however, numerous precious metals occurrences and prospects of small size which are found in individual fault or fissure veins and associated with argillized areas in late Tertiary felsic intrusive bodies. The Vulture district produced 970,000 tons of ore recovering 350,000 oz. Au, 264,000 oz. Ag, 298,000 lbs. Cu and 1,796,000 lbs. Pb.

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

by William A. Rehrig,
Muhammad Sahafiqullah and Paul E. Damon

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

Regional Setting:

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

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

Rock Types:

Pre-Tertiary rocks in the Vulture Mountains consist of a Precambrian metamorphic-igneous basement intruded by a composite Laramide batholith. Tertiary rocks include hypabyssal intrusive and extrusive rocks (Figure 1).

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

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

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

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

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

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

Tectonic Considerations:

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

Relationships (1) and (2) have been discussed by Rehrig and Heidrick (1976). In close association with the NNW aligned dike swarms of mid-Tertiary (~20-30 m.y. B.P.) age is the period of intense listric faulting which tilted shallow crustal rocks and extended them NE to E, in a direction approximately normal to the strike of the dike swarms. Silicic volcanics in the Vulture Mountains have been strongly affected by this style of deformation (Figure 1). The flat-lying Black Mountain and related basalts post-date the deformation, thus, bracketing the listric faulting event to the broad interval 26 to 13.5 m.y. Undeformed ultrapotassic rhyolite dikes intruding the flat listric faults and correlate with dated 16 m.y. dikes, further narrows the main extensional

faulting to the period from 26 to 16 m.y., or regionally from about 20 to 16 m.y. B.P.

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

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

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

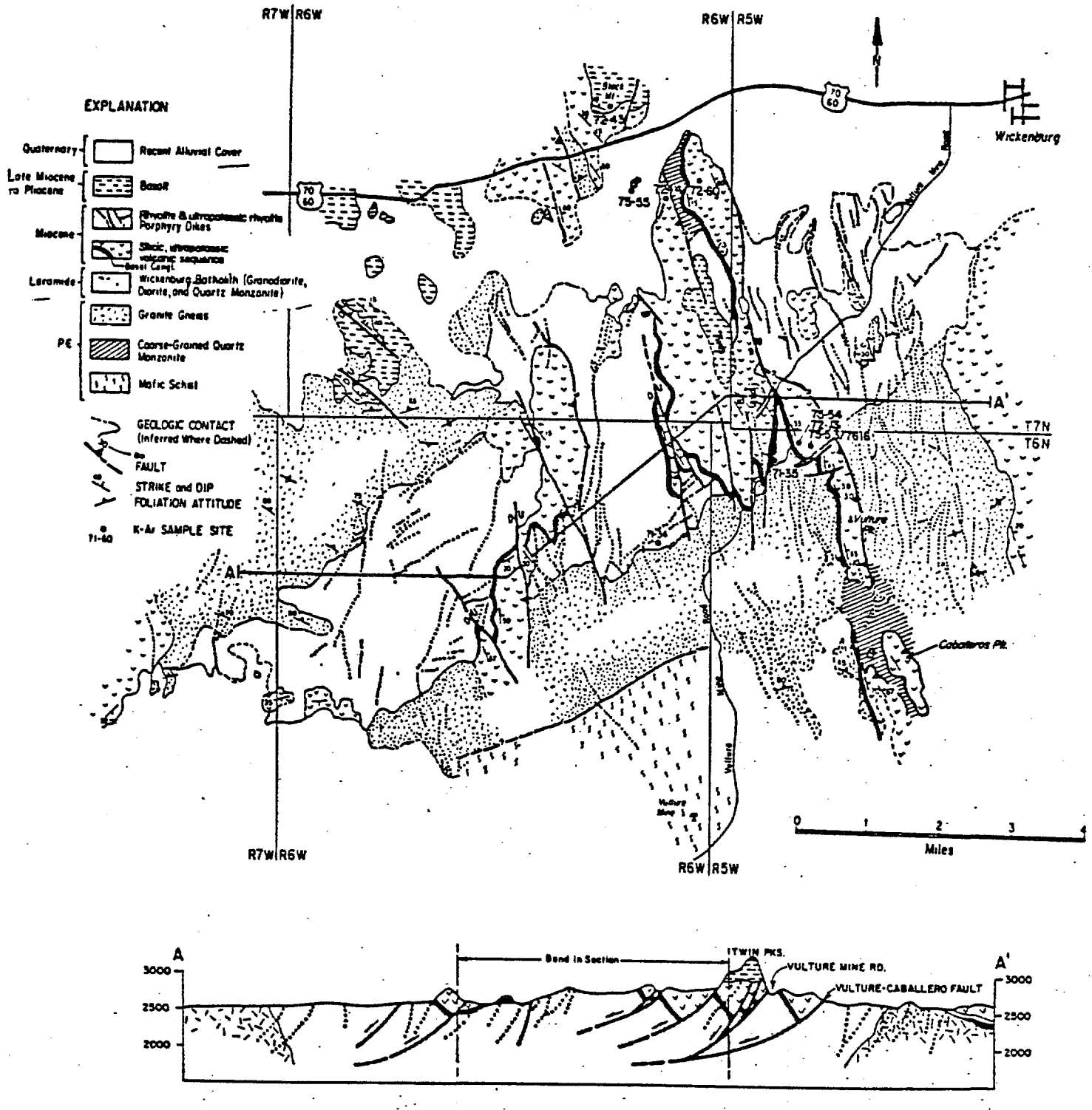


Fig. 1. Generalized geologic map and cross section of the Vulture Mountains. Note a crude northeast-oriented zonal pattern of Precambrian rocks. Mafic schists are common in the southern part. Silicic Tertiary rocks are intruded by a swarm of northerly trending dikes. Structural grain strikes north to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

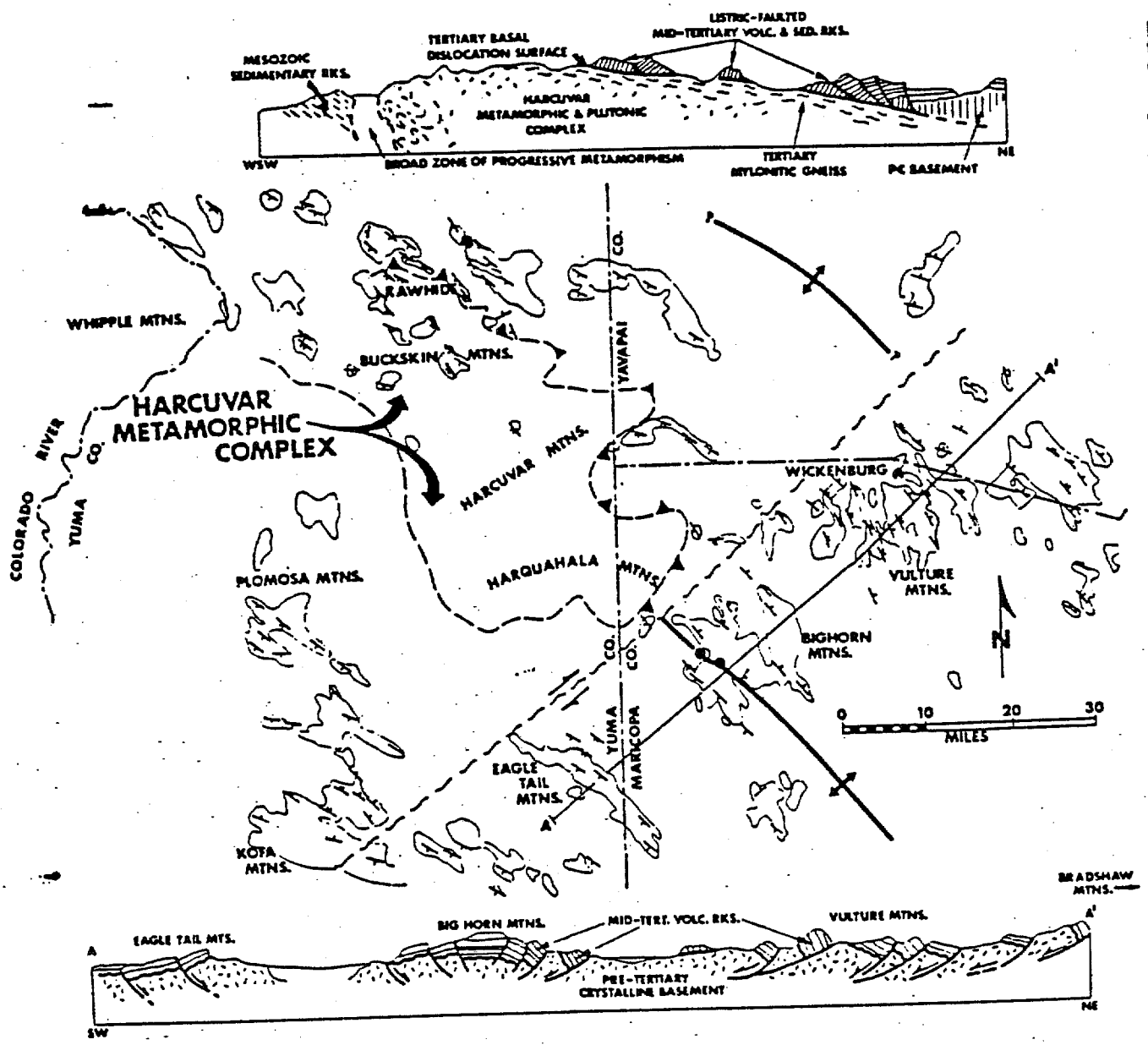


Fig. 2. Regional tectonic setting of the Vulture Mountains. Map shows outcropping areas of Oligocene-Miocene volcanic rocks (outlined areas) and their tilted attitudes. Double-bar dip symbols indicate dips > 45°. Sources for structural data include: Arizona county geologic maps; unpublished tectonic map (Cooley and others, n.d.); Rehrig and Heidrick (1976, p. 218); and first author's more recent field observations. Information (map and section) on Harcuvar metamorphic complex is from Rehrig and Reynolds (n.d.). Barbs along eastern front of Harcuvar complex indicate general trace of northeast-dipping, Tertiary dislocation surface. Heavy-lined, anticlinal symbols indicate axial position of regional antiform (i.e., Big Horn–Vulture antiform) of Tertiary tilting. Wavy-lined, northeast-trending lineament may displace antiformal axis as shown (Stewart, n.d.). This transform(?) boundary possibly allowed differential northeast crustal expansion between the highly extended Harcuvar metamorphic complex (upper cross section) and the Big Horn–Vulture antiform (lower section).

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

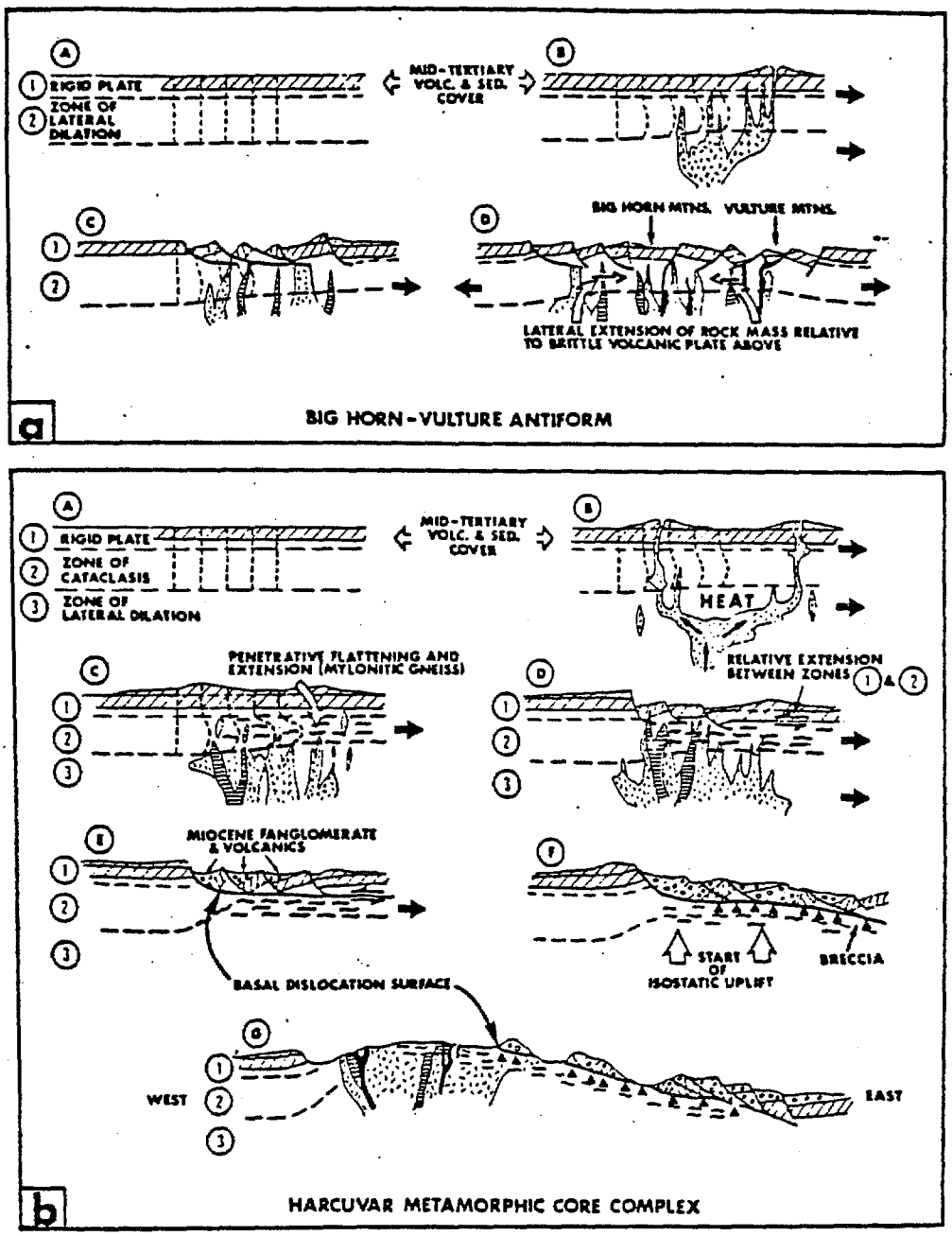


Fig. 3. Working hypothesis for development of listric faulting in the Big Horn-Vulture antiform (a) and Harcuvar metamorphic core complex (b). Large black arrows represent lateral extensional stress toward the northeast or southwest. Vertical dashed lines through plates 1 and 2 show extensional strain.

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

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

Parker
Kingman
Williams
MOHAVE VALLEY
HUALPAI
MOUNTAINS
BLACK
JUNIPER
BOZARTH
MESA
BUTLER
VALLEY
PLOMOSA
MOUNTAINS
SAN
FR

DAY 2

THE HARCUVAR MCC

US Highway 60-70 passes through what has been called the Harcuvar metamorphic core complex (Rehrig and Reynolds, 1980) from just west of the town of Aguila to Salome. The complex is formed by a combination of low-angle structural and metamorphic events of compressional origin and late Messozoic age with equally shallow-dipping, mylonitization and detachment structure caused by mid-Tertiary extension. The Tertiary deformation is found at the eastern end of the complex, where it overprints structure of Laramide age. Abbreviated descriptions, sketch maps and cross sections of the MCC appear in the following pages.

We will start by quickly looking at the Eagle Eye Peak detachment locality south of Aguila. Both Tertiary mylonitic rocks and gold-bearing chloritic breccia can be seen just beneath a detachment fault zone and outcrops of badly altered, auto-brecciated, Tertiary volcanics of the upper plate.

Farther into the complex we will examine an excellent exposure of the Hercules thrust fault, one of the major structures which has placed Precambrian metamorphic rocks on top of Mesozoic metasediments. This thrust as well as others structurally above it have affected the localization of precious metals mineralization in this region and we will compare details of the thrust zone with those in the Tertiary detachment zones. Later as we proceed toward Bouse on State Route 72, we will deviate to the east into the Granite Wash Mountains to see thrust-controlled mineralization at the Yuma mine.

The Buckskin Mountains form the northwest portion of the Harcuvar MCC as is suggested merely by the en echelon, ENE-trend to these ranges (parallel to the Harcuvar and Harquahala ranges). Lower-plate rocks of the Buckskins consist of

variably mylonitized metamorphic and plutonic rock thought to be an extemely complex, tectonized mass of Precambrian basement, Paleozoic and Mesozoic sedimentary rocks. Mesozoic thrusting and strong metamorphic gradients have been superimposed by higher-level, mid-Tertiary mylonitization and detachment. The detachment fault zones which fringe the edges of the NE-foliation arches are the foci for numerous hematite-copper-gold, copper and manganese occurrences (refer to following pages of data). We will examine the Swansea and Clara Park copper and copper-gold mines.

exhibit the smooth bulbous topographic profiles characteristic of metamorphic core complexes. These ranges are distinctive because of their northeasterly trend, which is anomalous amid the prevailing northwesterly trends of mountain chains in the Arizona Basin and Range province. The anomalous northeast trend is due to long, usually doubly plunging foliation arches in gently dipping quartzofeldspathic gneisses (Figs. 5, 6). The broach arches are arranged in en echelon fashion and collectively give the entire metamorphic core complex a northwest elongation.

Previously, the geology of the region had been interpreted to be largely Precambrian gneisses and schist intruded by Mesozoic and early Cenozoic plutons and fringed on the north and south by allochthonous Paleozoic, Mesozoic, and Cenozoic sedimentary rocks (Wilson, 1962; Wilson and others, 1969). Our recent and more detailed work indicates that most of the gneissic "basement" is not due to Precambrian deformation, but is the result of Mesozoic and Cenozoic plutonic, metamorphic, and tectonic events. The protoliths of the metamorphic rocks are believed to range in age from Precambrian to Tertiary.

We will first present some important geologic aspects of each range and then summarize general characteristics of the complex. We will then suggest possible inferences that can be made from our observations. Geologic study in the complex is continuing, and additional discussions will be presented elsewhere at later dates. Davis and others (this volume) describe the geology of the Rawhide Mountains and adjoining area to the west of the Harcuvar complex.

Harquahala Mountains

The main central and eastern mass of the Harquahala Mountains is composed of granitic and high-grade metamorphic rocks flanked on the south and southeast by Paleozoic and Mesozoic rocks locally of low to moderate metamorphic grades (Fig. 6). Plutonic rocks in the central crystalline core are locally foliated and consist mostly of biotitic granodiorite, porphyritic granite, equigranular muscovite-garnet granite, and abundant small tabular bodies of leucocratic alaskite and pegmatite. Other parts of the crystalline core are composed of migmatite, amphibolite, and biotite-bearing quartzofeldspathic schist and gneiss. Foliation in the metamorphic and plutonic rocks is generally gently dipping and defines a broad arch whose east-northeast–trending axis parallels the eastern crest of the range (Fig. 5). At least two directions of lineations are present in the rocks. A variable north- to northwest-trending metamorphic lineation occurs in central and western parts of the range and a younger northeast-trending mylonitic lineation is extensively developed in structurally high parts toward the northeast end of the range (Fig. 5). The older(?) metamorphic fabric is cut by a northwest-trending swarm of microdiorite-andesite dikes that yield somewhat discordant K-Ar hornblende and biotite ages of 28.6 and 22.1 m.y., respectively (Table 1).

South of the crystalline rocks, recognizable Paleozoic and Mesozoic sedimentary rocks are preserved (Fig. 6). Along the southern flank of the range, interbedded feldspathic sandstones and siltstones are exposed that are similar to Mesozoic strata in adjacent ranges (for example, Granite Wash). As these strata are traced northward toward the crystalline rocks, a progressive increase in metamorphism occurs until the two rock types ultimately merge. Farther to the east, metamorphosed calcareous sandstones and pure quartzites are overlain successively by siltstone-quartzite, marble, and interlayered pelitic schists and metasiltstones. This section, although metamorphosed and highly folded, may be in normal stratigraphic sequence and possibly represents parts of the upper Paleozoic Supai, Coconino, and Kaibab Formations and parts of the overlying impure Mesozoic arkose. Where adjacent to or overlain by granitic rocks which form the high crest of the range, the metamorphosed Mesozoic(?) rocks are locally gneissic and somewhat "granitic" in their appearance.

In the southwestern part of the range, large folds in a less-metamorphosed section of Paleozoic rocks (including Coconino and Kaibab Formations) have been mapped by Varga (1976). In and adjacent to

Varga's area, there are exposures of slightly metamorphosed impure clastic rocks of probable Mesozoic age. The contact between Paleozoic and Mesozoic rocks is locally complexly sheared, contorted, or covered by aluvium.

Recent mapping by S. B. Keith and S. J. Reynolds (1980, oral commun.) reveals that major rock units in this range are separated by multiple flat thrust faults. The impact of these structures on the pre-Tertiary history of this reigon is profound.

The youngest rocks of the range are probably those exposed at its extreme northeast end (Fig. 6). Here a sequence of dark, mid-Tertiary(?) volcanic breccia, conglomerate, sandstone, and siltstone dips 30°SW and is underlain by a dislocation surface that dips gently eastward. Below the dislocation surface are chloritic mylonitic gneisses that contain a pronounced N60°E-trending cataclastic lineation.

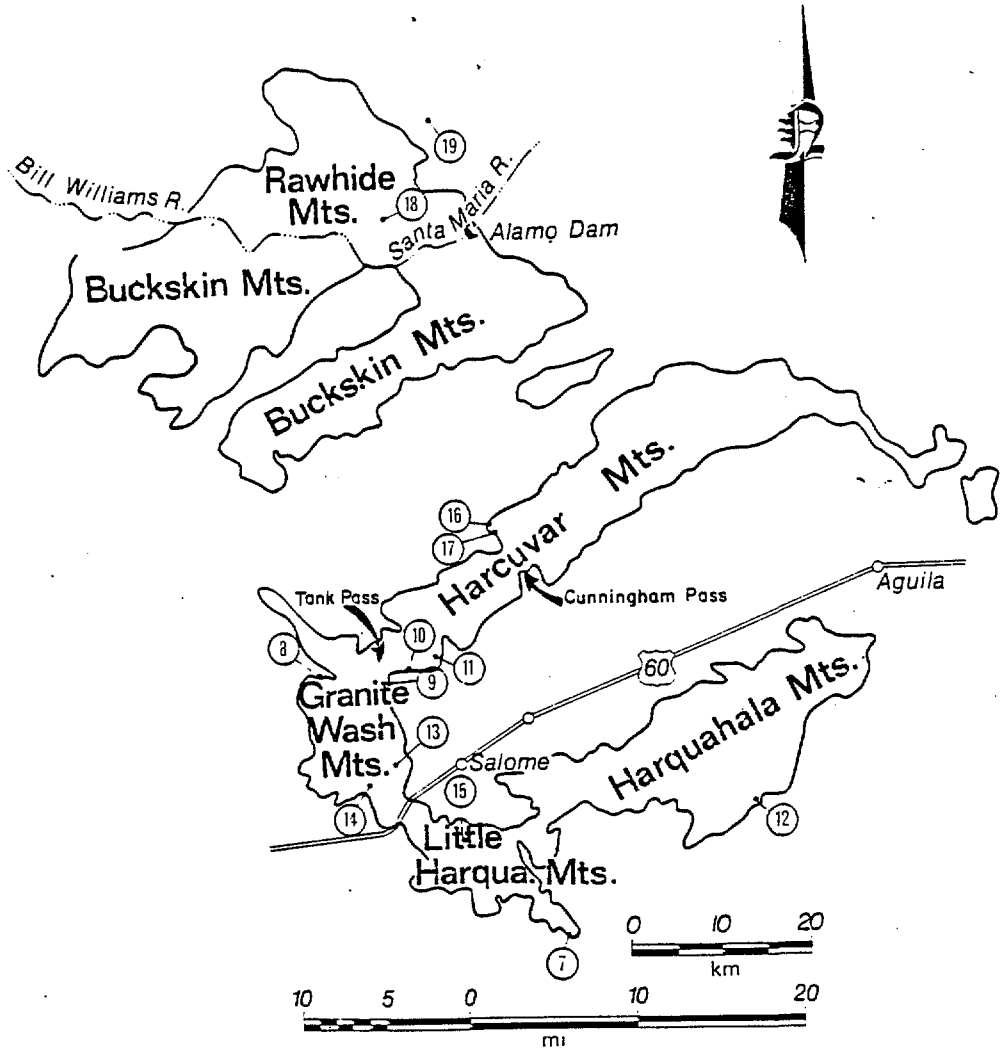


Figure 4. Geography and locations of samples used for dating, Harcuvar metamorphic core complex. Numbers refer to samples in Table 1.

Little Harquahala–Granite Wash Mountains

Southwest of the Harquahala Mountains lie the Little Harquahala Mountains, a range which although not a part of the metamorphic core complex per se, has some important geologic relationships that should be discussed. The folded Paleozoic section studied by Varga (1976) in the Harquahala Mountains continues southwest along strike into the Little Harquahala Mountains. As in Varga's area, the section is only slightly metamorphosed, but intensely faulted and folded (locally overturned); it partly consists of rocks tentatively correlated with the Cambrian Bolsa Quartzite, mid-Paleozoic carbonates (Martin and Redwall Formations), and the upper Paleozoic Supai Formation. A chloritic, feldspar-megacrystic, porphyritic granite underlies these sedimentary rocks in both the Little Harquahala and southwestern Harquahala Mountains. The contact between the Paleozoic rocks and the

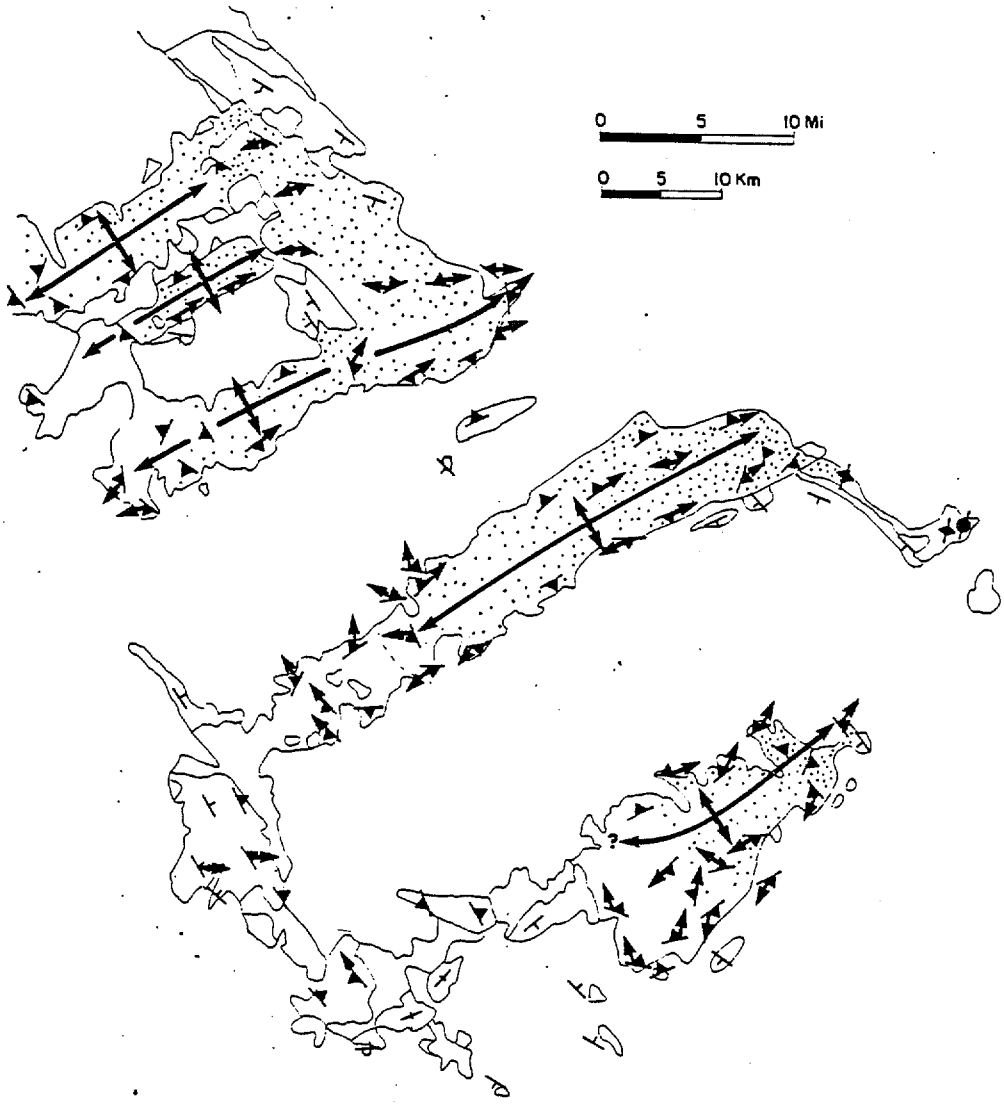
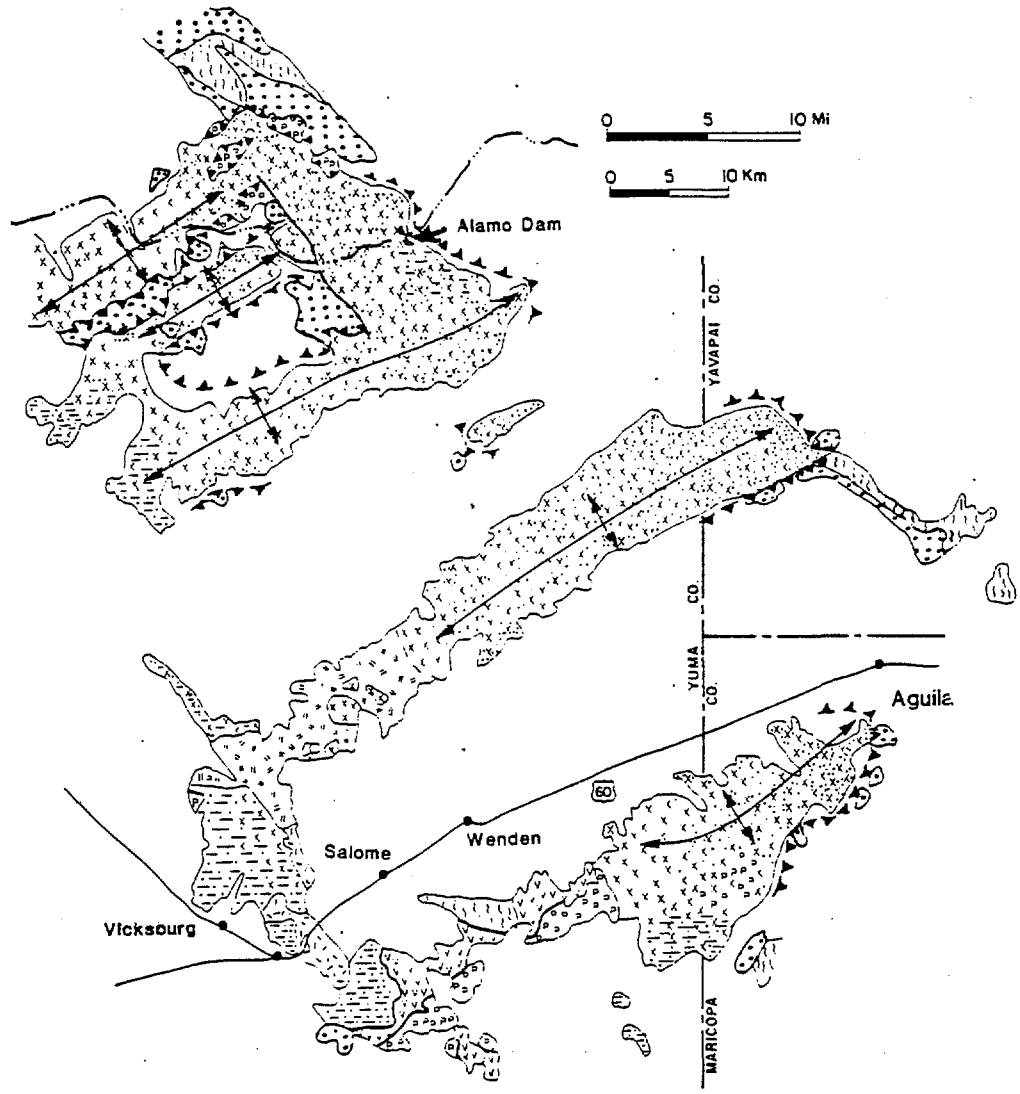


Figure 5. Structure map, Harcuvar metamorphic core complex. Refer to Figure 6 for explanation of symbology.



Major foliation arch

Dislocation surface (dashed where inferred, teeth on upper plate)

Fault

UPPER MIOCENE -RECENT	Surficial deposits
OLIGOCENE-MIDDLE MIOCENE	Sedimentary and volcanic rock
CRETACEOUS -TERTIARY	Metamorphic — igneous complex (stipple = mylonitic fabric)
UPPER CRETACEOUS	Granodiorite of Granite Wash Pass
	Granite of Tank Pass
MESOZOIC	Sedimentary and volcanic rock
PALEOZOIC	Sedimentary rock
PRECAMBRIAN	Granitic and metamorphic rock
PRECAMBRIAN OR JURASSIC	Megacrystic granite

Figure 6. Generalized reconnaissance geologic map of the Harcuvar metamorphic core complex. Parts taken from Shackelford (1976) and Wilson and others (1969).

variable, but generally dips about 30° to the southwest (Fig. 5). This orientation of foliation dictates that structurally lower rocks are exposed to the northeast. Indeed, toward the northeast, the granite is more intensely deformed (locally by flow-folding) and is involved in migmatization to a much larger extent. Near Cunningham Pass, the granite is extensively intruded by garnet-muscovite–bearing alaskite and pegmatite. The foliated granite and these later intrusions are all discordantly intruded by a swarm of northwest-trending Tertiary(?) dikes of andesite, microdiorite, and coarse, hornblende-bearing diorite.

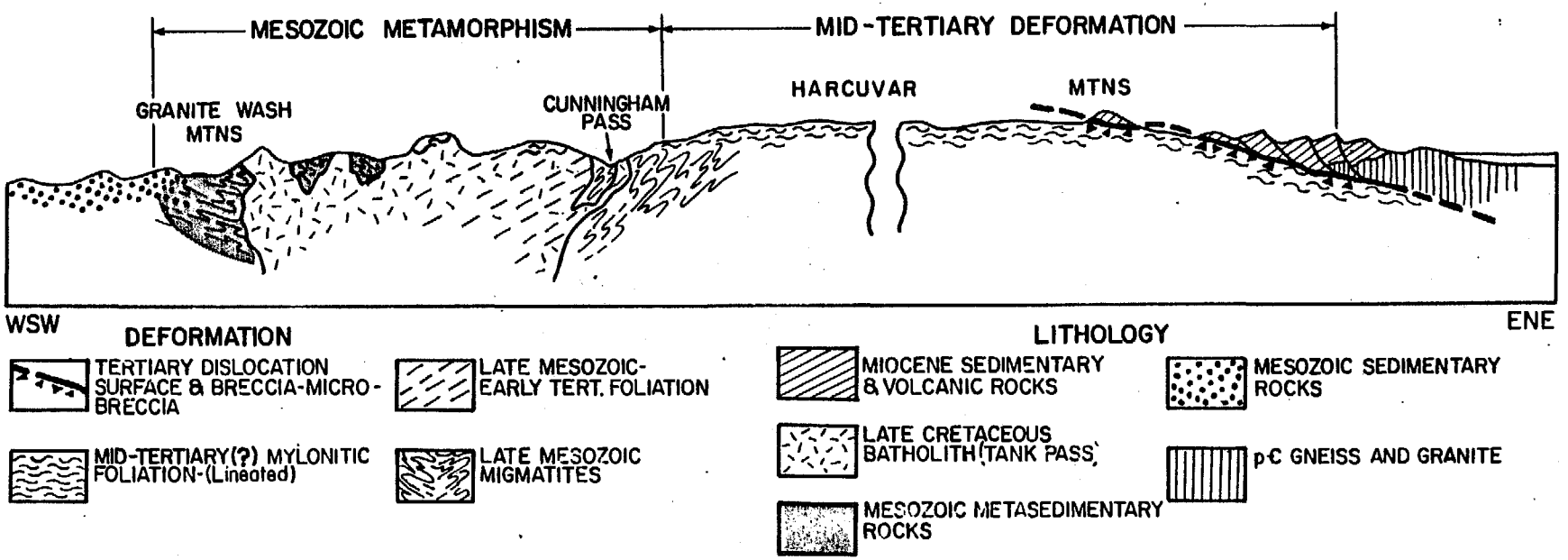
Roof pendants in the granite and migmatites adjacent to the granite consist of amphibolite, quartzofeldspathic gneiss, micaceous schist, foliated granodiorite-granite, and a variety of alaskite and pegmatite. These metamorphic rocks generally contain a northwest-trending metamorphic (nonmylonitic) lineation that is at least locally parallel to axes of flexural-flow and passive-flow folds. This fabric is largely pre-Tertiary, as K-Ar apparent ages of 70.3 m.y. on hornblende and 51 m.y. on biotite have been obtained from rocks containing the northwest-trending lineation (Table 1).

Near Cunningham Pass (Fig. 4), the northwest-trending folds and lineation are distinctly cut by low-angle structural surfaces exhibiting a southwest-trending mylonitic lineation. In addition, the northwest-trending folds and lineation are intruded discordantly by leucocratic pegmatites that are themselves cut by the mylonitic foliation and southwest-trending lineation. There is, therefore, evidence for two deformational-metamorphic events separated by the intrusion of leucocratic pegmatites and alaskites. The earlier metamorphic event produced migmatites and ductile folds with northward- and northwestward-trending lineation, whereas the second event was accompanied by the development of mylonitic foliation and conspicuous southwest-trending lineation. A K-Ar biotite apparent age of 25.3 m.y. (Table 1) on the mylonitic gneisses indicates mid-Tertiary cooling and possibly an equally young age for the mylonitization. This assemblage of rocks and structures makes up most of the remainder of the range to the northeast of Cunningham Pass, where the northeast-trending lineation and mylonitic foliation are progressively better developed. This later mylonitic foliation is also evidently most intensely developed at structurally higher levels along the top and outer margins of the range; thus an arched carapace is formed.

At the northeast end of the range, the mylonitic rocks described above are chloritic, brecciated, and overlain by a dislocation surface whose gentle dip mimics that of the underlying gneisses. In isolated hills above the dislocation surface are allochthonous mid-Tertiary volcanic and sedimentary strata. An additional interesting assemblage of upper-plate rocks apparently overlies the dislocation surface where the large northwest-trending ridge departs from the main range (Fig. 6). In this area, gneiss and schist of almost certain Precambrian age display a near-vertical, northeast-striking, nonmylonitic (crystalloblastic) foliation that is cut by a siliceous and brecciated dislocation surface underlain by gently east-dipping mylonitic gneisses containing a northeast-trending lineation. Above the upper-plate metamorphic rocks in depositional contact is a section of basal arkosic conglomerates overlain by probable mid-Tertiary trachytic welded ash-flow tuffs. The Tertiary section dips moderately to the southwest and is in part the same section exposed in the aforementioned allochthonous blocks.

Buckskin and Rawhide Mountains

The following discussion is based both on the excellent study by Shackelford (1976) in the Rawhide Mountains and our own observations in both the Rawhide and Buckskin ranges. At least three large northeast-trending folation arches in metamorphic rocks govern the structure and outcrop distribution in the Buckskin and Rawhide Mountains (Figs. 5, 6). Gently inclined metamorphic and mylonitic rocks are exposed in the arches, and remnants of overlying, mostly nonmetamorphosed, Precambrian(?) to Miocene dislocated rocks crop out in northeast-trending belts along the axis of the synforms. The metamorphic rocks in the "basement" arches consist of quartzofeldspathic gneiss, mica schist,


MESOZOIC METAMORPHISM
MID-TERTIARY DEFORMATION
GRANITE WASH MTNS
CUNNINGHAM PASS
HARCUVAR
MTNS
WSW
ENE
DEFORMATION
TERTIARY DISLOCATION SURFACE & BRECCIA-MICRO-BRECCIA
LATE MESOZOIC-EARLY TERT. FOLIATION
MID-TERTIARY(?) MYLONITIC FOLIATION-(Lineated)
LATE MESOZOIC MIGMATITES
LITHOLOGY
MIOCENE SEDIMENTARY & VOLCANIC ROCKS
MESOZOIC SEDIMENTARY ROCKS
LATE CRETACEOUS BATHOLITH (TANK PASS)
p€ GNEISS AND GRANITE
MESOZOIC METASEDIMENTARY ROCKS

Stacked Overthrusts of Precambrian Crystalline Basement and Inverted Paleozoic Sections Emplaced over Mesozoic Strata, West-Central Arizona

by

Stephen J. Reynolds[1], Stanley B. Keith[2], and Peter J. Coney[1]

BASE AND PRECIOUS METAL MINERALIZATION RELATED TO LOW-ANGLE TECTONIC FEATURES IN THE WHIPPLE MOUNTAINS, CALIFORNIA AND BUCKSKIN MOUNTAINS, ARIZONA

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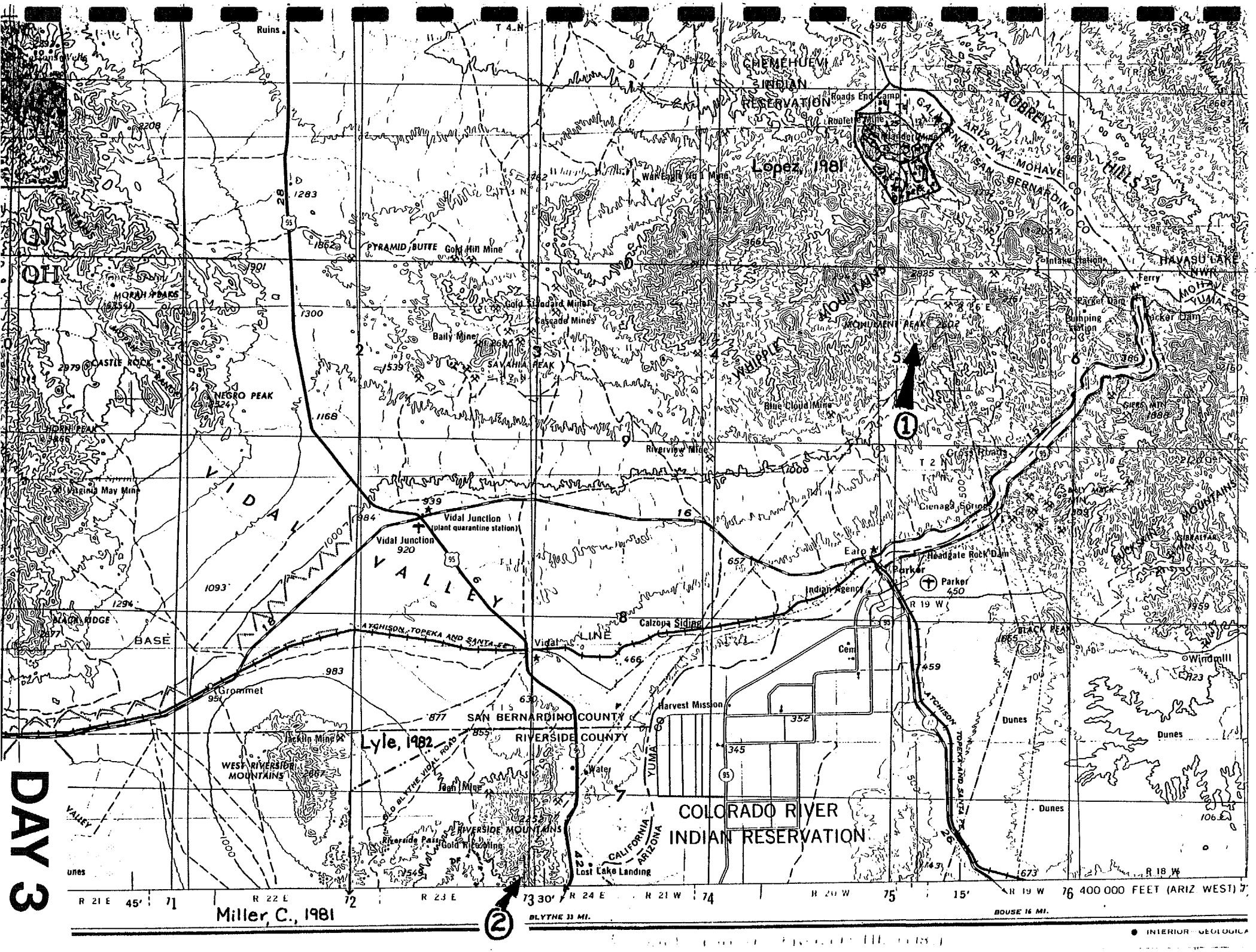
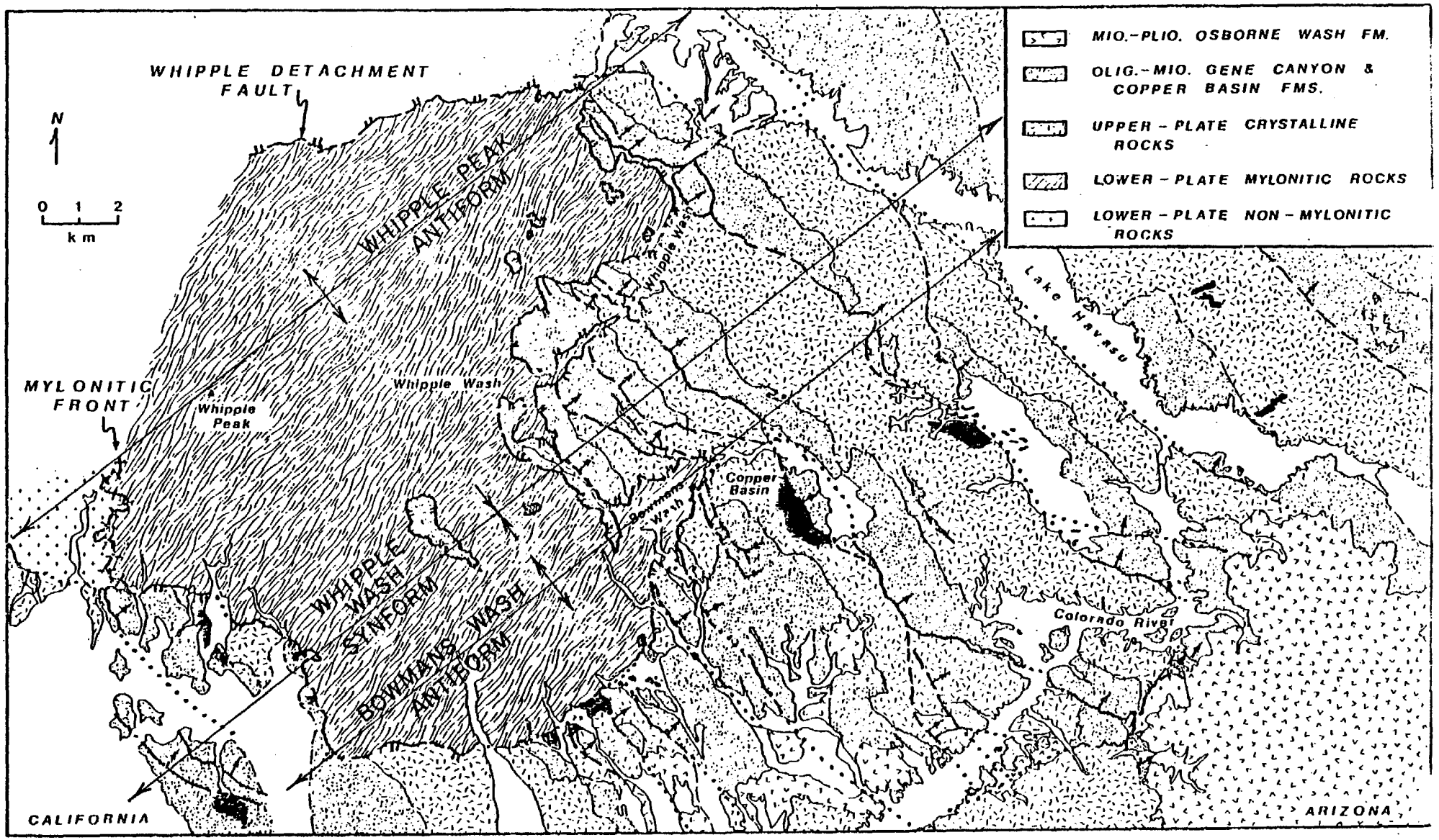

DAY 3
Lopez, 1981
Lyle, 1982
Miller, C., 1981
CHEMEHUEVI INDIAN RESERVATION
COLORADO RIVER INDIAN RESERVATION
SAN BERNARDINO COUNTY
RIVERSIDE COUNTY
CALIFORNIA
ARIZONA
MOHAVE CO
YUMA CO
AUBREY HILLS
WHIPPLE MOUNTAINS
VIDAL VALLEY
BASE LINE
HAVASU LAKE NWR
PYRAMID BUTTE
Gold Hill Mine
Vidal Junction
Vidal Junction (plant quarantine station)
Parker
Parker Dam
Headgate Rock Dam
Cienaga Spring
Calzona Siding
Harvest Mission
Grommet
Lost Lake Landing
Riverside Pass
Gold Rice Mine
Jackin Mine
Jean Mine
WEST RIVERSIDE MOUNTAINS
RIVERSIDE MOUNTAINS
OLD BLYTHE-VIDAL ROAD
ATCHISON, TOPEKA AND SANTA FE
Windmill
Dunes
BLACK PEAK
BLACK RIDGE
CASTLE ROCK RANGE
NEGRO PEAK
HORN PEAK
MORAH PEAKS
SAVAHIA PEAK
MONUMENT PEAK
Blue Cloud Mine
Riverview Mine
Baily Mine
Cascade Mines
Gold Standard Mine
Roulette Mine
Wan Eagle Hill Mine
Roads End Camp
Intake Station
Pumping Station
Ferry
Cross Roads
Indian Agency
Calzona Siding
Water
BLYTHE 33 MI.
BOUSE 16 MI.
400 000 FEET (ARIZ WEST)
R 21 E
R 22 E
R 23 E
R 24 E
R 21 W
R 20 W
R 19 W
R 18 W
T 4 N
T 2 N
45'
30'
15'
INTERIOR GEOLOGICA

THE WHIPPLE MTN. MCC

Magnificently exposed just northwest of Parker, Arizona in California is the Whipple metamorphic core complex. What makes it special is its broad dome-like morphology and the klippen of upper-plate, Tertiary volcanic rocks still preserved high up on the foliation arch. An abundance of mineral occurences rim the complex and exhibit a close spatial coincidence with the Whipple detachment surface (Ridenour and others, 1982). Articles by Davis and others (1980) and Davis and others (1982) describe details of the complex.

We will 4-wheel it up Bowman Wash into Copper Basin passing through the brick red to black outcrops of the 20^{+} to 16 m.y. old Copper Basin volcanic continental sequence (Correlates with the Chapin Wash Fm. seen yesterday in the Buckskin Mtns. of Arizona). These rocks are tilted and fragmented in chaotic fashion on top the Whipple Mtn. detachment fault zone. The volcanics and fanglomerates are potassically altered as are upper-plate rocks seen in the Picacho and Harcuvar complexes.

At the entrance to the Copper Basin we will traverse the detachment contact between strongly propylitized and brecciated crystalline rocks and the upper-plate Copper Basin rocks. Although previously mapped as lower plate, we will see that the crystalline metamorphic and granitic rocks are part of a nonmylonitic (in a Tertiary sense) middle plate. This chloritic brecciated plate was the site for rather extensive copper (minor gold) mineralization associated with a flat, intrusive body of dacite porphyry. We will walk into the western part of the copper deposit, checking out the detachment setting and silicified, gossan outcrops formed by flatly dipping detachment fault zones.


MIO.-PLIO. OSBORNE WASH FM.
OLIG.-MIO. GENE CANYON & COPPER BASIN FMS.
UPPER - PLATE CRYSTALLINE ROCKS
LOWER - PLATE MYLONITIC ROCKS
LOWER - PLATE NON - MYLONITIC ROCKS
WHIPPLE DETACHMENT FAULT
N
0 1 2
km
WHIPPLE PEAK ANTIFORM
MYLONITIC FRONT
Whipple Peak
Whipple Wash
Whipple Wash
Bowmans Wash
Copper Basin
Lake Havasu
WHIPPLE WASH SYNFORM
BOWMANS WASH ANTIFORM
Colorado River
CALIFORNIA
ARIZONA

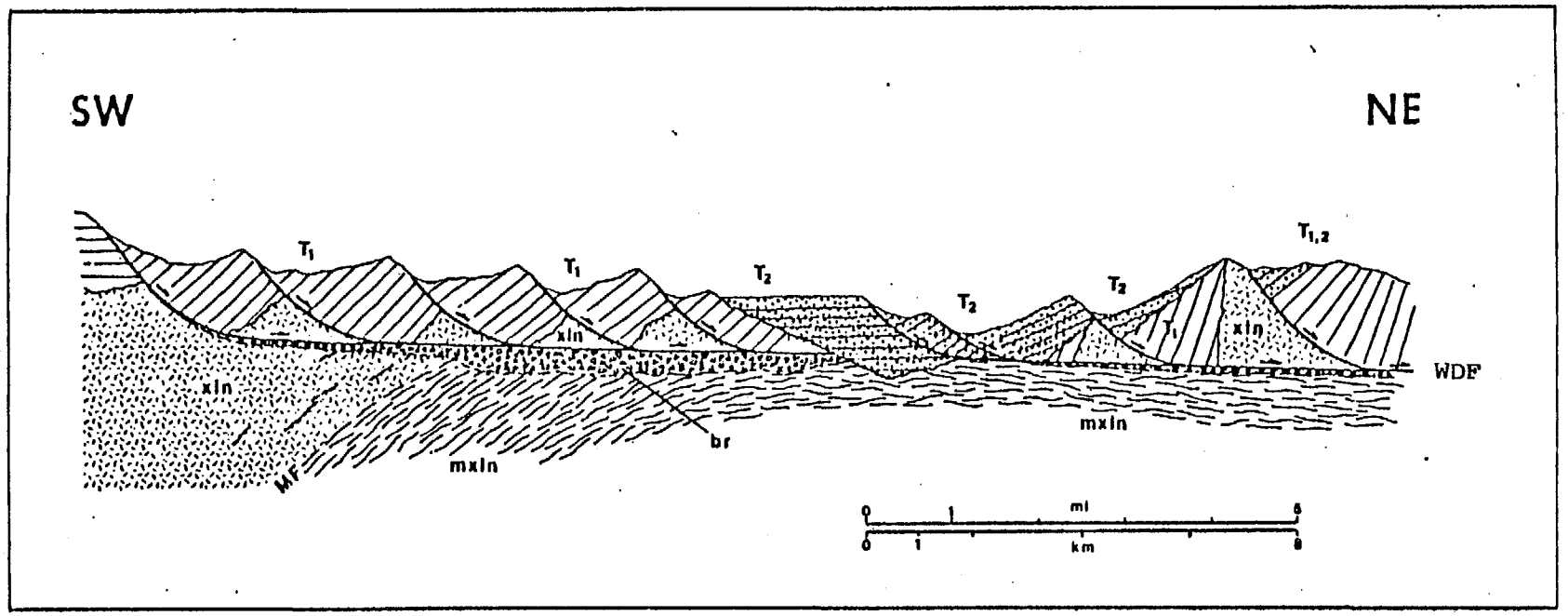


Figure 7. Diagrammatic cross-section across the Whipple Mountains, southeastern California, (see Fig. 3 for approximate location), illustrating middle Miocene geologic relations prior to domal uplift and warping of the Whipple detachment fault (WDF). The cross-section illustrates evidence for two phases of rotational, normal fault displacement along the Whipple detachment surface. T_1 = older Tertiary (Gene Canyon) sedimentary and volcanic rocks; T_2 = younger Tertiary (Copper Basin ?) sedimentary and volcanic rocks deposited across the detachment fault prior to their involvement in renewed fault displacement. MF = mylonitic front, the abrupt non-faulted contact between undifferentiated lower-plate metamorphic and intrusive rocks (xln) and their largely mylonitic equivalents (mxln); br = breccias developed below the Whipple detachment surface. Horizontal scale is approximate, but head, or break-away zone, for detachment probably lies in the Mopah Range, 25 km to the west. Vertical dimensions are somewhat less accurate and are intended to be diagrammatic only.

Anderson-Hamilton Volume - 1982

MINERAL OCCURRENCES IN THE WHIPPLE MOUNTAINS WILDERNESS STUDY AREA, SAN BERNARDINO COUNTY, CALIFORNIA

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ABSTRACT

The Whipple Mountains Wilderness Study Area (WSA) encompasses approximately 85,100 acres in San Bernardino County, California. An examination of mines, prospects, and mineralized areas within and near the study area was conducted during the spring of 1980, by U. S. Bureau of Mines personnel under the provisions of the Federal Land Policy and Management Act.

U. S. Bureau of Mines statistical files indicate that about $84,000 worth of copper-gold-silver ore was produced from mines in the Whipple mining district, exclusive of Copper Basin, from 1906 to 1969. Prospecting targets were the ubiquitous occurrences of chrysocolla, malachite, and hematite in fracture zones both above and below the Whipple detachment fault, the dominant structural feature in the WSA.

The predominant element assemblage consists of barium-manganese-iron-copper-gold-silver and is found in a wide variety of host rocks ranging in age from Precambrian (?) to Miocene. Petrographic analyses of selected copper-gold-silver occurrences indicate these elements are constituents of mineral assemblages largely composed of quartz, sericite, chlorite, and sulfides which have been altered to secondary copper and iron oxide minerals. These assemblages are indicative of an epithermal to perhaps lower mesothermal temperature range. Structural analysis of fractures associated with these occurrences indicates distinct populations above and below the detachment fault that are the result of crustal lengthening in the lower plate and dislocation of the upper plate. The younger age limit for these occurrences is believed to be the Osborne Wash Formation (mid-Miocene); the older age limit for these occurrences is thought to be early in the dislocation process, or late Oligocene, as is suggested by a 24.5±0.7-m.y. K-Ar date of sericite from one of the localities. Collectively, these indicate a temporal relationship between mineralization and dislocation in the Whipple Mountains.

The conceptual mineralization model suggested by these relationships is a low to moderate temperature hydrothermal system spatially related to the detachment fault and chlorite breccia zone immediately below it. Communication of fluids into the upper plate was provided by listric fault and antithetic fault conduits formed during dislocation of the allochthon. The sources of metallic elements for this model are thought to include pre-dislocation mineral deposits and syntectonic volcanic-metallogenic pulses.

INTRODUCTION

General Statement

Under the provisions of the Federal Land Policy and Management Act (Public Law 94-579, October 21, 1976), U. S. Bureau of Mines personnel conducted an examination of mines, prospects, and mineralized areas within and near the Whipple Mountains Wilderness Study Area (WSA). Field investigations were conducted from mid-March to mid-May 1980, with subsequent short visits to the area in September 1980 and October 1981. During our investigations, 643 hard rock samples and 39 petrographic samples were collected from the 49 mines and prospects shown on figure 1. Analytical results of these samples, detailed descriptions of sample localties, maps of workings (where applicable), and background data regarding mineral potential of the study area, are contained in a report at the Bureau of Mines Western Field Operations Center, Spokane, Washington.

A synopsis of our work plus geological, geochemical, and geophysical investigations of the study area conducted by the U. S. Geological Survey will be published as a Summary Bulletin and MF-series maps in the near future.

The purpose of this paper is to report our observations of the study area's mineral occurrences with emphasis on their geologic setting, and to comment on their time-space relationships to detachment faulting, probable origin, and mode of distribution.

Previous Investigations

Library and file research revealed many references concerning geology and mineral resources within and near the WSA. Davis and others (1980) present their latest findings regarding structure, stratigraphy, petrology, geochronology, kinematics of detachment and listric faulting, and geologic history in the Whipple Mountains. The reader is referred to this publication for a more detailed list of previous investigations dealing with these subjects. Recent published mapping includes Dickey and others (1980) in the southern part of the study area and a compilation of the Needles 1° X 2° sheet by Stone and Howard (1979). Site specific geological studies in the vicinity of the study area have been conducted by Frost (1980) and Anderson and Frost (1981). Early mining activity in the area has been recorded by Root (1909), Bancroft (1911), and Jones (1920). Specific descriptions or notations of various mines, prospects, and mineralized areas in the region are given by Bailey (1902), Turner (1907), Aubury (1908), Graeff (1910), Stevens (1911), Wilson (1918), Cloudman and others (1919), Tucker (1921), Tucker and Sampson (1930, 1931), Noble (1931), Trask and others (1943), Tucker and Sampson (1943), Eric (1948), Trask (1950), Wright and others (1953), Trengove (1960), and Fleury (1961). Several previous property examinations (unpublished) have been made by U. S. Bureau of Mines and California Division of Mines and Geology personnel. The tectonic history of the Vidal-Parker region has been presented by Carr (1981). A historical overview of mining in the California desert has been written by Vredenburgh and others (1981). Studies on Cordilleran metamorphic core complexes, of

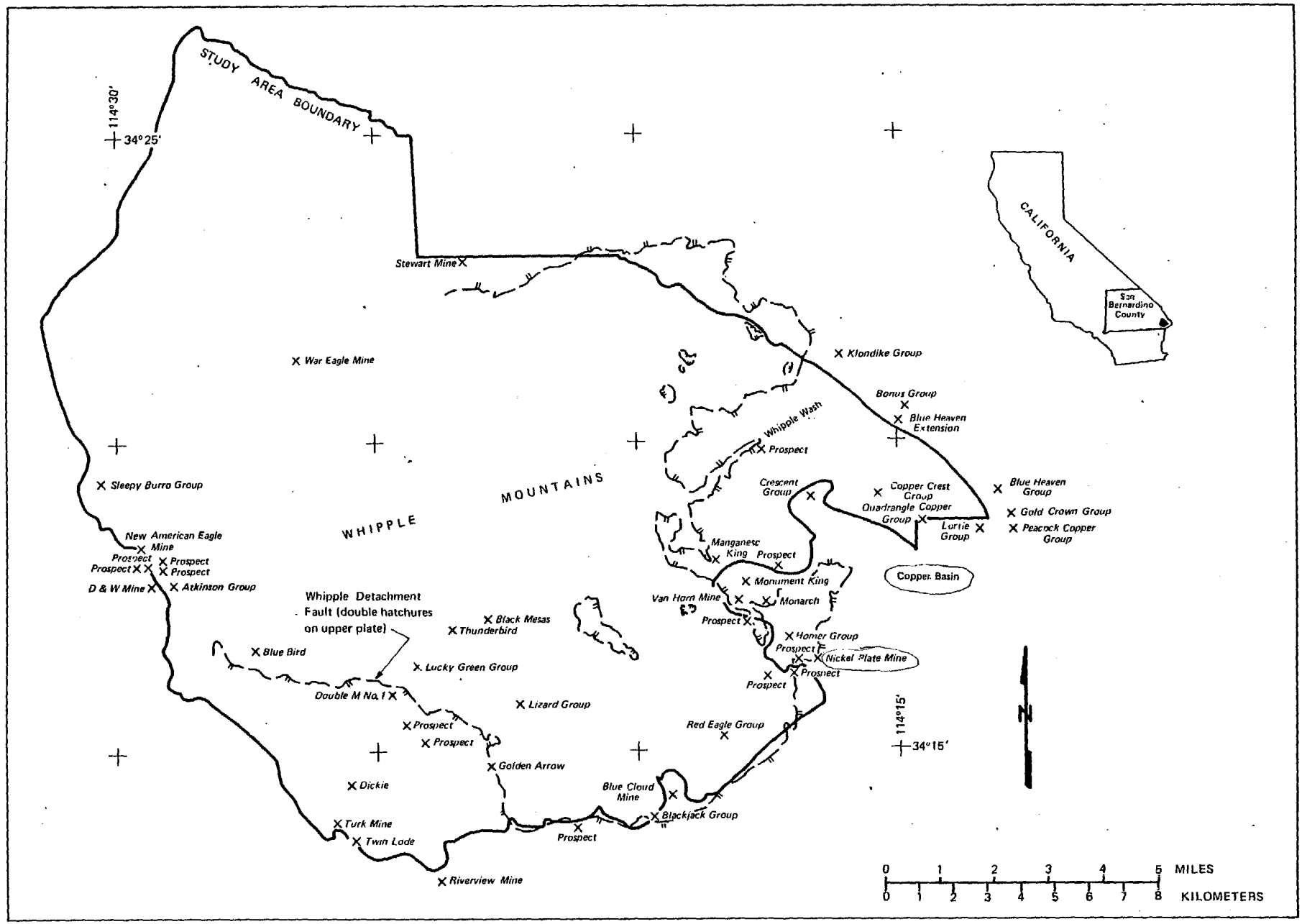

Figure 1. Mines and prospects in the Whipple Mountains WSA.

which the Whipple Mountains is but one, have been recently compiled by Crittenden and others (1980) and Coney and Reynolds (1980). Schuiling's work (1978) on the mineral assemblages of the Sacramento Mountains was used as a comparison to the assemblages we observed in the Whipple Mountains.

Mining in the Study Area

Bureau of Mines statistical files show that 5,123 tons of ore have been reported from 56 mines in the Whipple mining district beginning in 1906 and ending in 1969. The historic value of the ore is estimated at about $84,000; approximately 48 percent of the value came from gold and about 45 percent from copper, with silver, lead, and zinc constituting the remaining seven percent of the ore's value. In addition to gold-copper ores, about 2,500 tons of manganese were produced from five mines between World War I and the 1950's. Much of the mining activity has been limited to intermittent extraction of relatively small, high-grade pockets of mineralized rock. Prospecting targets were the ubiquitous occurrences of chrysocolla, malachite, and hematite in fracture zones. Underground mining was accomplished primarily by sinking shafts and subsequent drifting along the mineralized zones. Production records indicate mining activity was most prevalent prior to World War I and from the depression years through World War II.

MINERAL OCCURRENCES

General Statement

The investigation of mineral potential of the Whipple Mountains WSA has given us a unique opportunity to merge our observations regarding its mineral deposits with recent information on metamorphic core complexes in general and the Whipple Mountains in particular. Because detailed studies of the origin, temperatures of formation, geochemistry, and age of the deposits are beyond the scope of our investigation, we hope that our observations will stimulate more definitive studies of the economic mineral assemblages of this and other metamorphic core complexes.

Geologic Setting

The dominant structural feature of the study area is a low-angle detachment fault which juxtaposes contrasting lithologic terranes across its surface. As described by Davis and others (1980, p. 79), the fault

> ...separates a lower-plate assemblage of Precambrian to Mesozoic or lower Cenozoic igneous and metamorphic rocks and their deeper, mylonitic equivalents from an allochthonous, lithologically varied upper plate.

The allochthonous units (Davis and others, 1980, p. 80)

> ...include Precambrian to Mesozoic crystalline rocks, Paleozoic and Mesozoic metasedimentary rocks, Mesozoic metavolcanic rocks, and Tertiary volcanic and sedimentary rocks.

Immediately below the Whipple detachment fault lies an altered and highly disturbed zone termed the chlorite breccia zone (Frost, 1980). This zone is capped by a 2-to 25-cm-thick, resistant, flinty microbreccia (Davis and others, 1980, p. 112); consistent striae directions of N 50±10° E have been measured on its surface, indicating transport direction of the allochthon.

Salient geologic history of the Whipple Mountains, as documented by Davis and others (1980), includes Late Cretaceous and/or early Tertiary mylonitization and metamorphism accompanied by synkinematic intrusion of adamellite to tonalite sheets or sills, followed by Oligocene (?) to middle Miocene dislocation of the allochthonous terrane. The Whipple Mountains were asymmetrically domed after dislocation, and erosion has removed most of the upper plate terrane from the core area, leaving only a few isolated klippen of allochthonous rocks except in the east-central part of the study area.

Description of Assemblages

The commodity assemblages in the Whipple Mountains consist of barite-manganese-iron and copper-gold-silver. The barite-manganese-iron assemblage is found, in significant amounts, almost exclusively in upper plate rocks. Copper-gold-silver-bearing occurrences, on the other hand, are found in a wide variety of host rocks in both lower and upper plate positions and are megascopically indicated by the presence of chrysocolla, malachite, and iron oxides. Associated with these commodities is a pervasive chlorite-dominant propylitic alteration. The barite-manganese-iron-copper-gold-silver assemblage and its alteration products suggest epithermal temperatures associated with Tertiary volcanism (Park and MacDiarmid, 1970, p. 344-345). Eight samples were selected for detailed petrographic description from seven localities within and near the study area. Descriptions of these samples are summarized in Table 1. We believe these samples to be representative of the ubiquitous copper-gold-silver-bearing occurrences we observed during our field investigations.

Petrographically the mineral assemblages are composed largely of quartz, sericite, chlorite, and sulfides (now mostly altered to secondary copper and iron oxide minerals). Although not all constituents are always present in a given sample, where they do occur the sequence is fracturing and concomitant quartz-sericite-chlorite alteration followed by deposition of sulfides.

Although there are some important differences between the assemblages described here and those investigated by Schuiling (1978), we believe his assemblage B (quartz+minor pyrite+hematite+chrysocolla+barite) most closely approximates the Whipple Mountain assemblages. Temperatures of formation of the Sacramento Mountains assemblages ranged from 120° C to more than 310° C (epithermal to lower mesothermal); paragenetic sequences indicate that certain constituents were deposited in stages within distinct ranges of temperature and salinities (Schuiling, 1978, p. 53), perhaps indicating multiple stages of deposition. Overall alteration and geologic setting of these assemblages appears correlative with the Whipple Mountain assemblages.

Structural Patterns

Structures that control the occurrences of the assemblages described here include tension gashes, shears, and faults. These occur throughout the study area in nearly all types of rock in both upper and

Table 1. Petrographic Summary

Name	Setting	Rock type	Assemblages (minerals in decreasing order of abundance)	Paragenetic Summary
Whipple Wash prospect	Lower plate	Chlorite breccia	quartz-chlorite-sericite-sulfides-limonite-clay	Fracturing followed by simultaneous introduction of silica, sericite, chlorite-clay, and sulfides.
Crescent Group	Upper plate	Quartz vein	quartz-chrysocolla-limonite-malachite-sericite	Fracturing followed by introduction of vein quartz and chalcopyrite accompanied by silification and sericitic alteration; further fracturing followed by oxidation of chalcopyrite to limonite, chrysocolla, and malachite, accompanied by deposition of chalcedony.
Lortie Group	Upper plate	Brecciated porphyritic granite	quartz-clay-limonite-chrysocolla	Brecciation followed by introduction of chalcopyrite and its alteration to limonite and chrysocolla; alteration of plagioclase to clay.
Nickel Plate Mine	Upper plate	Adamellite microbreccia	quartz-clay-limonite-chrysocolla-sulfides	Microbrecciation followed by introduction of quartz, pyrite, chalcopyrite, and sericite. Later argillic alteration of plagioclase.
Lucky Green Group	Lower plate	Granitic cataclasite	quartz-sericite-chalcopyrite-limonite-malachite	Fracturing followed by quartz-sericite-sulfide mineralization; supergene alteration of chalcopyrite to limonite and malachite.
Blue Bird Mine	Lower plate	Graphic granite breccia	quartz-sericite-nontronite (?)-barite-chrysocolla-chlorite-limonite	Brecciation followed by introduction of quartz, nontronite (?), sericite, barite, and sulfides. Supergene alteration of sulfides to limonite and chrysocolla.
New American Eagle Mine	Lower plate	Sodic dacite porphyry (dike?)	quartz-chlorite-sulfides-sericite-limonite	Deformation followed by introduction of quartz, sulfides, chlorite, and sericite. Supergene limonitic alteration.
New American Eagle Mine	Lower plate	Siliceous volcanic breccia	quartz-limonite-malachite-clay	Brecciation followed by introduction of quartz and sulfides. supergene alteration of sulfides to limonite, malachite, and clay.

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lower plate position; they have been identified within a zone approximately 1200 feet both above and below the detachment surface. Faults, particularly listric normal ones, can be traced for several miles; shear zones and tension gashes can usually be traced along strike for only a few hundred feet.

Two hundred and eighty-six attitude observations of mineralized structures were separated into lower and upper plate populations and analyzed by computer. The resulting Pi diagrams (figure 2) show a concentration of poles in the lower plate oriented N 26° W, 48° NE; upper plate structures show a dominant cluster at N 45° W, 28° NE, and a secondary cluster centered about N 46° W, 66° SW. Upper plate data confirm the suspected structural control of these occurrences by NE-dipping listric and sympathetic normal faults and SW-dipping antithetic and bedding plane faults. The dominant lower plate structural grain is within limits predictable for tension fractures resulting from the N 50±10° E direction of crustal extension and direction of movement of the upper plate.

DISCUSSION

Our conclusions regarding the mineral potential of the Whipple Mountains WSA were based on the observation that the majority of the mineral occurrences observed at the mines and prospects we mapped and sampled were spatially related to the detachment fault and the premise that they are temporally related to the dislocation process. Because ground preparation is the dominant physical control on the mineral occurrences, a temporal link between the processes of dislocation and mineralization seems intuitive. As younger rocks, e.g., Osborne Wash Formation, have not been deformed by the dislocation process and are not known to contain occurrences of the type described here, a younger age limit of 13.5±1.0-m.y. (Kuniyoshi and Freeman, 1974) is placed on the mineralization and suggests that, if the processes were coeval, mineralization may have ceased with cessation of dislocation or shortly thereafter. We must also assume that if the mineralization process continued into Osborne Wash time, these rocks were unaffected.

The older age limit of mineralization is harder to define. These occurrences are found in rocks that may be as old as Precambrian (Davis and others, 1980, p. 86) or as young as Miocene (Davis and others, 1980, p. 95). Paragenetic relationships at the Lucky Green Group indicate that mineralization resulted during extensional fracturing discordant to earlier mylonitic fabric; those at the prospect in lower Whipple Wash indicate that sulfides formed during or after formation of the chlorite breccia. Finally, a K-Ar date on sericite from the Nickel Plate Mine is placed at 24.5±0.7-m.y., indicating probable formation of mineralization at this locality during early stages of dislocation.

In summary, we interpret the mineral assemblages as having been transported in a low to moderate temperature hydrothermal system, coeval with dislocation of the allochthon, and deposited in favorable physical and geochemical environments. As the dislocation process spanned some ±10 million years and apparently was not a continuous process, as indicated by local erosion into the chlorite breccia zone followed by renewed dislocation (Davis and others, 1980, p. 95), so must mineralization have also been somewhat discontinuous, if the two processes were coeval. We believe the main conduit for

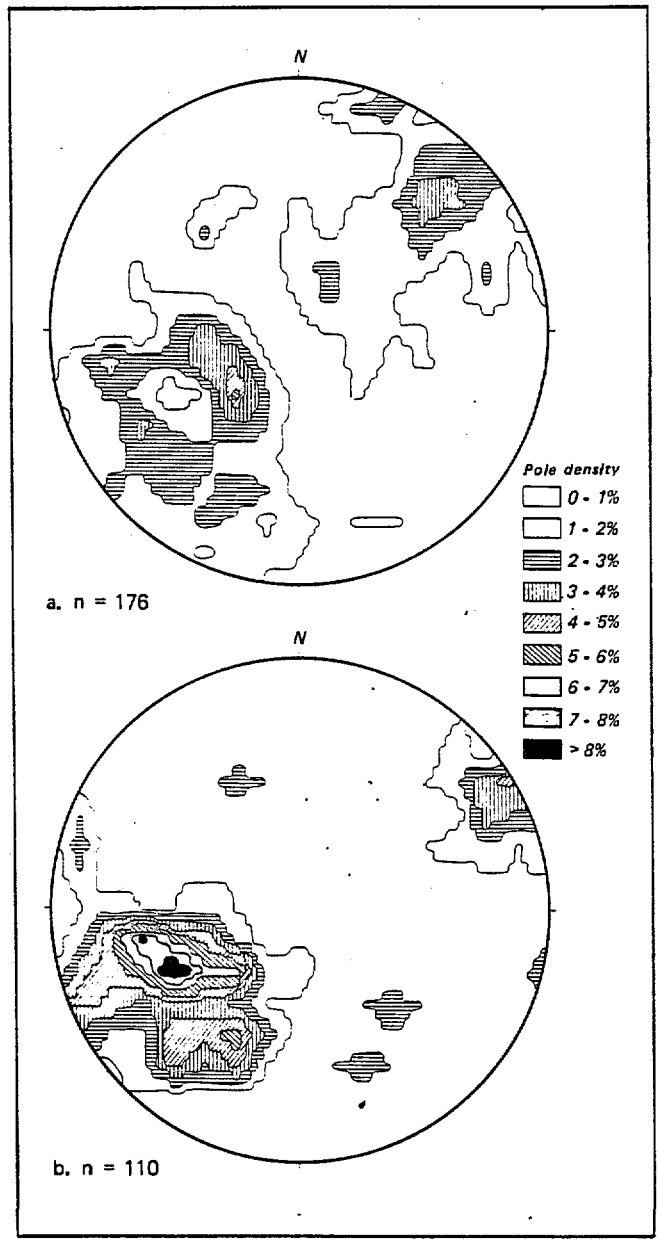

Figure 2. Pi diagrams of mineralized fractures in a. upper plate and b. lower plate rocks in the Whipple Mountains WSA.

these fluids was the detachment fault and chlorite breccia zone, and that the feeder conduits into the upper plate were listric and antithetic faults. The structurally lower limit of mineralization, as indicated by the study area's barren core, may simply reveal the boundary beyond which confining pressures exceeded hydrostatic pressures of the hydrothermal system.

Because this model requires either predislocation or syntectonic sources (or both) for the metallic elements such as copper, gold, and silver, we offer the following possibilities:

1. The work of Anderson and Frost (1981) demonstrates that a Cretaceous adamellite, a significant piece of which is in Copper Basin, was cut by the detachment fault and transported by the dislocation process into the Whipple Mountains area.

While this suggests its mineralization may significantly predate dislocation and, therefore, may have been transported, at least in part, to its present site, the hypogene minerals associated with this deposit, as described by Heidrick (1980, p. 20), indicate an epithermal, volcanic-derived assemblage, the constituents of which are also present throughout the Whipple Mountains and apparently temporally associated with dislocation. Therefore, the Copper Basin mineralization may be a consequence of dislocation rather than a contributor to the process.

2. The extreme western part of the study area is dominated by nonmylonitic rocks intruded by a northwest-trending dike swarm whose lithologies appear to range from rhyolite to andesite. A dacite (?) from this swarm has been dated at 41.9±6.7-m.y. (Eric Frost, personal communication). In apparent association with this dike swarm are podiform to lensoid and disseminated occurrences of sulfides at the D&W Mine (Aubury, 1908, p. 337) and New American Eagle Mine (Wilson, 1918, p. 4-6; Wright and others, 1953, p. 65). Because the sulfides formed later than the host rock, as indicated by paragenetic relationships at the New American Eagle Mine, and the dike swarm is in the lower plate and thus truncated by the detachment fault, we infer that these occurrences may have been one possible source for remobilized metallic elements.

3. Volcanic activity in the area both prior to and during dislocation has been documented by average dates of 27.8±2.8 and 17.7±0.6-m.y. for Gene Canyon and Copper Basin volcanic rocks, respectively (Anderson and Frost, 1981, p. 36). In addition, Carr (1981, p. 18) cites evidence of intermediate to calc-alkaline volcanism ranging in age from about 22 to 18 m.y., and basaltic volcanism beginning about 15 m.y. ago in the Whipple Mountains and vicinity. Of particular importance to this system is any syntectonic volcanism that could have supplied metals to the transporting conduit.

CONCLUDING COMMENTS

While we are relatively comfortable with the mineralization model presented here, we realize that much further work is necessary to define its parameters and that its application to detachment terranes elsewhere may not be valid. Nevertheless, using this model, we have defined areas in the Whipple Mountains where we believe there is a greater likelihood of discovery of potentially significant mineral resources. Because of dominant structural control of the occurrences, we believe larger scale structures should be examined in detail and with modern exploration methods and tools. In addition, thicker sections of upper plate crystalline rocks may be likely hosts for entrapment of ascending hydrothermal fluids generated during dislocation as well as favorable terrane in which to explore for significant remnants of predislocation mineral deposits.

ACKNOWLEDGEMENTS

We wish to acknowledge the assistance of the many individuals who contributed to our knowledge of the study area. Special thanks are due Eric Frost, San Diego State University, who not only provided most of the geologic and structural information necessary to our understanding the occurrence of the study area's mineral deposits, but also tirelessly answered our questions and offered much encouragement. Lawford Anderson and Greg Davis, University of Southern California, contributed clarifying points, through personal communication, regarding petrologic and structural aspects of the study area. Conversations with Sherman Marsh, U.S. Geological Survey, have helped us understand the probable geochemical conditions under which the minerals were formed. We also wish to thank Bill Rehrig, Phillips Petroleum Company, for sharing his observations of similar mineral occurrences and for critical review of the manuscript. Thanks are extended to our colleague Steve Munts for his technical review and many helpful suggestions for improvement of the manuscript. We thank Keith Howard and the U. S. Geological Survey laboratory for geochronological determination of a specimen collected during our investigation. Petrographic thin sections were prepared by Pacific Petrographics, Spokane, Washington; descriptions of these were done by Koehler Geo-Research Laboratory, Grangeville, Idaho. We are indebted to Clayton Morlock and Julia Bosma for their assistance during field investigations. Finally, appreciation is extended to the U. S. Bureau of Mines for allowing us to prepare and publish this paper.

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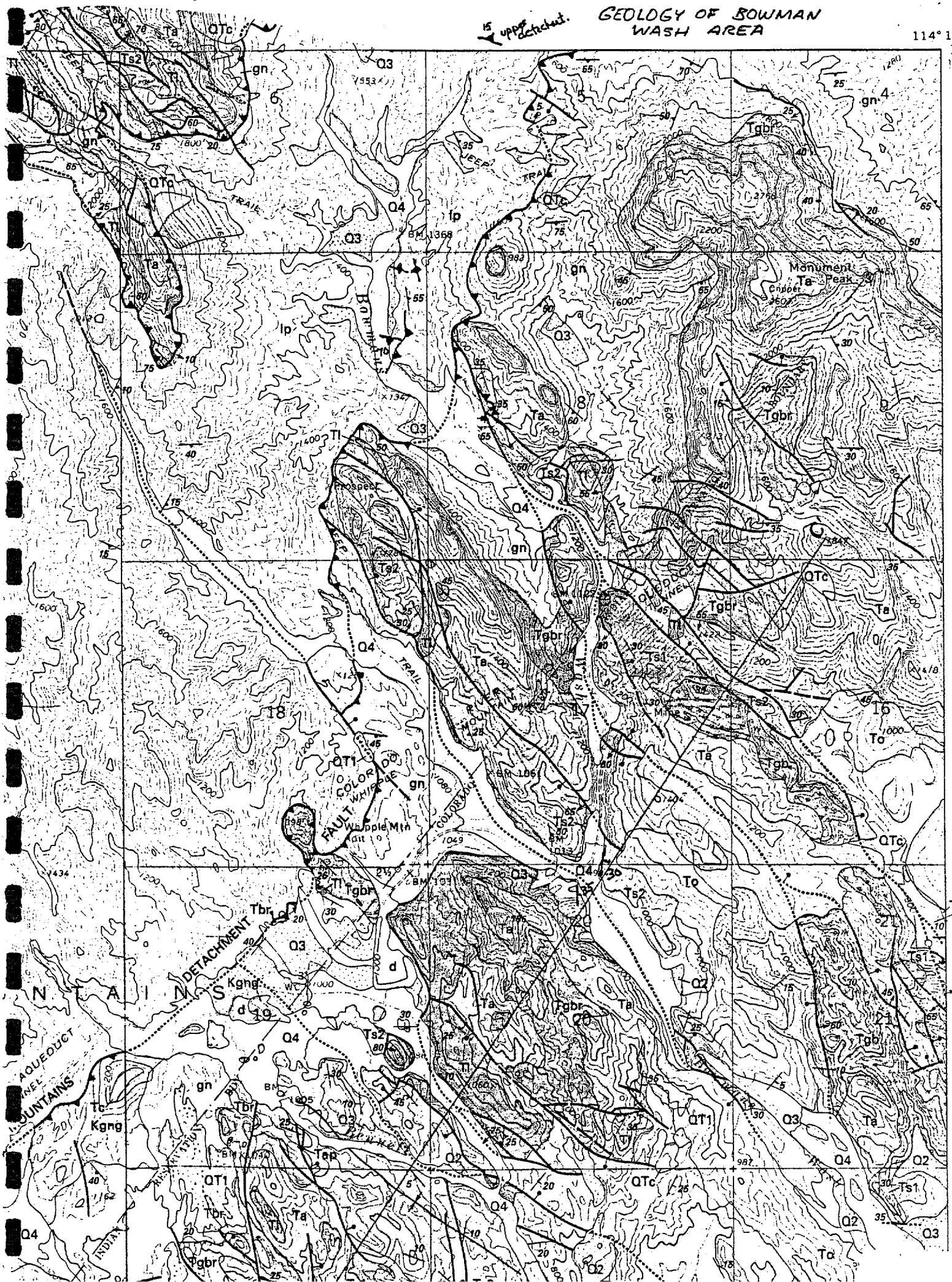
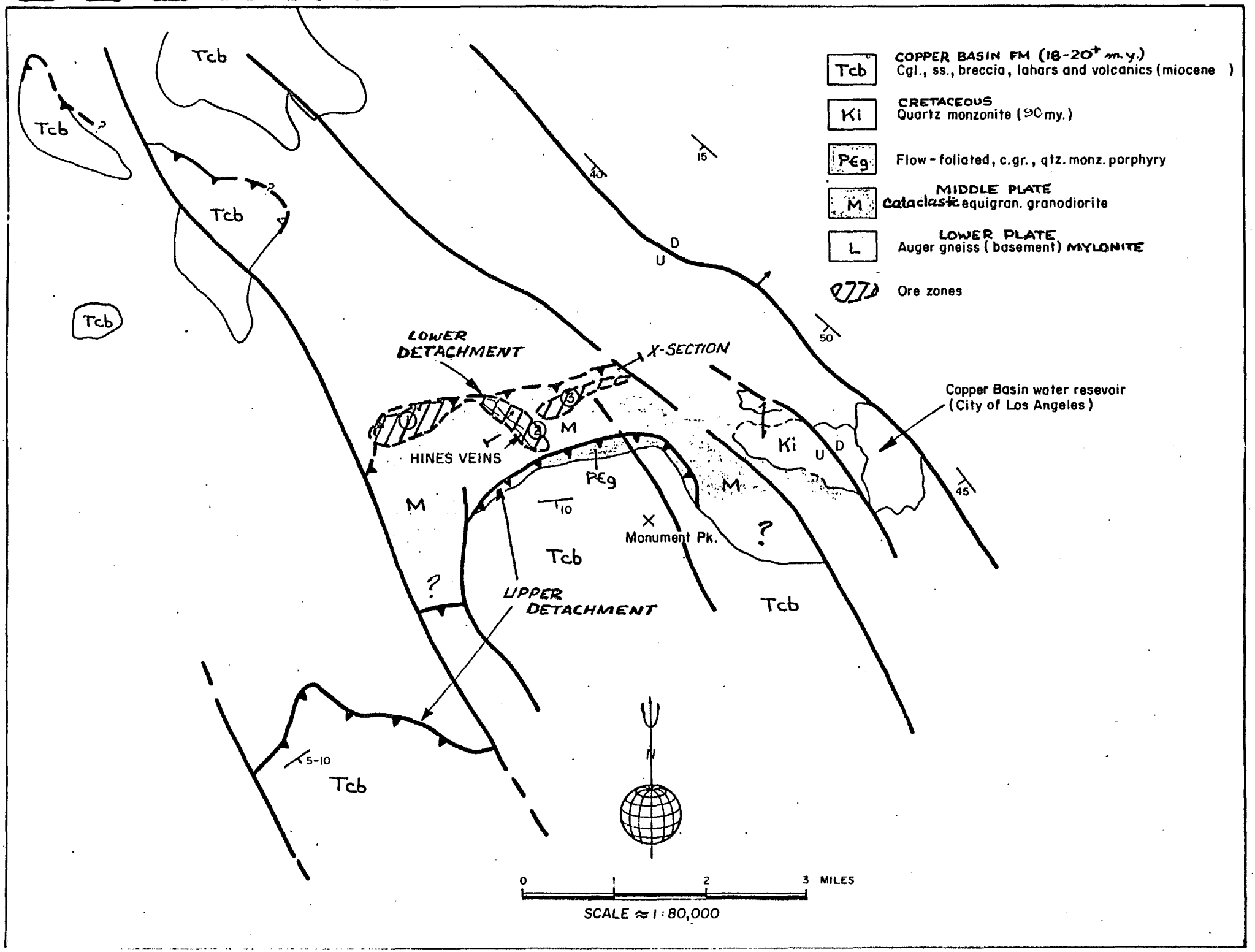
GEOLOGY OF BOWMAN WASH AREA

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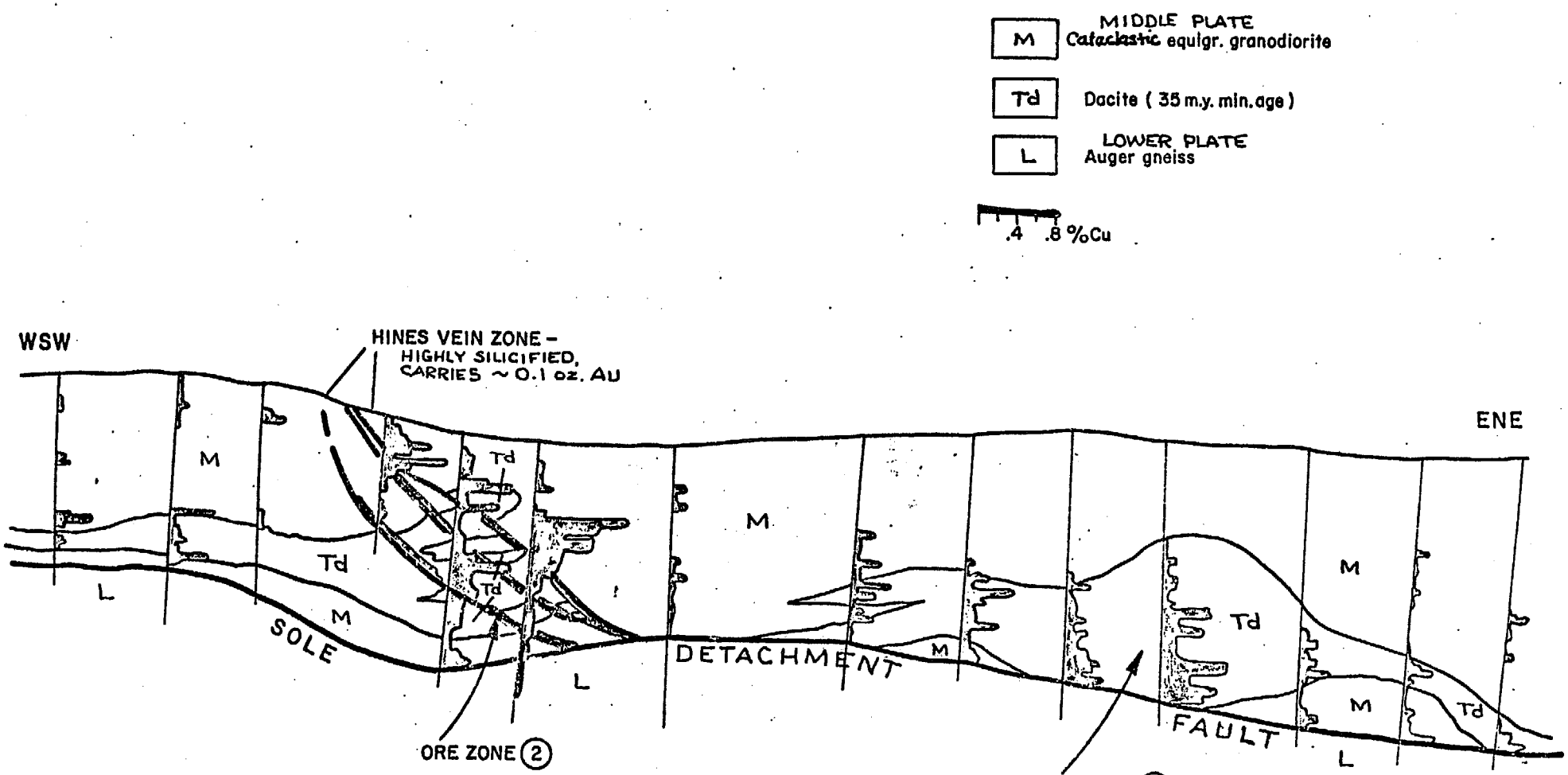
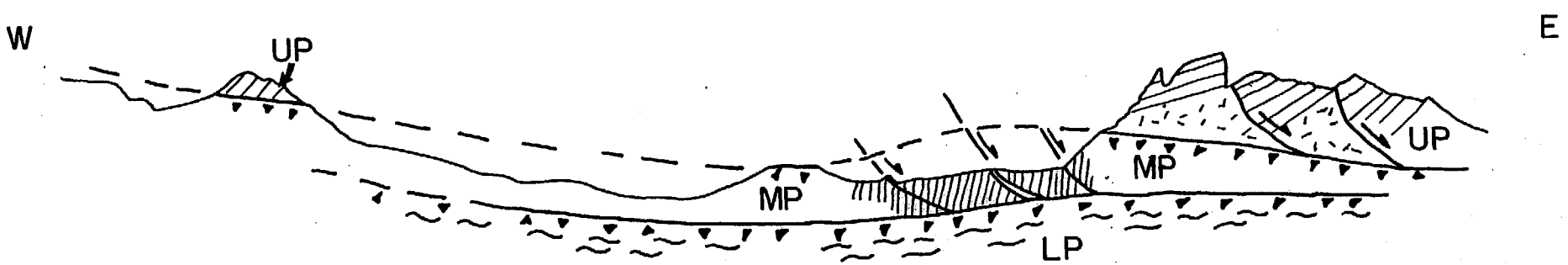


(NOTE: In this diagrammatic section the ore zone is shortened. There are several drill holes which have been omitted.)



UP — UPPER PLATE- MESOZOIC OR PRECAMBRIAN CRYSTALLINE ROCKS & MID-TO LATE TERTIARY VOLCANIC-CLASTIC ROCKS

MP — MIDDLE PLATE- PRECAMBRIAN(?) METAMORPHIC & PLUTONIC ROCKS; VARIABLY BRECCIATED, ALTERED & INTRUDED BY PHANEROZOIC INTRUSIVES

LP — LOWER PLATE- MYLONITIC QUARTZ MONZONITE AUGEN GNEISS

COPPER BASIN DEPOSIT

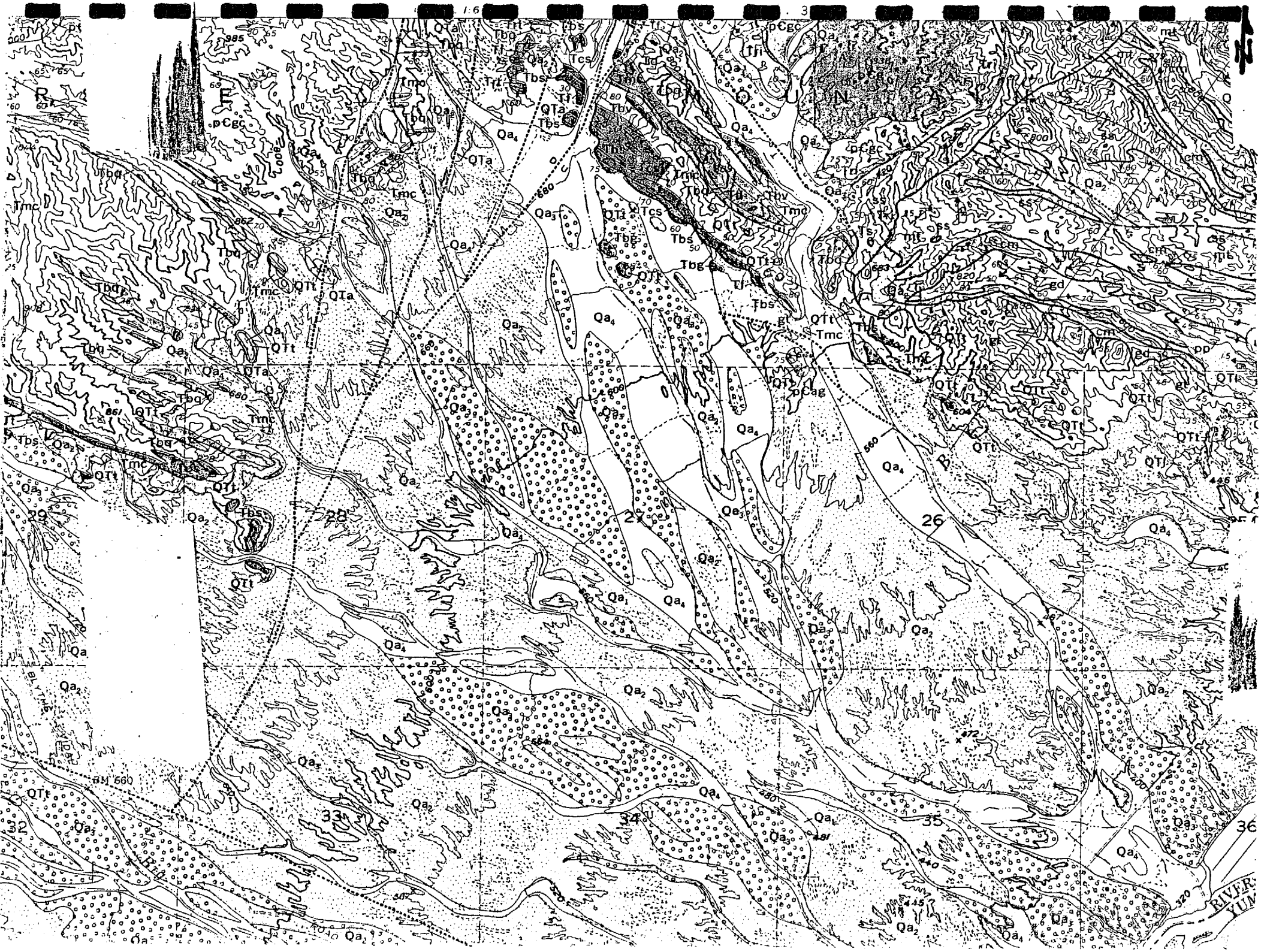
DETACHMENT FAULT W SUBJACENT CHLORITIC BRECCIA

MYLONITIC FOLIATION

THE RIVERSIDE MTNS.

South of the Whipple MCC, on the California side of the Colorado River are the Riverside Mtns. which expose an extensive, low-angle fault structure correlated by Carr and Dickey (1980) with the Whipple detachment surface. This flat fault does not everywhere seperate mid-Tertiary rock on the upper plate from crystalline lower plate lithologies, but commonly it is found within the pre-Tertiary rocks. Important differences between the Riverside fault and the Whipple detachment is that the former has no significant chloritic breccia and is not underlain by mylonitic rocks. Details on the overall geology of the range are contained in the attached article by Lyle (1982).

We will enter the range from the southeast, stopping first to examine a mismapped contact originally interpreted to be the Riverside detachment fault. Farther into the range the actual detachment structure will be observed where it cuts Mesozoic metamorphic rocks. Although exploration companies have recently staked a good portion of the detachment terrain in this range, there are not the quantity of known occurrences here as there are in the Whipple Mtns.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INTERRELATIONSHIP OF LATE MESOZOIC THRUST FAULTING AND MID-TERTIARY DETACHMENT FAULTING IN THE RIVERSIDE MOUNTAINS, SOUTHEASTERN CALIFORNIA

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ABSTRACT

The Riverside Mountains of southeastern, California are perhaps the clearest example of the superposition of Mesozoic compressional features with mid-Tertiary extensional phenomena in the lower Colorado River region. Hamilton (1964, 1971) describes isoclinally folded complexes of thrust sheets involving Precambrian basement interlayered with Mesozoic and Paleozoic metasediments of the Grand Canyon sequence, which are overprinted by a Tertiary low-angle fault on the southern side of the Riversides. Carr and Dickey (1980) label the low-angle fault the Whipple detachment fault and also show Mesozoic and Paleozoic thrust stacks on Precambrian units in the lower plate.

The Riverside Mountains resemble a horse-shoe morphology open to the north. The eastern Riversides define a major southwest-plunging antiform with several minor antiforms and synforms forming the rest of the range as a result of mid-Tertiary crustal warping. The detachment fault is locally exposed and flanks the southern margin of the Riversides conforming to the folded geometry of the range. The detachment fault separates a brittley distended upper plate consisting of Tertiary volcanics, fanglomerates, fluvial-lacustrine deposits and Precambrian schist and gneiss from a non-mylonitic, relatively unaffected lower plate consisting of interleaves of upright and overturned Paleozoic and Mesozoic sequences between Precambrian crystalline units that reflect deep-seated Mesozoic compressional deformation. Kinematic indicators suggest upper-plate transport to the northeast above a lower plate that shows partial K-Ar resetting to 38 myBP just below the fault. Lower plate metamorphic mineral assembleges suggest greenschist grade metamorphism and physical conditions of formation of 350-450° and 2-7kb. As a result, Paleozoic sequences display a highly ductile deformation fabric, yet remain relatively intact.

The lower-plate Mesozoic deformational history has been interpreted by palinspastically removing the mid-Tertiary deformation. Two distinct episodes of Mesozoic folding and thrusting (f_1,f_2) have been recognized on the basis of superposed large-and small-scale folds and their associated structural elements. Northeast-verging folds (f_2) are most conspicuous in all lower-plate rocks as they refold previously formed f_1 folds and thrusts and produce a locally developed northeast-trending lineation. F_1 folds are east to southeast vergent, generally recumbent and fold inverted thrust limbs. Although geochronologic data is poorly constrained, the f_1 east-to southeast-vergent folds seemingly reflect elements of the late Mesozoic Sevier foreland fold and thrust belt.

The thick Precambrian section and interleaved metasedimentary rocks appear to be structurally higher than rocks below the detachment fault in the adjacent Whipple and Buckskin Mountains. This may suggest that the coeval mylonitic fabric and northeast-trending lineation that are so widely exposed in ranges northeast and east of the Riversides is of simple-shear origin. If so, the origin of the northeast-trending lineation associated with northeast-vergent folds (f_2) in the Riversides may be explained as a result of antithetic overthrusting in conjunction with late Mesozoic synthetic underthrusting. This underthrusting appears to have produced the mylonitic horizons so widely exposed as tectonic windows throughout southeastern California and western Arizona. These tectonic windows are products of the mid-Tertiary crystal warping associated with the development of detachment-related antiforms and synforms.

INTRODUCTION

The Significance of Mid-Tertiary Overprint

Ernie Anderson's study (1971) of low-angle faulting in the Eldorado Mountains, Nevada, 100 km north of Needles, California, was geologically, a revolutionary breakthrough. His work was the first to attribute the low-angle faults of the Colorado River area to non-compressional tectonics. He described an area characterized by Miocene imbricate normal faults, which involved pronounced eastward rotation of Tertiary strata and interpreted these faults as flattening downward and merging with a subhorizontal basal fault surface below which extension by normal faulting had not occurred.

Further south in the Whipple-Buckskin-Rawhide Mountains of southeastern California and western Arizona, Davis and others (1979) studied a terrane with geological characteristics similar to those described by Anderson (1971) in the Eldorado Mountains, nearly 200 km to the north. They described the low-angle faulting as being extensional in origin and as having formed at shallow depths (< 5 km). They also pointed out that this low-angle normal fault, or detachment fault is a wave-like surface folded into an antiformal-synformal geometry that coincides roughly with the general morphology of the ranges and valleys covering tens of thousands of square kilometers.

Recent studies by a number of workers (Frost, 1981; Otton and Dokka, 1981; Frost and Cameron, 1981) indicate that many ranges in southeastern California and southern and western Arizona probably owe their

morphology to the development of northwest-and/or northeast-trending antiformal-synformal basement warps, which appear to be related to the origin of regional detachment faulting. The recognition of this Tertiary deformational overprint has provided the geometric and kinematic constraints to palinspastically remove the penetrative Tertiary deformation from the exposed geologic record. In areas that involve Sevier and/or Laramide related folding and thrusting, Tertiary crustal warping has exposed these features allowing the deciphering of pre-detachment structural configurations and kinematics. It is extremely important therefore, that low-angle faults be correctly identified as either mid-Tertiary "extensional" detachment faults or "compressional" Mesozoic thrust faults, in order to correctly interpret the geologic history of an area.

This paper describes the geologic characteristics and kinematics of detachment faulting and the effects of their superposition on Mesozoic deep-seated compressional deformations that are recorded in the Riverside Mountains of southeastern California. The Riversides are unique in that they are perhaps the clearest example of the mid-Tertiary extensional overprint on Mesozoic compressional features in the lower Colorado River region.

Regional Mesozoic (Sevier-Laramide) Folding and Thrusting

Several works in the recent literature describe thrust faults related to compressional tectonics in the lower Colorado River region and adjacent areas (Fig.1) Burchfiel and Davis (1971) describe east-directed thrust faulting and folding in the Clark Mountains, California as a continuum of the Sevier (Mesozoic) foreland fold and thrust belt. In a later paper (1977) they extend the thrust belt further south to the New York Mountains, California. Like the Clark Mountains, the same sense of eastward-fold vergence and thrusting prevails but with a different structural style, which they attribute to the change in tectonic setting from a miogeoclinal to a cratonal environment.

Howard, Miller and Stone (1980) and Howard (1981) describe southeast-vergent folds and associated thrusts in the Little Piute Mountains, Old Woman Mountains and Kilbeck Hills, and suggest the continuance of the foreland fold and thrust further to the south. They note that deformation is highly ductile with local metamorphism reaching sillimanite grade, which they attribute to "deep-seated expressions of the Sevier orogenic belt exposed to the north."

Thrust faults exposed in the Big Maria Mountains have been described as being both northeast (Hamilton, 1971; this volume) and southwest vergence (Ellis, 1981; this volume) and southwest vergence (Ellis, 1981; this volume; Ellis and others, 1981). Southwest-to south-vergent folds and associated thrust faults have also been described in the Little Maria Mountains (Emerson, 1981), Palen Mountains (Demaree, 1981), and Arica Mountains (Baltz, this volume) and seem to be associated with southwest-vergent ductile nappes, which Krummenacher and others (1981) attribute to northeast-directed underthrusting.

In the Chocolate and Peter Kane Mountains further south, Haxel and Dillon (1978) describe thrust faults related to the Vincent-Chocolate Mountains thrust system. Considerable controversy exists about the kinematics of this system, with both northeast underthrusting and overthrusting as possibilities (Haxel and Dillon, 1978; Jacobson, 1980).

Thrust faulting in the Plomosa Mountains, Arizona, has been described by Miller (1970) and Miller and McKee (1971) although data describing kinematics and timing are loosely constrained. Thrust faults dip eastward separating upper-plate fossiliferous Paleozoic sections from lower-plate deformed Paleozoic sections. They suggest that the eastward dip and spatial relationships of Paleozoic sections in western Arizona indicate that the upper plate moved westward relative to the lower plate.

The Harquahala Mountains of western Arizona, contain many thrusts that can be related to compressional tectonics as described by Reynolds, Keith, and Coney (1980). In the Harquahalas, southeast-vergent folds are discordantly severed by a later episode of thrusting that Reynolds and others interpret as having northerly to northeast tectonic transport.

The thrust faults in ranges described above and shown in Figure 1 are unequivocally of compressional origin. Several other ranges shown in Figure 1 may actually contain thrust faults as well, but Tertiary extensional deformation makes original genetic inference difficult. The ages of the thrust faults described above are not tightly constrained, making it difficult to correlate faults in one range to those in other ranges.

Regional Mid-Tertiary Detachment Faulting

Mid-Tertiary detachment faults in the Colorado River area and adjacent ranges (Fig. 1) are well documented in the literature. Where detachment faulting and associated deformation are superposed on Mesozoic and Tertiary mylonitic terranes, the term "metamorphic core complexes" has been used (Davis and Coney, 1979; Crittenden and others, 1980).

Shackelford (1975, 1976a, 1976b, 1980) was the first to describe this relationship in the lower Colorado River region in his studies of the Rawhide Mountains of western Arizona. Davis and others (1977, 1979, 1980), Rehrig and Reynolds (1980), Dickey and others (1980), Frost and Otton (1981), and Lucchitta and Suneson (1977, 1980) have also described extensive areas of detachment faulting in the Whipple, Buckskin, Rawhide, Harcuvar, and Harquahala Mountains of western Arizona and eastern California. In these ranges, mid-Tertiary clastic and volcanic rocks dip rather uniformly to the southwest, suggesting northeastward transport above the regionally subhorizontal detachment fault. This detachment fault is folded into a series of major antiformal-synformal structures, which expose the lower plate by creating the mountain ranges in this terrane (Davis and others, 1979, 1980).

In the Riverside Mountains a detachment fault is locally exposed along the southern margin of the range. This low-angle fault is folded into an antiformal-synformal geometry. Northeast-dipping normal faults in the upper plate rotate strata to the southwest indicating motion to the northeast (Carr and Dickey, 1980; Carr, 1981).

Detachment faults are also seen to the south of the Riversides in western Arizona in the Trigos (Garner and others, this volume), Mohawks (Mueller and others,

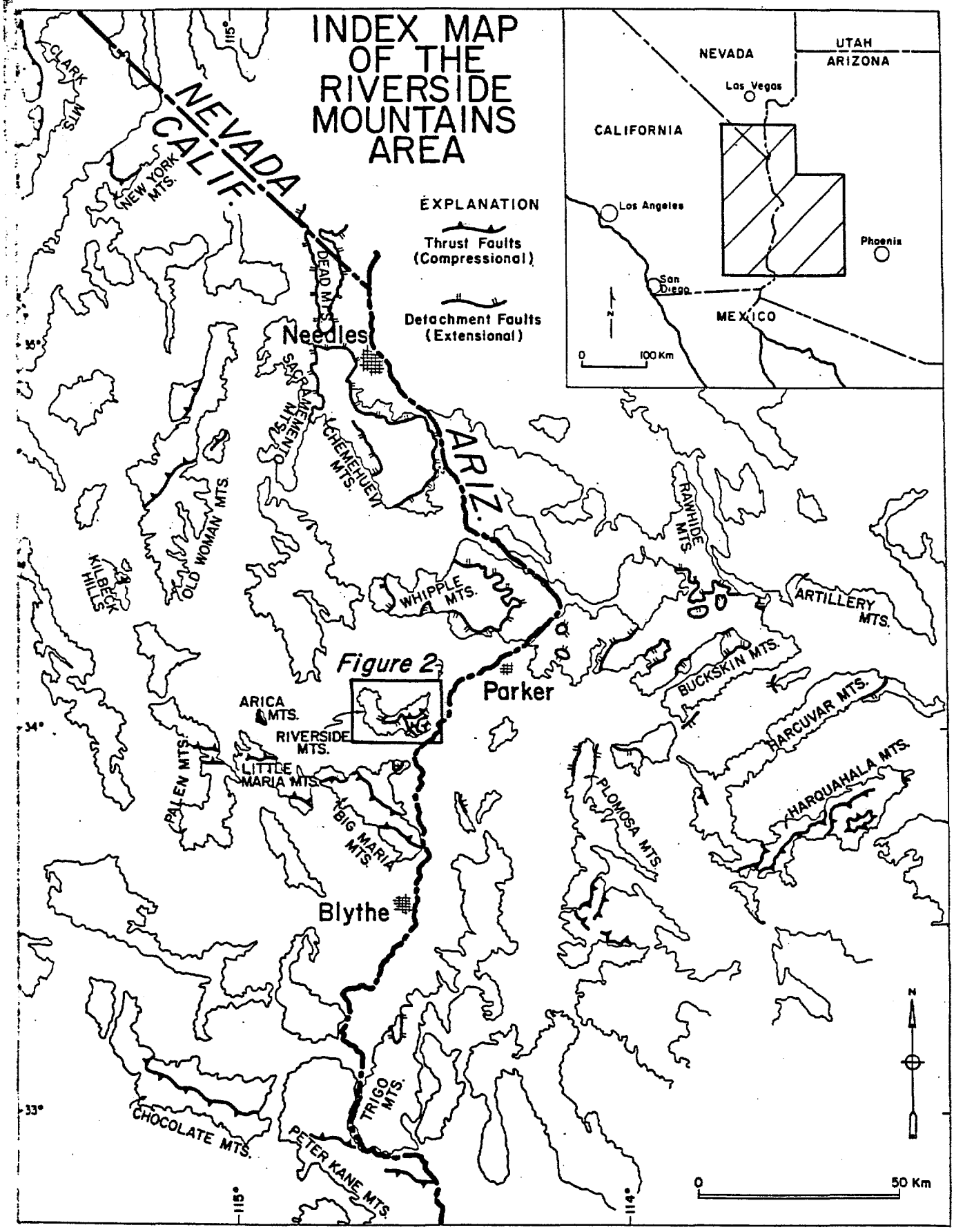

Figure 1. Index map of the location of the Riverside Mountains, California and their relation to low-angle faults of compressional (thrusts) and extensional (detachment) origin in adjacent areas (for thrust faults, sawteeth are on the hanging wall, for detachment faults, prongs are on the upper plate).

this volume), Baker Peaks - Copper Mountains (Pridmore and Craig, this volume), and Castle Dome Mountains (Gutmann, 1981, this volume; Logan and Hirsch, this volume). Detachment faults or detachment-related deformation is also present in California in the Big Maria Mountains (Hamilton, this volume; Ellis, 1981; this volume) and Midway Mountains (Berg and others, this volume).

Previous Studies In The Riverside Mountains

Previous geological studies of the Riverside Mountains of southeastern California are extremely limited. Gold was discovered in the Riversides in 1898 and active mining continued in several underground mines until about 1920. Mining resumed in the 1930's but again faded, leaving the extensive workings in the range in total disuse. Several short paragraphs have been published (Merril, 1919, 1929; Tucker and Sampson, 1945) in California Division of Mines and Geology's Report of the State Mineralogist in reference to the Bendigo or Riverside Mountains mining district. Most of these summaries describe the mining operations and conclude that ore bodies are replacement-type zones that occur along southwest-to northwest-dipping limestone-schist contacts. These tectonic contacts are host to gold, copper, silver and manganese mineralization. Some of the ore deposits described are "as much as 15 feet thick, and extend to depths of 200 feet." Brief mention is also made of extensive gypsum deposits, which are sporadically located throughout the range.

Hamilton (1964, 1971) has described isoclinally folded complexes of thrust sheets involving Precambrian basement interleaved with Paleozoic metasedimentary rocks, which are overprinted by Tertiary low-angle faulting in the southern portion of the range. Besides his 1964 map, which includes part of the southern Riversides, Hamilton has mapped the entire Riverside Mountains (Fig. 2) in reconnaissance fashion (unpublished mapping shown on the Needles 2° Geologic Sheet, Bishop, 1963).

Carr and Dickey (1976, 1977, 1980) and Carr (1981) describe stacks of imbricate thrust faults of Mesozoic and Paleozoic rocks on Precambrian basement in the Riverside Mountains. They label Hamilton's (1964) low-angle fault in the southern Riversides as the Whipple detachment fault. Carr (1981) and Carr and Dickey (1977, 1980) also suggest that Hamilton's interval of Coconino Sandstone in the Paleozoic section may be equivalent to the Queantoweap Sandstone of McNair (1951). They also defined a number of Mesozoic (?) units in their efforts to unravel the complicated structure of the range.

Recent work by Stone, Howard, and Hamilton (in press) in various ranges throughout southeastern California suggests that the metasedimentary section exposed in the Riverside Mountains probably correlates more accurately with the classic Paleozoic Grand Canyon sequence. Many of the units defined by Carr and Dickey (1980) are assigned Paleozoic formation names correlative with exposures in the nearby Big Maria Mountains (Stone and others, in press).

GEOLOGY OF THE RIVERSIDE MOUNTAINS

General Description

The Riverside Mountains are located approximately 50 km north of Blythe, California (Fig. 1). The range is horse-shoe shaped, with its open end facing north. This distinct morphology is a product of mid-Tertiary deformation, and the development of large-scale northeast-trending antiforms and synforms (see Figure 2, northeast-trending f_3- fold axes). A low-angle normal fault, or detachment fault, divides the range into two distinct structural provinces: an upper plate characterized by brittley distended Tertiary volcanic and clastic rocks, Precambrian basement, and minor occurrences of Paleozoic and Mesozoic metasediments; and a lower plate that reflects deep-crustal deformations with interleaves of upright and overturned Paleozoic and Mesozoic sequences between Precambrian crystalline units (Fig. 2).

Stratigraphy

The lithologic units within the Riverside Mountains are diverse and range in age from Precambrian crystalline rocks to recent alluvial deposits (Fig.3).

Precambrian Metamorphic Rocks

Precambrian metamorphic rocks exposed in the Riverside Mountains consist of quartzo-feldspathic metasedimentary rocks and a variety of granitic metaplutonic units similar to those described in the Whipple Mountains by Davis and others (1979, 1980). These units are highly deformed, locally migmatitic and are generally much coarser than Paleozoic and Mesozoic metasedimentary units found in the range. A large - body of the 1.4-1.5 byBP rapakivi granite (Silver and others, 1977; Anderson and other, 1979) is present on the southwestern side of the Riversides.

Paleozoic Metasedimentary Rocks

Paleozoic metasedimentary rocks are exposed predominately in the eastern Riversides. Although impressively deformed in most localities, the Paleozoic section remains relatively intact within individual, fault-bounded sheets. On a lithologic basis, the sequence correlates with the classic Grand Canyon sequence described by McKee (1976). Hamilton (1971) and Stone, Howard and Hamilton (in press) suggest that, although there are minor stratigraphic variations in Paleozoic sections exposed in the Riverside, Big Maria, Little Maria, Arica and Palen Pass areas in southeastern, California, a remarkable lithostratigraphic correlation exsists with the Grand Canyon section. Ductile deformation and greenschist-grade metamorphism have destroyed nearly all macro and micro fossils and make any accurate estimation of the original depositional thickness very difficult. The units are still lithologically distinct and therefore are of enormous aid in deciphering the structure of the range.

The base of the Paleozoic section in the Riversides is always in tectonic contact with either

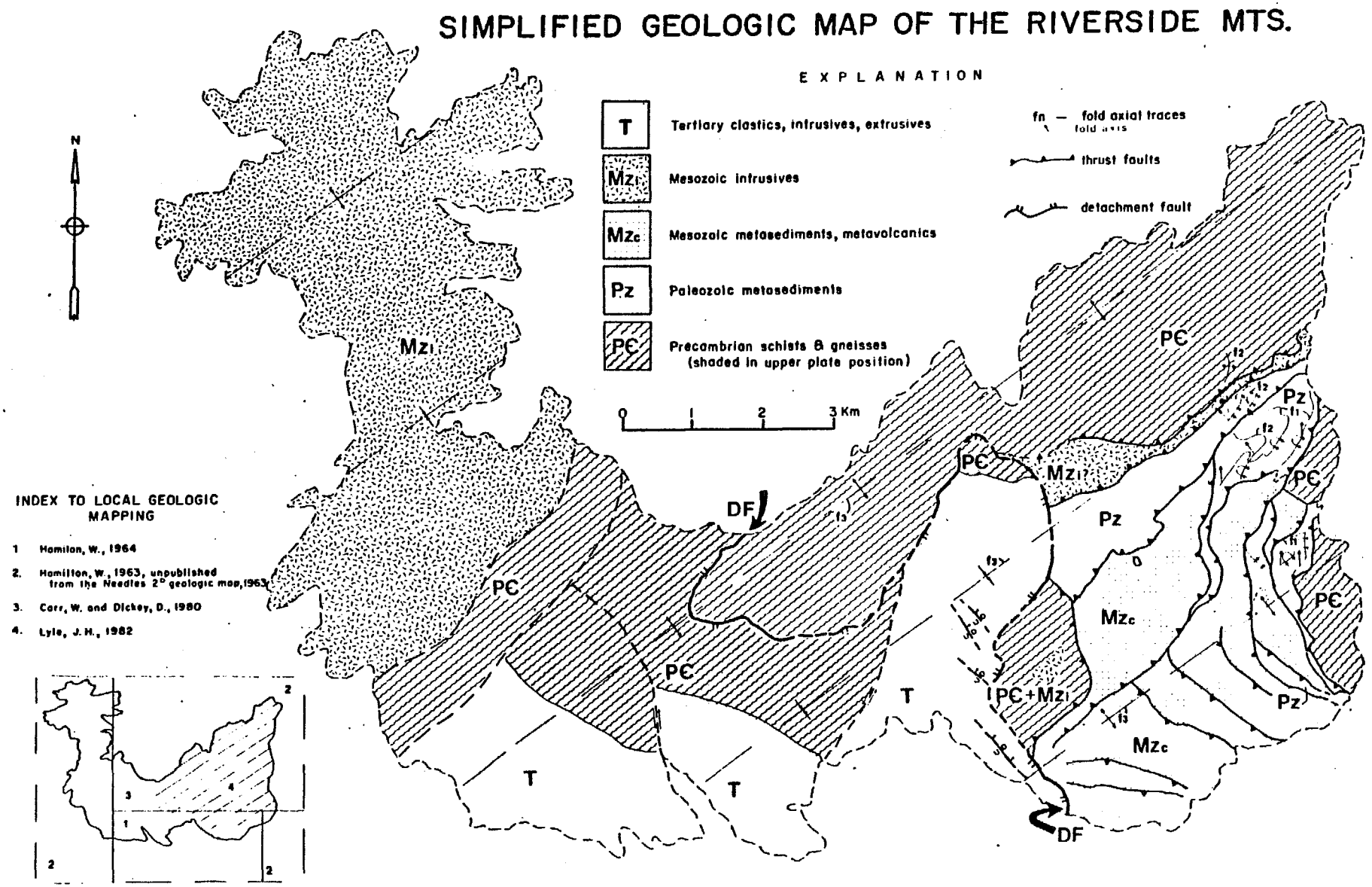

Figure 2. Simplified geologic map of the Riverside Mountains, California. Geology is characterized by two distinct tectonic domains: 1) an upper-plate terrane characterized by brittle Mid-Tertiary extensional deformation in conjunction with development of the detachment fault and f_3 antiforms and synforms, and: 2) a lower plate that reflects f_3 folds yet preserves multiple Mesozoic compressional deformations (f_1,f_2 fold sets) involving interleaves of upright and overturned limbs of Precambrian, Paleozoic and Mesozoic units.

Precambrian or Mesozoic metamorphic rocks. Both the Tapeats Sandstone and Bright Angel Shale were originally present, but are faulted out of the Paleozoic sections in most parts of the Riversides. Where they are exposed, these units are relatively thin, well-foliated micaceous quartzite and phyllite. They tend to be highly deformed with small-scale folding and are best recognized by their stratigraphic position between the Cambrian Muav Limestone and Precambrian crystalline rocks.

Overlying the Tapeats and Bright Angel is the metamorphosed Muav Limestone, which consists of mottled bluish-gray and yellow dolomitic and calcite marbles. Gradationally above this unit is a relatively thick section of massive, orange-brown dolomitic marble. Stone and others (in press) describe this unit and point out that is has no recognized nonmetamorphic equivalent in the eastern Mojave. Several workers have suggested that these thick (50-200 m) dolomitic marbles may represent the Cambrian Bonanza King or the Devonian Martin Formations.

Overlying these massive dolomitic marbles is a sequence of interbedded black-varnished quartzite and brown dolomitic marble, which is correlated with the Temple Butte Limestone. The quartzite and marble interbeds are consistently 5 to 15 cm thick, making this unit quite distinctive. This unit has not been recognized in neighboring ranges (Emerson, 1981; Ellis, 1981), but may have been removed along the unconformity that typically bounds this unit (McKee, 1976), removed by faulting, or simply not recognized.

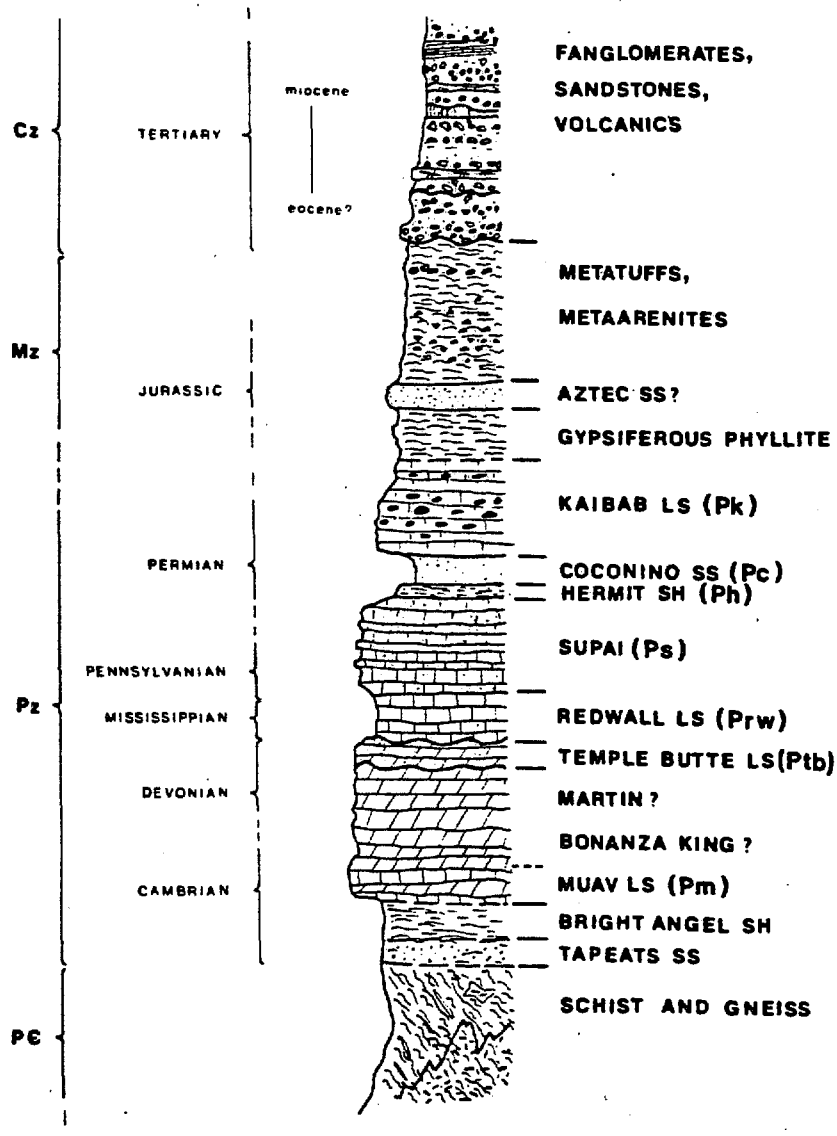

Figure 3. Diagrammatic stratigraphic column of nonplutonic rocks exposed in the Riverside Mountains area. Column does not necessarily suggest relative depositional thicknesses as exposures reflect Tertiary and Mesozoic deformation. Mesozoic metatuffs and metaarenites are undifferentiated. Tertiary units are exclusively upper plate (with respect to the detachment fault) and are undifferentiated.

Massive white calcite marble overlies the unit that has been described as Temple Butte. This calcite marble is extremely variable in thickness (0-60 m) due to pronounced attenuation by ductile flow, but is very distinctive because of its pure white color and coarse grain size. This white marble is interpreted to be the equivalent of the Mississippian Redwall Limestone of the Grand Canyon or the Escabrosa Limestone of southeastern Arizona.

Overlying the massive calcite marble is a unit composed of resistant, dark brown, massive, poorly bedded quartzite and calc-silicate layers. This unit is very diagnostic and typically forms steep, imposing cliffs. Of all the Paleozoic formations, this one maintains its thickness and identity the best. This formation is correlative with the Pennsylvanian and Lower Permian Supai Group of the Grand Canyon section.

Above the Supai Group is a greenish-white, porcelaneous, chloritic schist, which can be correlated to the Hermit Shale of Permian age. This unit has a maximum thickness of 5 m, but is usually much thinner.

A massive maroon and white orthoquartzite overlies the porcelaneous schist and is interpreted as the metamorphic equivalent of the Coconino Sandstone. The Coconino is a non-resistant unit that usually forms rubbly outcrops due to the penetrative fractures that characterize this unit. Large-scale cross stratification has not been recognized in the Coconino, probably because of the metamorphism and deformational overprint on the sedimentary fabric.

Overlying the quartzite is a white to gray, massive marble with local cherty and dolomitic horizons that can be roughly correlated with the Kaibab Limestone of the Grand Canyon area. The uppermost horizon is locally gypsiferous but this may be in part due to thermal remobilization of gypsiferous metasediments which directly overlie this unit described below.

Mesozoic Rocks

Mesozoic rocks exposed in the Riverside Mountains include a variety of metasedimentary metavolcanoclastic, and metaplutonic rocks as well as plutonic units (Hamilton, 1964; Carr and Dickey, 1980; Stone and others, in press).

Unlike the Paleozoic section, the Mesozoic section is not characterized by a "layer-cake" of diagnostic lithologies. Recent work by Miller (1981) in the Big Maria Mountains and adjacent ranges suggests that the Mesozoic section is extremely variable even on a local scale due to both original depositional patterns and later deformational events. Except for a gypsiferous phyllite and sericitic quartzite (described as Aztec Sandstone by Meitzner, 1981, in the Big Maria Mountains), which locally overlie the Paleozoic sections, only a general inference to the relative Mesozoic stratigraphy has been made in figure 3. The gypsiferous phyllite is a very enigmatic unit. In most areas, the gypsum does not appear depositional, but rather seems to have been remobilized or generated by later metamorphism and/or hydrothermal activity associated with sulfide mineralization. Sericitic quartzite (Aztec Sandstone?) that overlies the gypsiferous phyllite is locally present in Mesozoic sections. Above the locally present Aztec Sandstone (?) are undifferentiated metatuff, metaarenite, thin metadolomitic calc-silicate layers and thin (1 meter) metaconglomerates.

Quartz monzodiorite tectonites are found locally between thrust sheets (Fig. 2). These intrusives appear to have been injected synkinematically with thrusting and may have, in part, facilitated the low-angle motion along fault surfaces. Large (2-8mm) porphyroclasts are nested in a matrix of biotite, chlorite, orthoclase and smeared quartz.

Relatively nontectonized Mesozoic granite and quartz monzonite dominate the western Riversides as described by Carr and Dickey (1980, 1981). A K-Ar date of 98.5$\pm$4.0 myBP on the granites of the West Riversides is reported by Bishop (1963) on the Needles 2° Geologic Map.

Tertiary Rocks

The Tertiary rocks exposed in the Riverside Mountains consist of sedimentary breccia, fanglomerate, fluvial-lucustrine sediments and a variety of bimodal volcanic rocks (Fig.3). (Carr and Dickey, 1980; Hamilton, 1964). Stratigraphic sections composed of these units range in age from latest Oligocene (?) to Miocene and are exclusively found in an upper-plate position with respect to the detachment fault (Fig.2). In the lower plate, olivine diabase dikes, similar to olivine tholeiitic dikes described by Davis and others (1979) yield a K-Ar age of 26.3$\pm$0.8 myBP. A rhyolite intrusive plug also found in the lower plate intruding a thrust fault contact gave an age of 42.9$\pm$1.3 myBP.

Detachment Faulting

Geometry

The eastern Riversides are defined by a large, southwest-plunging arch (Fig. 4) with several minor superposed northeast-trending antiforms and synforms (see Figure 2, f_3 fold axes). This geometry is supported by the folded nature and exposed expression of the detachment fault along the southern flank of the range and the arched nature of the Mesozoic tectonite fabrics and thrusts. From geomorphic and structural data, the dominate fold axes trend N55°E. Small-scale (F_3) antiforms and synforms have wavelengths on the order of 2 to 4 km and amplitudes of 200 m. The large-scale folds likely have wavelengths and amplitudes an order of magnitude larger. Fold limbs dip variably from 0 to 40° depending on the relative distance from the axis of the central arch. The relative structural position of any feature on the major arch is quite important, therefore, for palinspastically removing the mid-Tertiary deformation. Northwest-trending folds in the Riversides are not pronounced so that they were not included in the palinspastic corrections.

Upper-Plate Kinematics

Upper-plate kinematics in detachment terranes of adjoining ranges all indicate that upper-plate distension is facilitated by northeast-dipping synthetic normal faults and accompanying southwest-dipping antithetic normal faults which effectively rotate units to the southwest while translating them to the northeast (Davis and others. 1979; Shackelford, 1979, 1980; Rehrig and Reynolds, 1980).

Figure 4. Southwest view of the eastern Riversides expressed as a gently southwest-plunging arch and exposed as a consequence of mid-Tertiary crustal warping.

Very similar structural characteristics are common in the upper-plate terrane of the Riversides. Striations on several northeast-dipping normal faults Fig. 5) that cut southwest-dipping Tertiary strata were measured and all (Fig. 6) indicate that the hanging walls moved to the northeast. In some localities where southwest-dipping upper-plate strata are truncated by the detachment fault, drag folds are present and suggest northeast translation of the upper plate (Fig. 7, 8).

Although upper-plate normal faults have not been traced across the entire upper-plate terrane because of recent alluvial cover, they must exist or the Tertiary section would be on the order of 5000 m thick.

Collectively, the kinematic indicators in the allochthonous upper-plate terrane (northwest-striking normal faults, northeast-trending striae on normal faults, southwestward rotation of hanging-wall strata, sense of northeast drag on strata against the detachment fault) consistently indicate that displacements along the detachment fault and coeval extension in the upper plate were to the northeast (N 25-65 E, ave. N 50 E).

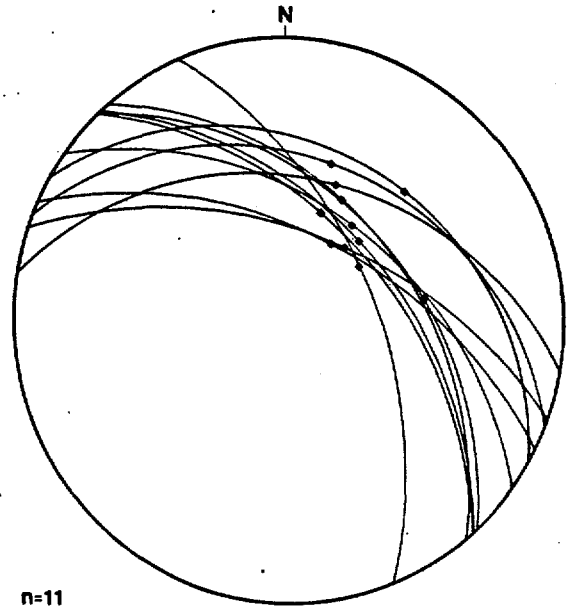

Figure 6. Equal-area stereographic projection (lower hemisphere) of upper-plate normal faults (great circles) with striations (diamonds) indicating hanging-wall kinematics to the northeast. Range of down-plunge striae strike are N25-65E with an average being N50E.

Figure 5. Typical upper plate normal fault surface displacing a silicified volcanic breccia. Slickensided mullions are parallel to striae (orientation of rock hammer) on northeast dipping synthetic normal fault, typical of those measured (Figure 6).

Figure 7. Tilted upper-plate Tertiary strata hydrothermally altered and discordantly in tectonic contact with a sub-horizontal detachment fault (Figure 8). Local drag folding of Tertiary strata against the detachment surface (deflected to the right) suggests upper plate translation to the left (northeast). Note Mark Adams for scale.

Figure 8. Exhumed detachment fault showing the polished and ledge-like detachment surface. The background just above the fault shows the hydrothermally altered fault breccia and illustrates the intense shearing commonly associated with detachment faulting (note scale on the foot wall).

Timing and K-Ar Resetting

The timing of detachment faulting in the Whipple, Buckskin and Rawhide Mountains immediately north of the Riversides (Fig. 1) is known from extensive K-Ar dating of upper-and lower-plate rocks Martin and others, 1980; Davis and others, this volume). Upper-plate units that are involved in growth-fault motion in the Whipples indicate that detachment faulting was well under way by 18 myBP and that it ceased about 13 myBP. The time of initiation of detachment faulting is not known, but is inferred to extend back at least to earliest Miocene-latest Oligocene time.

Tertiary units in the Riversides are lithologically similar to those described by Davis and others (1979, 1980) and suggest the same timing for detachment faulting in the Riversides as determined for the Whipples. One of the units involved in the upper-plate rotation has been dated at 23.5±1.0 myBP indicating that faulting was active after this time. The presence of the Peach Springs tuff in the Riversides Carr, 1981; Young, 1981), in a tilted, upper-plate position further indicates that detachment faulting continued until after the 17-18 myBP age of the Peach Springs tuff. The oldest unit not involved in detachment faulting is the latest Miocene-Pliocene Bouse Formation (Metzger, 1968; Smith, 1970; Carr and Dickey, 1980), indicating that faulting was over prior to Bouse time.

The timing of the formation of the antiforms and synforms can be inferred based on the Tertiary stratigraphic sections in the same way as the timing of detachment faults. In the Whipple Mountains, the older Tertiary units are preserved in the synclines with the younger units deposited across the already partially developed antiforms and synforms. The growth of the large-scale antiforms and synforms appears to have occurred at the same time as detachment faulting, during at least most of Miocene time (Frost, 1981; Otton and Dokka, 1981; Frost and Otton, 1981).

This same timing is inferred for the Riversides, where the preserved Tertiary section is much smaller. In addition, the culmination of crustal warping is interpreted to have post-dated the last recorded movement of the detachment fault. This is suspected because of the lack of evidence supporting any divergent radial movement of upper-plate rocks about the developing antiform. Therefore, it seems unlikely that the maximum amplitude of the presently exposed antiform could have been reached during detachment faulting.

The use of K-Ar dating on detachment faulting has proven to be a powerful tool for analyzing the presence or absence of the mid-Tertiary extensional deformation. Recent work by Krummenacher and Martin (Martin and others, 1980; 1981 a,b, and c) in the Whipple-Buckskin Mountains and several other ranges in the lower Colorado River region has shown that pronounced isotopic resetting appears to be characteristic of detachment faulting. Dates of samples taken in the lower plate show a progressive younging toward the detachment fault, indicating that isotopic resetting is associated with the faulting. Where adjacent lower-plate rocks are mylonitic, resetting yields ages as young as mid-Miocene on a regional basis. Where the rocks are nonmylonitic, resetting appears to be to a lesser degree and gives early to mid-Tertiary and older ages. The degree of resetting appears related to several factors that include thickness of the zone of brecciation along the fault and the degree of hydrothermal activity along the fault (Martin, pers. comm; 1981).

In the Riverside Mountains, nonmylonitic rocks just below the detachment fault with near absence of any brecciation give ages of 36-38 myBP, while rocks further away from the detachment fault (up to 100 m) give ages of 60-120 myBP (Martin and others, 1981; this volume). These ages suggest that only partial K-Ar resetting has occurred in the Riversides. This is consistent with the geologic characteristics (nonmylonitic nature and absence of major brecciation) of the Riverside detachment fault and is similar to that seen in other ranges with nonmylonitic lower plates (Martin and others, 1981, this volume).

Pre-Detachment Thrust Faulting and Folding

General Statement

Lower-plate units in the eastern Riversides record multiple episodes of deep-crustal compressional deformation. Calcite-epidote-tremolite-quartz to albite-epidote-actinolite mineral assemblages in the calc-silicates are common in the Paleozoic section. These assemblages indicate middle greenschist grade metamorphism at physical conditions of 350-450°C and P_{H_2O} values from 2-7 Kb as suggested by Winkler (1978). These parameters suggest minimal depths of metamorphism at 7-12 km. The ductile behavior of the Paleozoic strata and the formation of metamorphic tectonites suggest that metamorphism accompanied deformation.

The lower-plate Mesozoic deformational history can largely be divided into two distinct episodes of folding (see Figure 2: f_1, f_2 fold axes) and thrusting on the basis of superposed large-and small-scale folds and other structural elements, and the deformational characteristics of the superposed tectonite fabrics. These studies include using kinematic indicators such as fold axes, fold asymmetries, axial surfaces, and synkinematic lineations, all associated with the thrust faults. Palinspastically removing the mid-Tertiary synforms and antiforms is of tremendous assistance in interpreting these Mesozoic kinematic elements.

F_1 Folds and Associated Structural Features

Multiple folding and thrusting events have made structural relationships very complex in the Riverside Mountains. Northeast-verging folds (f_2) are most conspicuous in Mesozoic, Paleozoic and Precambrian rocks but detailed mapping and structural data indicate that these folds refolded and thrust earlier-formed (f_1) folds (Figs. 2,9,10,12).

Large-scale f_1 folds are generally recumbent except where axial surfaces dip to the west associated with west-dipping thrusts (Fig. 10). Most of the north-northeast striking thrusts shown on Figure 2 are related to f_1-thrusting. This can also be inferred because the orientations of north-east trending structures are relatively unaffected by mid-Tertiary related folds since they also trend northeast.

THE MIDWAY MTNS

This range consists mainly of Precambrian (?) metamorphic rocks faulted against mid to late Tertiary volcanic and volcaniclastic rocks of the Palo Verde sequence. The fault has been interpreted as a detachment fault in the attached article by Berg and others, (1982). We will critically examine the characteristics of this fault zone in the light of our past observations. The structure controls the localization of manganese mineralization along it and in cross fractures. The objective of this stop is to show that care must be taken in interpreting detachment structures both in the field and from the literature.

MID-TERTIARY DETACHMENT FAULTING AND MANGANESE MINERALIZATION IN THE MIDWAY MOUNTAINS, IMPERIAL COUNTY, CALIFORNIA

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ABSTRACT

Detachment faulting of late Oligocene to middle Miocene age has been recognized as a significant feature of the Cenozoic geology of western Arizona, southeastern California, and Nevada. Field studies have now shown that a detachment fault is present in the Midway Mountains of southeasternmost California. The Midway detachment fault separates the rocks of the Midway Mountains into an allochthonous upper plate, and autochthonous lower plate. The two upper plate rock units in the Midways are an andesitic member of the Oligocene to Miocene Palo Verde volcanic sequence and the Miocene Tolbard fanglomerate. The upper plate has been extended along northwest-striking, northeast-dipping normal faults that transported upper-plate fault blocks to the northeast. Regional folding of the fault surface has warped the Midway detachment fault into its present domal form. The Midway detachment fault can be correlated to similar faults exposed to the northeast in the Trigo Mountains of western Arizona, and to the west in the Chocolate Mountains of California. In the Midway Mountains, deposits of manganese oxides are localized along the detachment fault as well as along normal faults within the upper plate. Psilomelane, pyrolusite, and manganite are the most common manganese minerals present.

INTRODUCTION

The Midway Mountains are located in the northeastern corner of Imperial County, California, approximately 50 km east of Brawley and 35 km south of Blythe. Neighboring mountain ranges in California include the Palo Verde Mountains to the north and Chocolate Mountains to the west with the Trigo Mountains of Arizona to the east of the Midways. The easiest access to the range is along a jeep trail off California Highway 78 between mile marker 67 and 68. This jeep trail extends for 10 km back into the range (Fig. 1), and connects with numerous other, more primitive roads.

The first geologic studies in the Midway Mountains were done by Jarvis B. Hadley (1942), a Survey geologist interested in the manganese deposits of the Paymaster mining district. Subsequent work was completed in 1960 by Southern Pacific Land Company geologists Danely, Gamble, and Gardner in their mineral evaluation of the area (Gardner and others, 1960). The purpose of their study was to determine if any potentially economic deposits were present on the Southern Pacific land holdings. They did not attempt any structural or regional interpretations of the geologic features of the range. In their reconnaissance mapping of the area, they considered the detachment fault of this study to be a

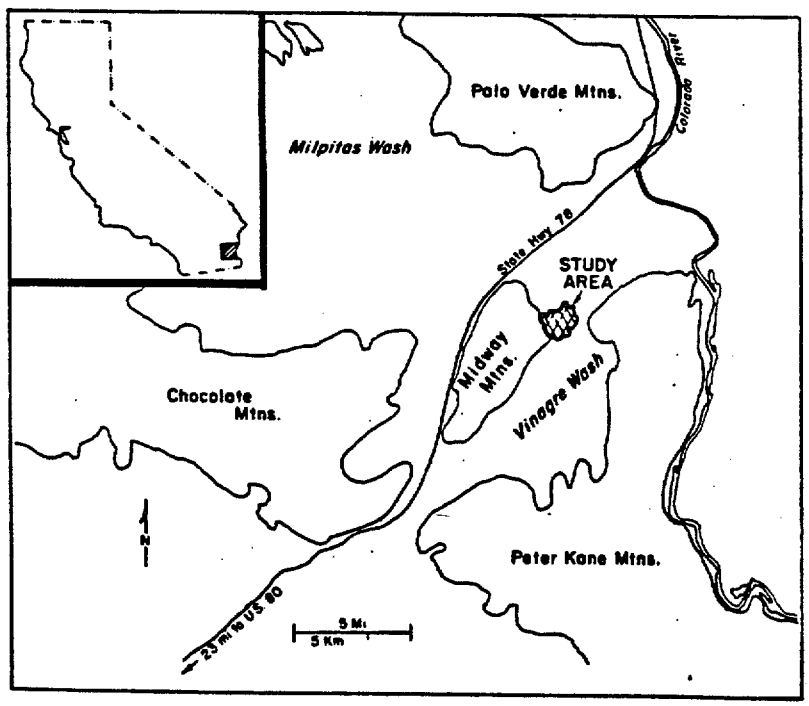


Figure 1. Major geographic features of the area adjacent to the Midway Mountains.

normal fault or an unconformity. Most recently, the Pioneer mine of the Midway Mountains was discussed by Morton (1977) who described the history of the mining operations.

Detailed study of the rock units and structure of the nearby Chocolate, Peter Kane, and Cargo Muchacho Mountains has been done by Dillon (1976), Haxel (1977), and Haxel and Dillon (1978). They defined the overall structural relationships of the Pelona-Orocopia schist and its overlying Precambrian crystalline complex. They have also mapped the contact between the two assemblages as the Orocopia-Chocolate Mountain thrust of Mesozoic age.

Study of the Tertiary volcanic stratigraphy was done in the adjoining Palo Verde Mountains by Crowe and others (1979). They described the volcanic rocks of this area as consisting of several major packages of differing lithologies and varying in age from Oligocene to mid-Miocene. The exact correlation of the Tertiary section in the Palo Verde Mountains to the Midway Mountains is not as yet known.

Much work has been done in the past ten years (1971-1981) to define the structure and extent of detachment faulting in western Arizona, southeastern California, and southern Nevada (Anderson, 1971, 1977, 1978; Schackelford, 1976, 1980; Davis and others, 1979, 1980; Rehrig and Reynolds, 1980; Frost and Martin, 1982). These workers have found that (1) the detachment fault appears to be of late Oligocene to middle Miocene age, (2) it is a tensional feature resulting from northeast-southwest crustal extension, (3) regional folding of the detachment fault occurred, producing antiformal ranges surrounded by synformal basins, and (4) the detachment fault separates the geology of this region into two separate structural units, a lower plate and an upper plate with an unknown amount of offset between the two.

The closest, previously described, exposures of detachment faulting to this part of California are in the Eagle Tail (130 km away, Rehrig and others, 1980), Harquahala (140 km away, Rehrig and Reynolds, 1980) and Riverside Mountains (90 km away, Carr and Dickey, 1980). Recently discovered exposures of the regional detachment fault are described in this volume by Garner and others in the adjacent Trigo Mountains, Logan and Hirsch in the Castle Dome Mountains, Pridmore and Craig in the Baker Peaks, and Mueller and others in the Mohawk Mountains. The Midway Mountains, thus, appear to be part of the regional continuation of the detachment terrane into southwestern Arizona and southeasternmost California. As such, they also appear to have been affected by the same manganese mineralization as other parts of the detachment terrane, and as the Whipple Mountains (Ridenour and others, this volume).

LITHOLOGIC UNITS

Lower-Plate Rock Units

The rock units in the Midway Mountains can be divided into lower-plate units, upper-plate units, and younger units that postdate detachment faulting.

The oldest lithologic unit exposed in the Midway Mountains is the Chuckwalla complex, of Morton (1966), which is a Precambrian metamorphic suite, that is probably about 1.7 billion years old. This metamorphic-igneous complex consists of quartzdiorite gneiss, foliated hybrid granitic rock, schist, and fine-grained granitic rocks, all of which have been intensely folded and faulted. Accentuating the folded appearance of this unit are metamorphic segregations of quartz, feldspars, micas, and hornblende into distinct mineral bands. The metamorphic rocks grade without apparent intrusive contacts into the granite gneiss and into locally structureless, gray, biotite granite. Variably developed lineations within this unit trend northeast (Gardner and others, 1960), but are not associated with a mylonitic fabric. No mylonitic rocks appear to crop out in the lower plate of the Midway Mountains, although they are exposed in nearby mountain ranges (Crowell, 1981).

In the Midway Mountains pegmatite dikes of Cretaceous age (?) cut the lower-plate, metamorphic-igneous complex. The pegmatite dikes have not been foliated and place an upper limit on the deformation present in the rocks of the lower plate. Similar types of pegmatitic dikes pervade nearby ranges such as the Big Maria Mountains (Hamilton, this volume; Martin and others, this volume) and Trigo Mountains (Weaver, 1982). In both these ranges the pegmatites are late Mesozoic in age, and suggest that the pegmatites in the Midways may be of the same age.

Upper Plate Rock Units

The oldest upper-plate rock unit in the Midway Mountains is an andesitic member of the Palo Verde volcanic sequence (of Morton, 1977). The rocks of this unit are red-black in color and are stained by manganese oxides in places. These volcanic rocks formed an autobreccia during their deposition. The autobrecciated nature was further accentuated by later deformation and appears to have played an important role in controlling the passage of mineralizing fluids. The rocks of this unit exhibit a porphyritic texture with elongated laths of plagioclase in an aphanitic groundmass. The thickness of the Palo Verde volcanic sequence is estimated to be 400 to 500 meters in the Midway Mountains. In nearby mountain ranges this unit contains pyroclastic volcanic rocks along with tuff-breccia and mudflow-breccia, none of which are found in the Midway Mountains. The volcanic rocks in the Midway Mountains are probably Oligocene to Miocene in age on the basis of the regional occurrence of similar units (Crowe and others, 1979; Dillon, 1976; Keith, 1978). K-Ar age determination of the Midway volcanic rocks is under way.

Overlying the volcanic rocks in the upper plate is a younger sedimentary unit, the Tolbard Fanglomerate, which is Miocene to Pliocene in age (Danehy and others, 1960). It is well indurated, red-brown to tan in color, and is locally stained by manganese oxide deposits. This unit forms steep irregular slopes with massive, rounded summits. It is composed largely of subrounded to angular clasts ranging in size up to 60 centimeters. These clasts are set in a fine-pebble to coarse-sand matrix. The ratio of sand to clasts is roughly 1.0 to 1.5 with volcanic rocks accounting for seventy percent of the clast and crystalline rocks making up the remaining thirty percent. Lenses of coarse, crossbedded sandstone, 10 to 50 centimeters thick, are common throughout the formation. The Tolbard Fanglomerate is cemented by silica and hematite, with some secondary calcite cementation. Paleocurrent indicators within this unit such as channeling, trough crossbedding, and imbricated cobbles suggest transport toward the northwest. The high degree of variation from the mean of N30W may be

a function of the alluvial fan depositional environment and may be the result of flow dispersion across the former fan surface. A detailed study of the sedimentology of this unit is presented in the following paper by Jorgensen and others (this volume).

Younger Rock Units

Deposited unconformably upon all older rock units is the Pliocene-Pleistocene(?) Barren Mountains Group (Danehy, 1960). The two members of the Barren Mountains Group present in the Midway Mountains are the Arroyo Seco and the Vinagre Formation. The Barren Mountains Group is generally an undeformed, flat-lying fanglomerate containing clasts of volcanic and metamorphic rocks, some of which may be reworked clasts from the Tolbard Fanglomerate. In places, the Barren Mountain Group has been cut by northeast-striking, high-angle faults juxtaposing it against older rock units.

The Arroyo Seco Formation is a poorly consolidated fanglomerate, which contains crossbedded sand lenses with gravel to boulder-size clasts in a sandy matrix. This unit contains predominantly volcanic-rock clasts in most areas. Locally it contains over 50% metamorphic-igneous complex rocks, which give the unit a light gray color (Gardner, 1960).

The Vinagre Formation consists of subangular to subrounded, gravel to boulder-size clasts. The clast composition of the unit is 65% volcanic rocks, 25% gneissic and crystalline rocks, and 10% pegmatitic rocks. Small sand lenses also occur, with faint but fairly common crossbedding. These beds are usually flat-lying or dip very gently away from the range.

The youngest deposits are of Quaternary age and have been subdivided into an older and younger alluvial gravel deposit. These two units lie unconformably on all older rock units and largely obscure the contact between the upper and lower plate around much of the range. No faults are known to cut these younger alluvial deposits.

STRUCTURAL GEOLOGY

The Midway detachment fault separates the rock units of the Midway Mountains into upper-plate and lower-plate assemblages. The Midway detachment fault is well exposed along the northern flank of the range, but elsewhere is either eroded away or covered by younger sediments (Fig. 2). Its present outcrop pattern and the domal form of the range suggest that the Midway detachment fault was once continuous over the range but has since been removed by erosion.

Lower-Plate

Developed within the lower-plate rocks of the Midway Mountains is a chlorite breccia zone. This zone has a gradational lower boundary with a sharp, upper surface, which is the detachment fault. Rocks within this zone, which is up to ten meters thick, have been brecciated on both a microscopic and a macroscopic scale. The brecciation of the crystalline rock appears to have allowed for the transmission of large volumes of fluids through this zone, which leached and altered the rocks. Movement along the detachment fault seems to be responsible for the brecciation of these rocks. The combination of the leaching and chloritization of the lower-plate rocks near the detachment fault gives these rocks their

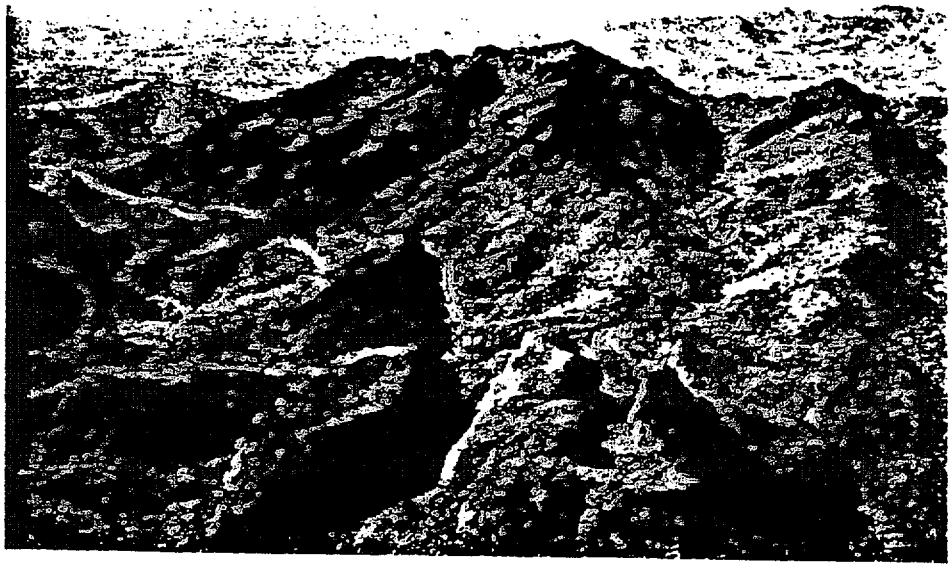


Figure 2. Oblique aerial view of the northern flank of the Midway Mountains. Lower-plate rocks of the Chuckwalla complex form the metamorphic core complex of the range. The upper-plate rocks (foreground) are the andesitic member of the Palo Verde volcanic sequence. Mining operations have exhumed portions of the detachment fault surface and removed over 50,000 cubic meters of material from the main ore body in the Palo Verde volcanic sequence.

Figure 3. A view of the lower plate where the detachment fault has been removed by erosion, showing the ramp surface as developed in the Midway Mountains. The line drawn in the photograph parallel the ramp surface.

Figure 4. (Below) One of many upper-plate normal faults in the Tolbard fanglomerate. The upper-plate normal faults generally dip to the northeast.

distinctive coloration with greens and dark reds dominating. Where the upper plate has been removed by erosion, the more resistant lower-plate rocks form what is referred to as the detachment ramps. By tracing the outcrop area of the ramp one can infer the trace of the detachment fault even though the fault surface has been removed by erosion (Fig. 3). The ramp appears to flatten near the top of the range and is steeper at the base. The unusually steep dip of the detachment fault (from 30° to 60°) as exposed near the base of the range, may thus not be characteristic of the overall attitude of the fault surface.

Foliation within the lower-plate rocks is truncated by the detachment fault as are Cretaceous (?) pegmatite dikes. The dikes do not share any of the foliation, indicating that the foliation-forming event was pre-pegmatitic and therefore pre-detachment faulting. The foliated fabric within the lower plate appears to have no genetic connection to detachment faulting and is probably Precambrian in age. Lower-plate extension in the Midways cannot be equated to the presence of a mylonitic fabric, since none is present.

Although the foliation is not mylonitic, it appears to define a pronounced domal form, much like that in ranges with mylonitic fabrics. This arched form is best seen in morning light looking west into the range. The development of the domal form of the Midway fault may be related to the development of large-scale folds during mid-Tertiary crustal extension (Otton and Dokka, 1981; Cameron and Frost, 1981) as described in better known portions of the detachment terrane. Superposition of two fold sets, one trending northeast and the other northwest, may have produced the mid-Tertiary uplift of the Midway Mountains.

Upper Plate

The dominant structural element of the upper plate in the Midway Mountains is a series of northwest-striking, northeast-dipping, high-angle normal faults, with dips from 54 to 60° (Fig. 4). Striae on the fault surface indicate many different movement directions, suggesting complex motion of the fault blocks during transport. On the whole, however, striae and mullion structures indicate a down-dip sense of motion. Tear faults perpendicular to the high-angle faults provide another kinematic indicator for the direction of transport, and suggest down-dip motion on the normal faults. Back rotation of the upper-plate into the detachment surface also suggests the same northeast (N70E) transport. Some upper-plate faults indicate other directions of transport but do not seem to have major offset across them.

Motion along upper-plate faults was probably coeval with motion along the detachment fault, as it is in other ranges (Davis and others, 1980) where the upper-plate structure is better exposed. The amount of offset across the detachment fault is unknown because the same units have not yet been identified from the two plates. If the upper-plate volcanic and sedimentary rocks reflect the full amount of extension, then the amount of extension does not appear great. Because the rocks of the Midways were transported relatively to the northeast, a great amount of transport does not seem possible because rocks in the Trigo Mountains moved to the southwest. These rocks in the Trigos lie along the direction of tectonic transport for the Midways and thus make it difficult to postulate large offsets during mid-Tertiary extensional tectonics.

Within the study area, faulting in the upper-plate has juxtaposed the andesite of the Palo Verde volcanic sequence with the Tolbard fanglomerate near the Midway detachment fault (Fig. 5). The andesite has the geometry of a tectonic slice between the fanglomerate and the metasedimentary rocks (Fig. 5). The tectonic slice is present near the hinge of the antiformal bend in the detachment fault. Intense shattering of the volcanic unit has apparently resulted from its motion along the detachment fault.

MANGANESE MINERALIZATION

History of Mining Operations

Mining operations to recover mangnaese in the Midway Mountains first began in 1917 and continued through 1918. During this period ore was recovered from the main ore body in the andesitic member of the Palo Verde volcanic sequence and had an average manganese oxide content of 46% by weight. Production resumed in 1941, continued throughout most of World War II and ended in 1944. The most recent mining operations in the Midway Mountains were undertaken as part of a federal stockpiling program, which was active between the years 1952 and 1959. More than 22,000 tons of ore were taken from the workings and averaged 43% manganese oxides by weight. During field work in the Midway Mountains in the fall of 1981, several claim markers dating from 1980 were observed, suggesting renewed interest in the manganese deposits.

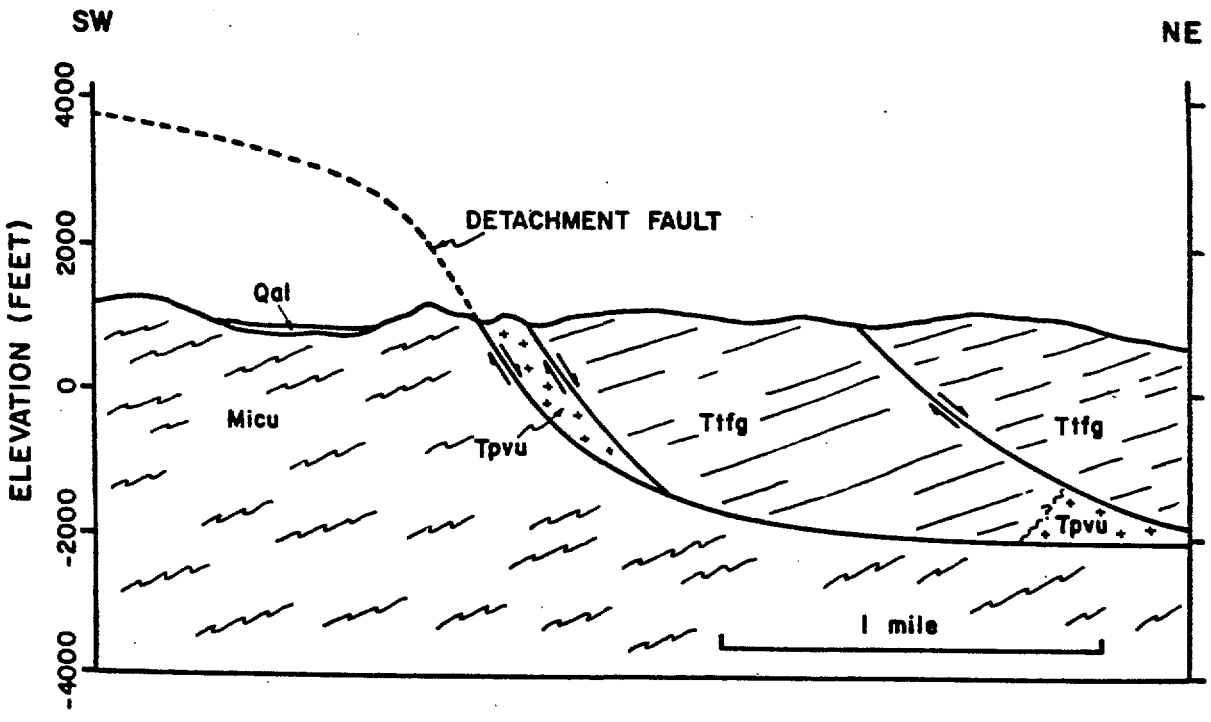


Figure 5. A generalized cross section of the Midway detachment fault separating the rocks into upper-plate units (Ttfg and Tpvu) and lower-plate units (Micu). Normal faults cut the upper-plate unit and sole into the detachment fault surface. Transport of upper-plate fault blocks is to the northeast. The detachment fault forms an antiform over the range.

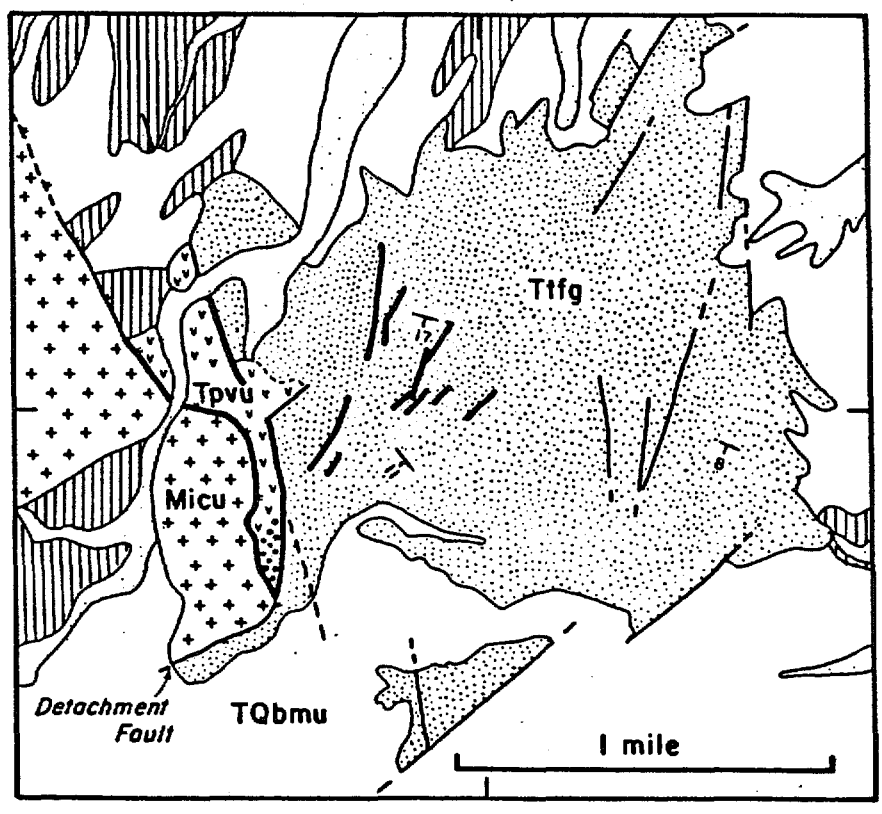
General Description of Manganese Deposits

Manganese mineralization in the Midway Mountains occurs as open-space filling of fractures and pore spaces, and as replacement mineralization throughout the brecciated rock adjacent to the detachment fault. Mineralization is confined to the upper-plate units of the detachment terrane and is concentrated in the fault zone directly above the detachment surface. Primary manganese mineralization does not occur in the Barren Mountains Group or younger alluvial deposits. The principal manganese minerals present in the Midway Mountains are psilomelane, pyrolusite and manganite with lesser amounts of braunite and ramsdellite (Hadley, 1942).

The main manganese ore body is located adjacent to the detachment fault in the upper-plate andesite (Fig. 6) and contains mostly psilomelane, pyrolusite and braunite. Manganese minerals are concentrated in veins that occur as hydrothermal fracture fillings within normal faults and associated stress fractures. Individual veins range in width up to 1.5 meters and extend for lengths of over 100 meters.

Two cuts have been extensively mined within the ore body, exposing excellent cross sections of the intensely fractured andesite. These cuts are 14 to 18 meters wide, 100 meters long, and were worked to a depth of 20 meters so that 32,000 cubic meters of material was removed from each cut (Morton, 1977). Large fragments of unbroken andesite are found within the more extensive veins. The degree of shattering in the andesite, thus, appears to be directly proportional to the degree of mineralization.

In the Tolbard fanglomerate, veins containing manganese mineralization follow both normal faults and fracture surfaces and commonly occur in mammillary or botryoidal structures on the fault surface. These faults have well-defined footwalls and brecciated hanging walls, the latter of which are considerably mineralized (Fig. 7). The veins range in width up to 2 meters and are up to 100 meters long. Mining operations within the Tolbard Fanglomerate consisted of working a series of drifts and raises with up to 20 meters of vertical section and 90 meters of horizontal section removed from individual veins in this manner. Within several of the larger stopes, this mining has exposed well-defined mullion structures on the footwall (Fig. 8). Manganese deposits are also present along small fractures that pinch out upward within the fanglomerate. Hydrothermal solutions responsible for the manganese mineralization thus appear to have radiated upward through the unit along zones of high porosity and permeability. The



Manganese mineralization along fault surfaces

Main manganese ore body

Figure 6. Geologic map of the northeastern flank of the Midway Mountains showing areas of manganese concentrations. Also indicated is the trace of the detachment fault.

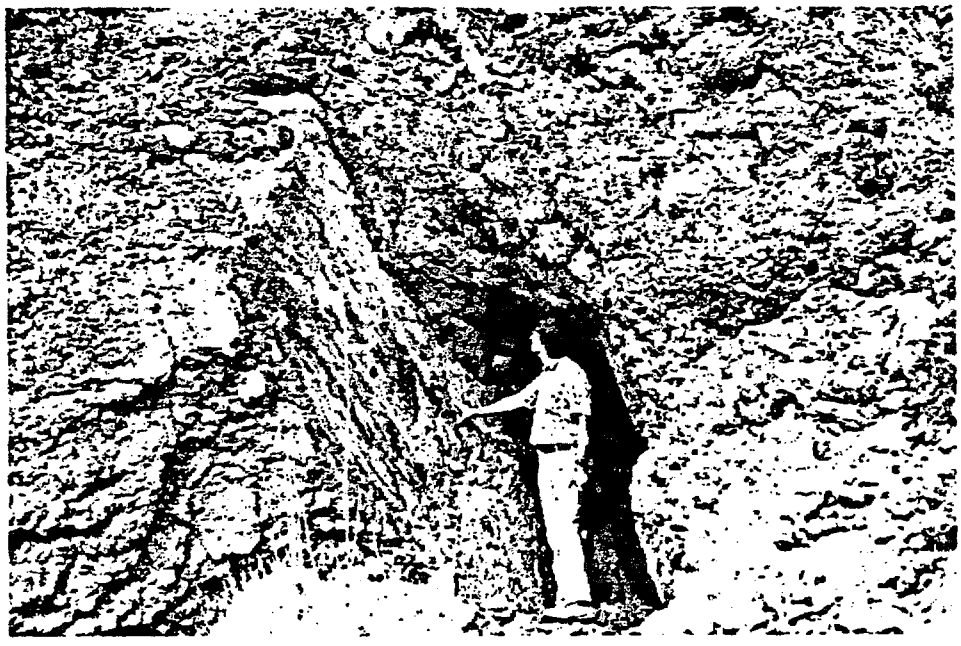


Figure 7. Northeast trending veins of manganese show well defined footwalls and gradational hanging walls.

Figure 8. (Below) Mullion structures apparent along upper-plate fault surfaces indicate normal movement.

brecciated fault zones and associated fractures apparently localized the passage of the hydrothermal fluids and suggest a through going plumbing system between most of the vein deposits.

Origin and Chemistry of Mineralization

Manganese oxide deposits in the Midway Mountains are thought to be hypogene fault deposits formed by hydrothermal processes (Fig. 9). Present-day hot springs are known to deposit manganese oxides and thus suggest that the Midway Mountain deposits are a product of the flow of hot springs through structurally controlled vein systems. The hot springs origin of these manganese deposits is suggested by both mineralogy and chemistry. Coarse grained white calcite, finely divided carbonates and chalcedony are the principal gangue minerals. This calcite forms a thin layer above the manganese and shows retrograde solubility. Magnetite is found in small veins within the main ore body as well formed crystals which commonly weather to hemitite.

Chemical factors such as pH, Eh and the concentration of dissolved manganese are important factors controlling the precipitation of manganese. Many meteoric waters plot in the acidic area of the Eh-pH field where iron oxides have a low solubility and manganese oxides have a high solubility. Manganese deposits are, therefore, common in volcanic associations because the metal is readily dissolved out of the rock by dilute acids. Where dilute acids are present, manganese will be dissolved, transported, and after passing the critical Eh-pH conditions necessary for the deposition of manganese, redeposited (Fig. 10). Although no fluid inclusion studies are yet available for the Midway Mountains, the pH of the transporting solution is inferred to have been in the acidic range.

The origin of manganese deposits in the Midway Mountains was influenced by several factors including the temperature of the hydrothermal solution that transported the manganese, the mineral composition of the rock unit from which the manganese was derived

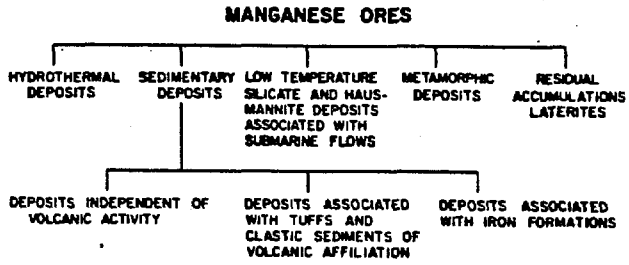


Figure 9. Genetic classification of manganese ore deposits. Deposits in the Midway Mountains are hydrothermal in origin (after Park, 1956).

and the behavior of manganese in solution. The depth of the detachment fault in Oligocene to middle Pliocene time could not have been greater than a few kilometers as determined by reconstruction of upper-plate structures. At such depth the temperature of the meteoric water, which is the proposed transporting agent of the manganese, would have been only 100 to 200°C. While hydrothermal solubility data is not yet available for this element, manganese oxides are relatively soluble at 25°C and should become even more soluble with a tendency toward increasingly more complex ion formation at higher temperatures (Crerar and others, 1980).

One possible source rock for the manganese is a mafic volcanic member of the Palo Verde volcanic sequence. As a generalization more-mafic, higher-temperature igneous rocks are decomposed at a greater rate by chemical weathering than their more-felsic, lower temperature counterparts. Manganese is generally more concentrated in mafic igneous rocks than in felsic igneous rocks (Wedepohl, 1980). Therefore, manganese is leached relatively rapidly from mafic rocks, and because it is also more concentrated in such rocks, these rocks may provide an important supply of the element.

Structural Control of Manganese Mineralization

Manganese mineralization and the development of ore bodies in the Midway Mountains were controlled by the structural features of the range, including both the detachment fault and upper-plate faults. Brecciation associated with the detachment fault and upper-plate faults appears to have created porous and permeable conduits for the hydrothermal solutions rising from below. Intense shattering within the andesite is probably largely responsible for the concentration of mineralization within the unit. The preferential shattering of the andesite is probably a result of both the brittle character of the unit and its structural position adjacent to the detachment fault.

Another, perhaps less obvious, structural control for the mineralization is the antiformal shape of the detachment fault. Where the main ore bodies are located in the Midway Mountains is in proximity to the hinge of the detachment-related antiform. If the mineralizing fluids were rising from below along the structurally controlled conduit of the detachment fault, they would have been concentrated near the crest of the fold. Flow of hot-spring waters would thus be concentrated from over the entire limbs of the folds to the hinge area. Precipitation of the mineralization is inferred to have taken place in this general hinge area.

The age of mineralization is indicated by the structural control of the ore deposits. Hydrothermal fluids were moving along the brecciated zones, requiring that mineralization is either coeval with, or post faulting. The widespread development of slickensided and striated surfaces that have involved mineralized rock further require that mineralization occurred before at least some of the deformation. Mineralization, thus, appears to have been at least in part contemporaneous with extensional faulting and rise of the Midway Mountains.

REGIONAL CORRELATION

The Midway detachment fault appears to be an isolated exposure of a much more extensive detachment fault, which extends over western Arizona, southeasternmost California, and Nevada. This wavelike fault surface is exposed on the flanks of several ranges in this region. In the Trigo Mountains of western Arizona, 18 km northwest of the Midways, a well developed detachment fault is exposed (Garner and others, this volume; Kitchen, pers. commun., 1981). The detachment fault is exposed as an antiform in the Trigos with a gentle synform between the Trigo and Midway Mountains (Fig. 11).

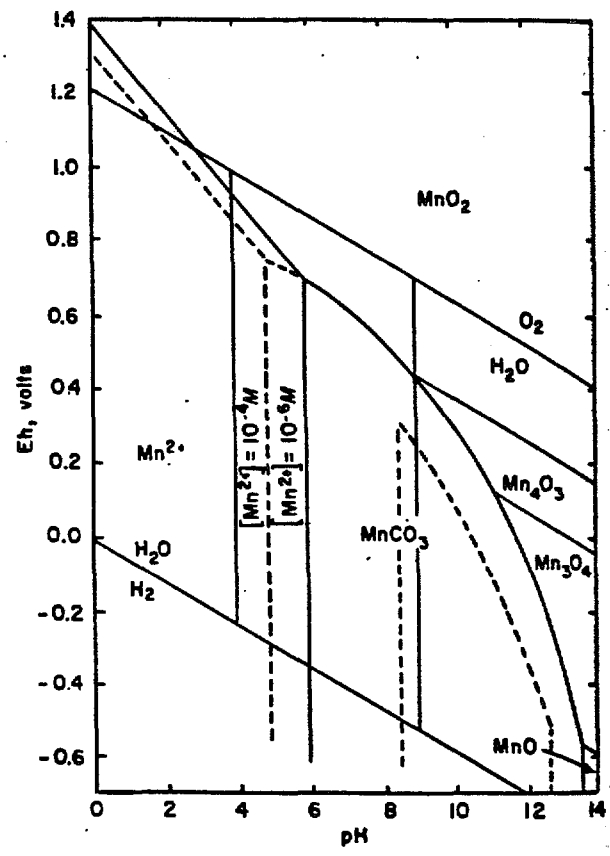
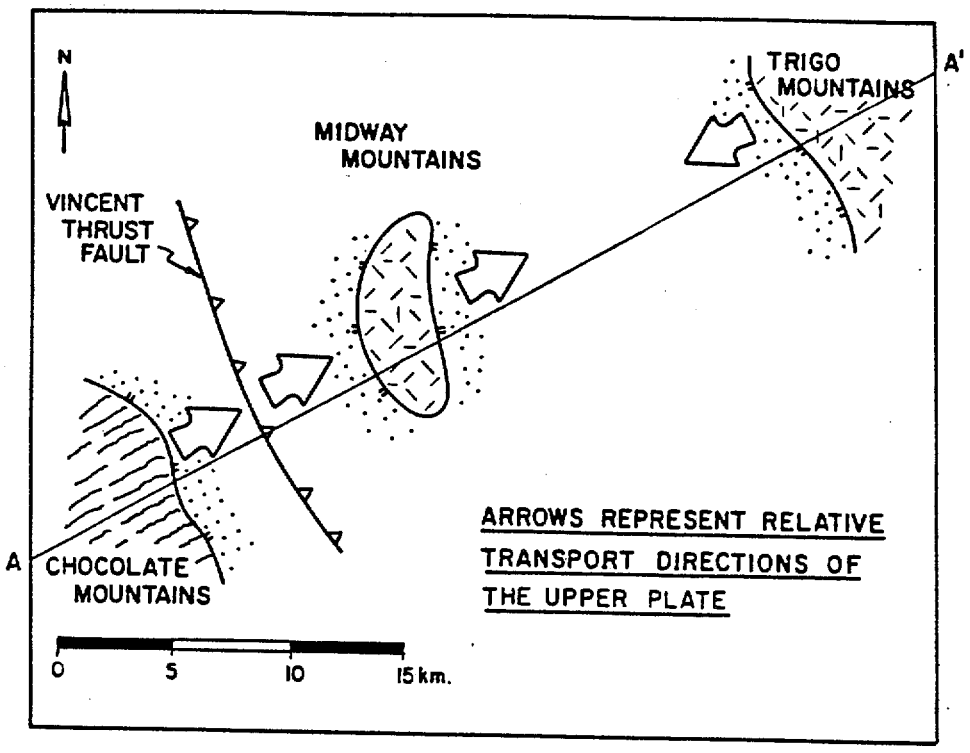


Figure 10. Eh-pH diagram showing stability fields of common manganese minerals. Assumed concentrations are: total dissolved carbonate, 1M; total dissolved sulfer, 10^{-6}M (after Krauskopf).



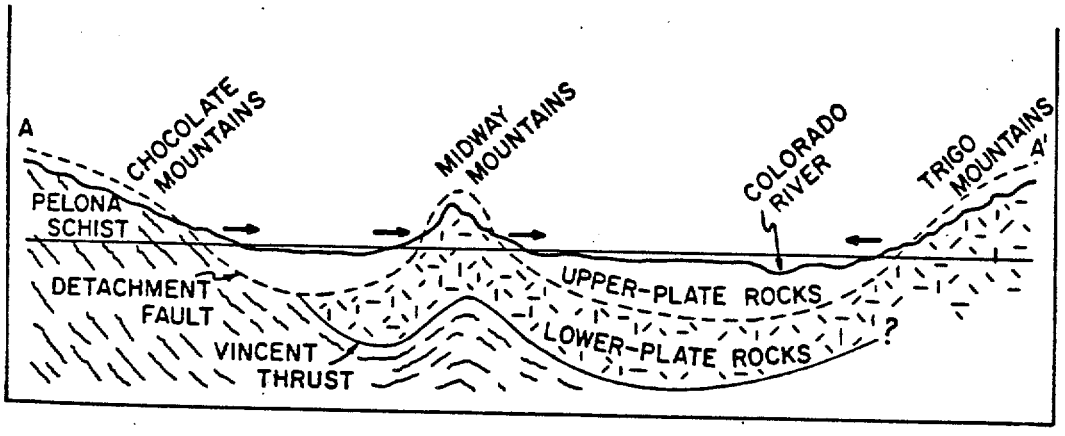


Figure 11. Schematical representation of the antiformal and synformal nature of the detachment fault between the Midway Mountains and the adjacent ranges (after Frost).

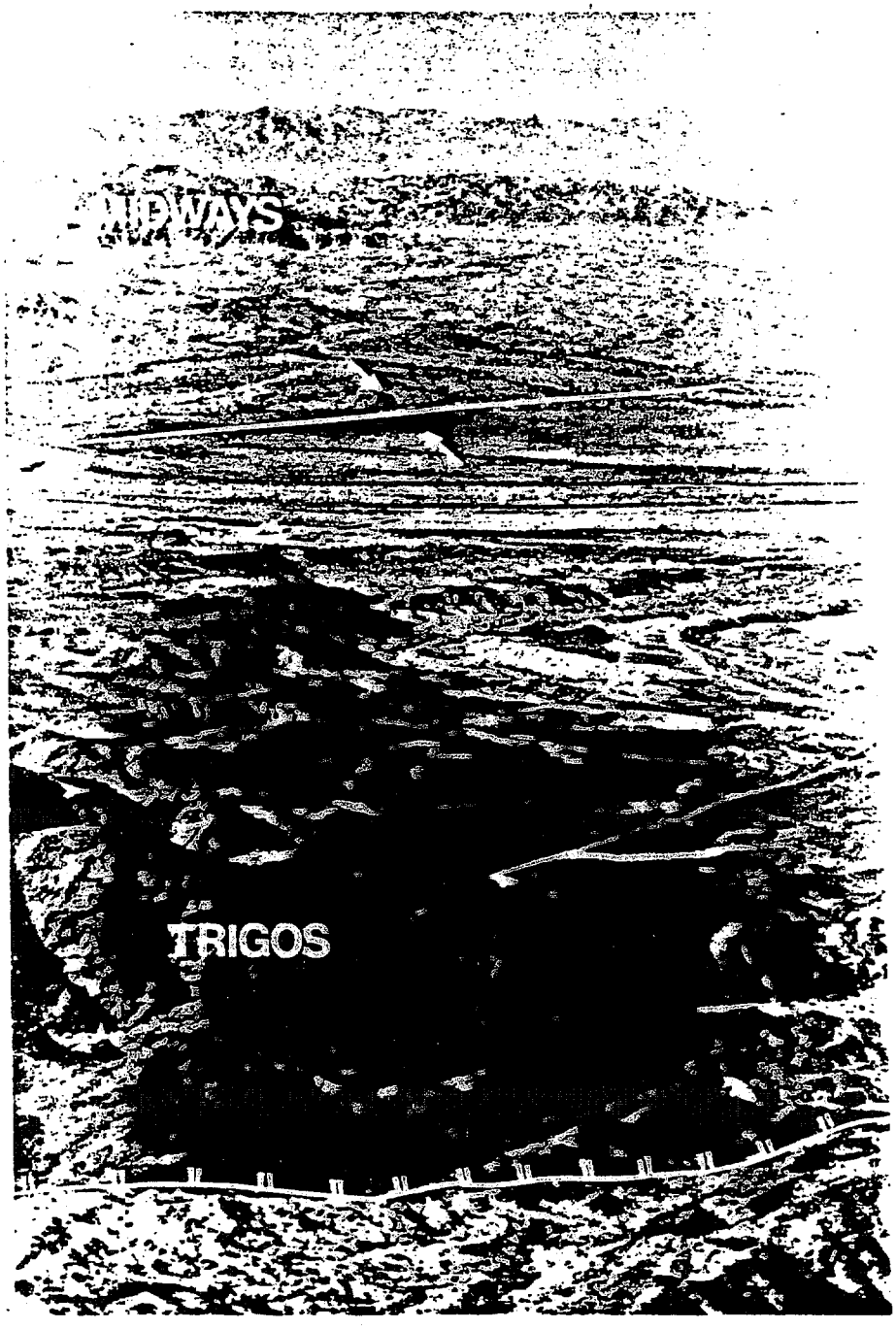


Figure 12. Southwestern view depicting that the detachment fault has been warped into antiforms in the Trigo Mountains (foreground) and the Midway Mountains (background). Between the two ranges is a corresponding synform in which the Colorado River currently flows.

The transport direction of the upper plate in the Trigos is to the southwest, opposite that of the upper plate in the Midways. These opposing upper-plate movement directions along the direction of tectonic transport may indicate that the upper plate has not been transported long distances. It may also indicate that individual fault blocks were essentially rotated in place during regional crustal extension.

In the Chocolate Mountains, approximately 10 km southwest of the Midways, an exposure of the detachment fault has been reported (Richens and Smith, personal communication, 1981). This contact was well mapped by Dillon (1976) as a normal fault that truncates tilted Tertiary volcanic rocks from underlying crystalline rocks. Correlating this normal fault in the Chocolates to the regionally developed, wavelike normal fault system would then indicate that the Chocolates have undergone detachment related deformation in mid-Tertiary time. Transport above this normal fault has been rather uniformly to the northeast as judged from the northwest strike and southwest dips of large packages of volcanic and crystalline rocks in this area (Morton, 1966; Dillon, 1976).

As defined by the mapping of Dillon (1976) and Morton (1966), the fault that may be the detachment fault is folded into several doubly plunging, northeast-trending antiforms and synforms. Also folded in this geometry is the Orocopia-Chocolate Mountains Thrust, which separates gneissic rocks from the underlying Pelona-Orocopia schist (Dillon, 1976; Morton, 1966, 1977). Correlation of these fold structures and the attendant detachment fault from the Chocolates to the Midways to the Trigos is depicted on a diagrammatic cross section in Figure 11. If this correlation is correct, then the Mesozoic Pelona schist and the Vincent thrust would also show this folding (Fig. 11).

CONCLUSIONS

Field studies in the Midway Mountains have defined the existence of Oligocene (?) to Miocene extensional deformation that appears to correlate with similar normal faulting seen on a regional scale. The major fault in the Midways appears to be a detachment fault, separating upper-plate volcanic and sedimentary rocks from lower-plate metasedimentary units. The domal form of the range exposes the fault, which is also well developed just across the Colorado River in the Trigo Mountains of Arizona. The folded character of the fault is similar to that seen elsewhere in the detachment terrane and suggests that correlative detachment faults may be present in the adjoining Chocolate and Peter Kane Mountains to the west and south.

Motion of the upper-plate volcanic and sedimentary rocks has been to the northeast along northwest-striking, northeast-dipping normal faults. Offset between individual upper-plate faults does not appear great. Offset on the detachment fault is unknown because of the mismatch of upper- and lower-plate units, the low relief, and the restricted area of this study. Because upper-plate units in the Trigos moved to the southwest, opposite and on line with the movement in the Midways, major offset across the Midway fault is probably not present(Fig. 12).

Manganese mineralization in the Midway Mountains was influenced by the presence of the detachment fault and upper-plate normal faults. Manganese-bearing solutions used the faults as conduits and precipitated manganese oxides along them. Psilomelane, pyrolusite and manganite are the principal ore minerals in the major manganese deposits within the Midways. Most mineralization occurs as either open-space filling of fractures or as replacement mineralization within the brecciated fault zones. Mineralizing fluids appear to have been controlled by the geometry of the detachment surface and reflect the paleohydrology of these hot spring type fluids.

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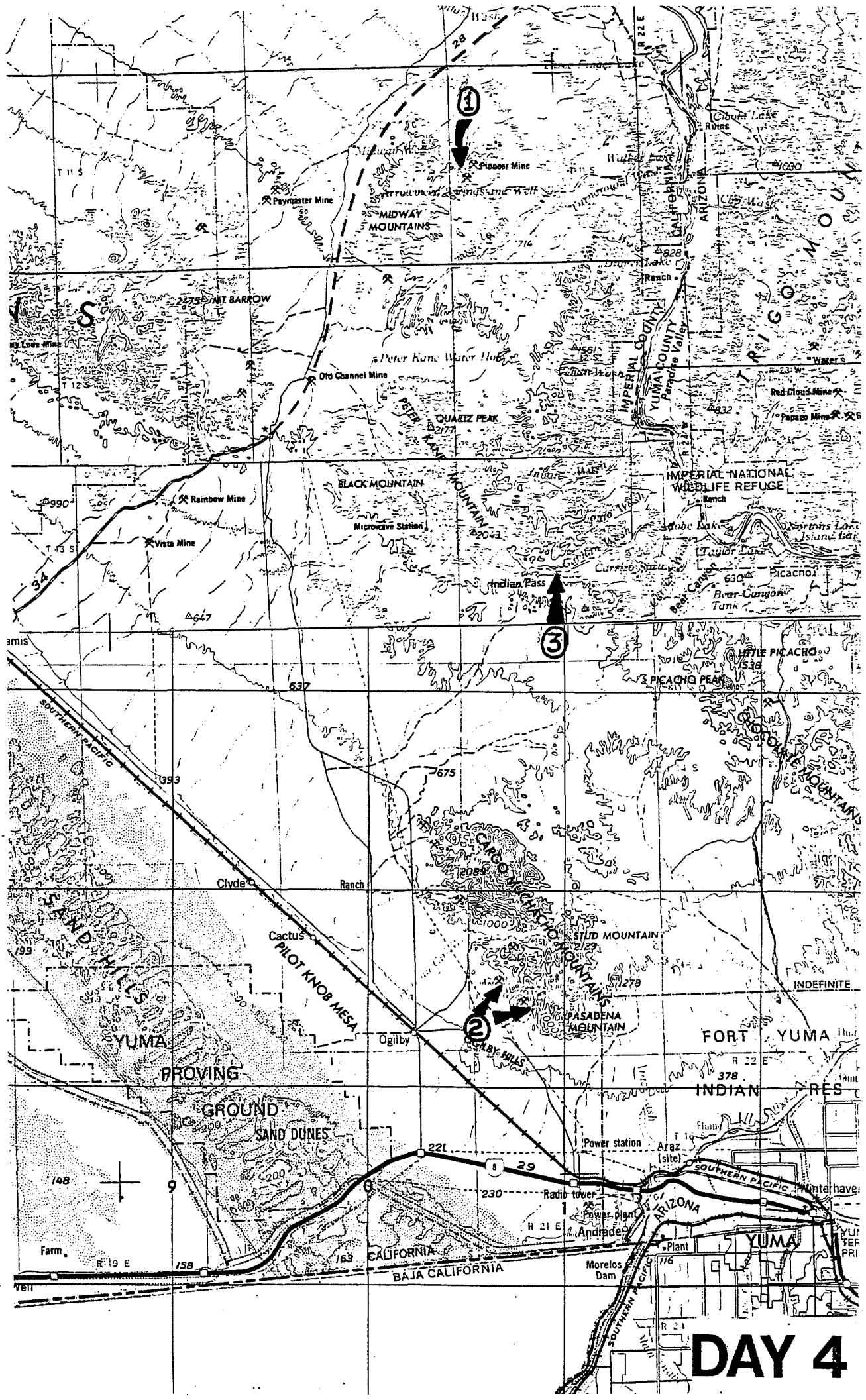

Pioneer Mine
Paymaster Mine
MIDWAY MOUNTAINS
MT BARROW
Peter Kane Water Hole
Old Channel Mine
QUARTZ PEAK
PETER KANE MOUNTAIN
BLACK MOUNTAIN
Rainbow Mine
Microwave Station
Vista Mine
Indian Pass
IMPERIAL NATIONAL WILDLIFE REFUGE
Picacho
LITTLE PICACHO
PICACHO PEAK
CARGO MUCHACHO MOUNTAINS
STUD MOUNTAIN
PASADENA MOUNTAIN
INDEFINITE
Clyde
Ranch
Cactus
PILOT KNOB MESA
Ogilby
SANDHILLS
YUMA PROVING GROUND
SAND DUNES
FORT YUMA INDIAN RES
Power station
Araz (site)
Radio tower
Power plant
Andrade
Morelos Dam
YUMA
CALIFORNIA
ARIZONA
BAJA CALIFORNIA
SOUTHERN PACIFIC
Farm

DAY 4

THE CARGO MUCHACO MOUNTAINS

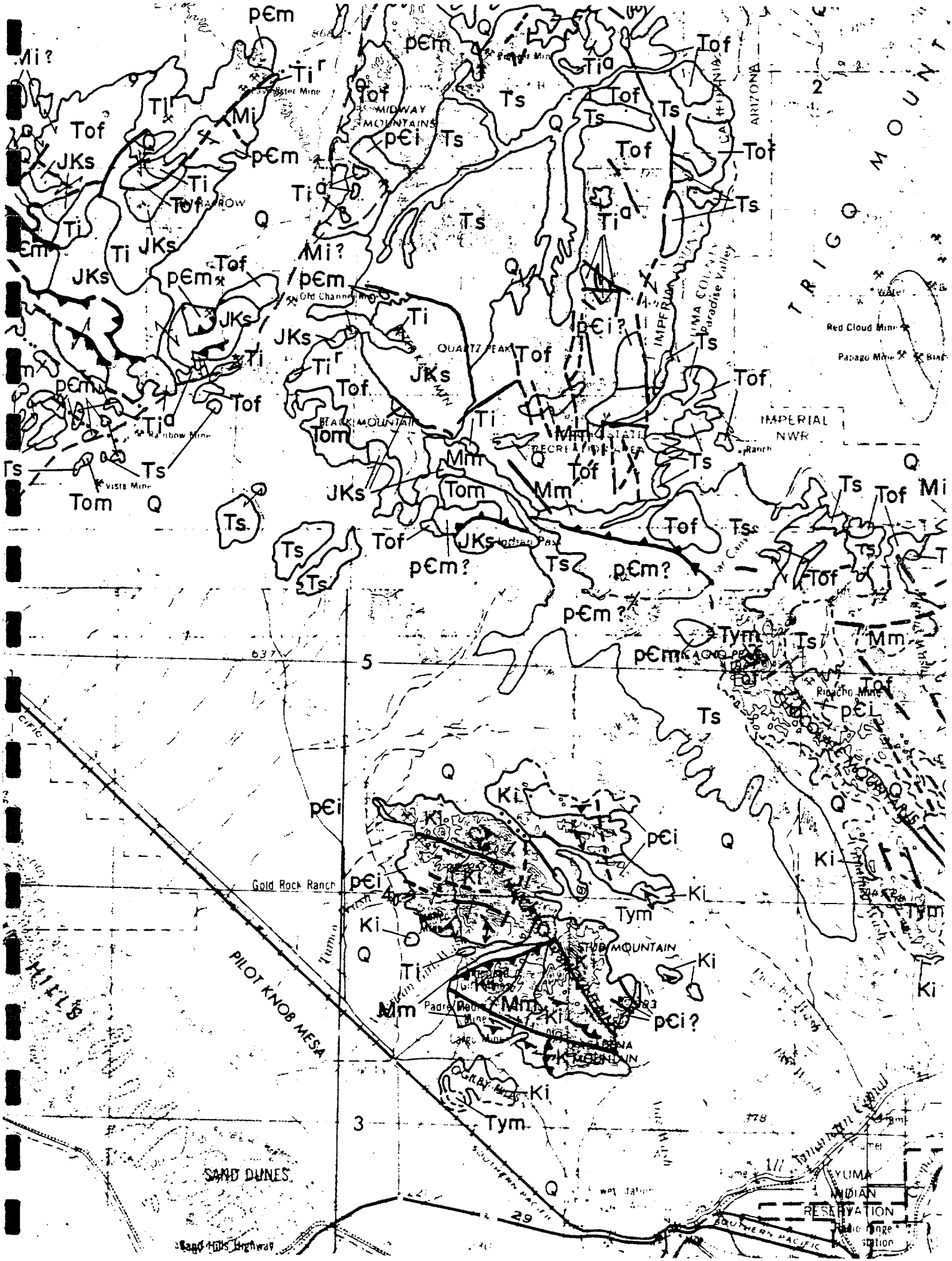
These rugged mountains consist of Jurrasic granitic plutons intruded into an unusual assemblage of metamorphic rocks. The plutons vary from diorite to granite. Most are deformed or foliated to varying degrees and some have interacted chemically with their wall rocks. Pegmatite dikes are abundant possibly as late phases of the main plutonic cycles. The metamorphic host rocks include the Tumco and Vitrifax Formations which mainly occur along the southern flank of the range and dip shallowly southward. Foliation in metamorphics and plutons is roughly conformable and indicates deformation or metamorphism post-dated intrusion.

The Tumco Formation is a thick sequence of meta-arkosites or graywackes which after metamorphism resembles a fairly uniform, foliated granodioritic looking rock. The Vitrifax formation consists of a meta-aluminous series of quartz muscovite schists which contain an exotic mineral assemblage of kyanite, dumortierite, tourmaline and in places, sulfides. The protolith for this formation is difficult to determine. It may have either been a highly pelitic sandstone or tuffaceous unit which has suffered hydrothermal alteration or leaching prior to metamorphism.

The entire igneous-metamorphic assemblage is cut by a series of low-angle thrust faults which occur structurally above the major Vincent-Chocolate Mtns. overthrust. In the Cargo Muchaco's one thrust places Jurrasic plutonic rocks upon Vitrifax Fm along the American Girl Fault and numerous thrusts can be mapped within the Tumco Formation.

Three major gold deposits occur in the Cargo Muchaco Mtns. The Tumco district at the west end contains gold, copper and minor tungsten mineralization in certain stratigraphic zones within the Tumco formation and along thrust zones. The American Girl and Padre Madre gold deposits are also tungsten bearing with relatively high base metal geochemistry. They are apparently controlled by the thrust zones such as the American Girl fault and to the south, the Padre Madre fault zones. We will examine the Padre Madre structures which generally seperate foliated dioritic rocks of the upper plate from biotite granite of the lower plate. Some have interpreted these structures as Tertiary detachment faults.

Time permitting, we will head north into the Chocolate Mtns. over Indian Pass to see an exposure of the Vincent thrust and lower plate Orocopia schist. There may be a superimposed relationship of detachment faulting in Gavilan Wash as well which we will want to evaluate.


p€m
Mi?
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Ts
MIDWAY MOUNTAINS
p€i
Tia
ARIZONA
CALIFORNIA
TRIGO MOUNTAINS
Red Cloud Mine
Papago Mine
IMPERIAL NWR
Paradise Valley
IMPERIAL RIVER
QUARTZ PEAK
BLACK MOUNTAIN
Tom
Mm
Rainbow Mine
Vista Mine
Old Channel Mine
Indian Pass
p€m?
p€i?
Tym
Ki
Gold Rock Ranch
STUD MOUNTAIN
PILOT KNOB MESA
SAND DUNES
Sand Hills Highway
SOUTHERN PACIFIC
YUMA INDIAN RESERVATION
Radio Range Station
Padre Mine
Quiney Mine
Rancho Mine
2
5
4
3
29

PHYSIOGRAPHY

The processes and the land forms produced by weathering and erosion under arid conditions have been analyzed in detail by Lawson, Bryan, and others.

Approximately a mile to the south of the range lies a compact group of hills which are completely traversed by valleys draining to the south. In a similar manner, at least one small valley cuts northeastward through the lower hills which lie to the northeast of the main range. These valleys must have been either superimposed or antecedent. Coupled with this phenomenon is the fact that in the southern portion of the range the valleys which drain to the north may be observed to be long, of gentle gradient, and relatively open in contrast to the short precipitous steep-walled canyons draining southward. Furthermore, the older types of alluvium stand as much as 75 feet above the present alluvial surface. Overlying this older alluvium are remnants of what may once have been a single flow of basalt.

All of these facts may be coordinated by hypothesizing that the streams flowing away from the range gained their courses on a cover surface of old alluvium or perhaps even on the basalt, and maintained these same courses as the subjacent rock was exposed.

GEOLOGIC AGE AND CORRELATION

No means are at hand for determining the exact geologic age of the rocks of the Cargo Muchacho district. The lithologic units are similar in nature to the rocks of adjacent areas which have been described, *e.g.*, Eagle Mountains, California, 80 miles to the northwest,[21] various mountains of southern Yuma County, Arizona,[22] Tinajas Altas, Tule, and O'Neil ranges[23] 50 miles and more to the southeast, and S. H. or Kofa Mountains[24] 60 miles to the northeast.

In each case the author cited admits that his dating of the rocks is based upon similarity of rock type and degree of metamorphism to corresponding features in rocks of known date of other areas. In no case was it possible to date by paleontological evidence or by direct continuity of outcrop.

The same lack of adequate evidence as to geologic age prevails in the Cargo Muchacho district. Accordingly the following tabulation of geological events is accompanied by hypothetical age assignments.

GEOLOGIC HISTORY

1. A great thickness of quartz sandstone and arkosic sandstone was deposited, either preceded or followed by the formation of limestone beds and silty quartz sandstone strata. Probably pre-Mesozoic.

2. A series of granitoid rocks intruded the area, commencing with quartz diorite in the south and terminating with leucogranite, aplite, and pegmatite in the north. Probably Mesozoic.

[21] Harder, E. C. Iron-ore deposits of the Eagle Mountains, California. U. S. Geological Survey Bull. 503. 1912.

[22] Wilson, Eldred D. Geology and mineral deposits of southern Yuma County, Arizona. Univ. of Ariz., Ariz. Bur. of Mines Bull. 134. 1933.

[23] Bryan, Kirk. The Papago Country, Arizona. U. S. Geological Survey, Water Supply Paper 499, pp. 58-59. 1925.

[24] Jones, E. L., Jr. A reconnaissance in the Kofa Mountains, Arizona. U. S. Geological Survey Bull. 620, p. 155. 1915.

3. Hydrothermal solutions accompanying the intrusions recrystallized the sediments, locally developing metamorphic minerals.

4. Shortly after the intrusion, the area was faulted by thrusts from the south. Solutions rose along the faults and mineralized part of the area.

5. Minor andesitic intrusion. Probably Tertiary.

6. Erosion almost to the present stage.

7. Deposition of old coarse boulder alluvium.

8. Deposition of fine rounded jasper and quartzite pebble alluvium.

9. Basalt flow. Probably Quaternary.

10. Erosion to the present stage and development of outwash alluvial deposits.

ECONOMIC GEOLOGY—METALS

GENERAL CHARACTER OF RESOURCES

Gold is the most important single resource of the region. In the past several large gold mines have been worked. At present all activity is restricted to a number of small-scale operations. Copper was produced along with the gold at the American Girl mine. Other mineral products of the district are sericite and kyanite.

STRUCTURE OF THE GOLD VEINS AND LODES

The gold deposits of the Cargo Muchacho district are all confined to the western side of the range. Although some mines are located in the far north and others in the far south, those in the Tumco Valley region have been most productive. All of the lodes have certain characteristics in common. They are all tabular bodies, usually associated with a definite footwall or a definite hanging wall, but rarely with both. All but three of the lodes trend east and west, parallel to the major thrust faults of the area. Locally, of course, strikes widely at variance with this may be found. Dips of the lodes are fairly limited in their scope. With extremes at 16°S. and 52°S., most of them lie between 20°S. and 40°S. The three major lodes which do not trend eastward are the easternmost mines of the district, the Pasadena, Guadaloupe, and Cargo Muchacho. They all trend roughly east of north and dip steeply to the east, parallel to some of the major north-trending faults of the area. Ore zones have been traced for considerable distance along the strike. Though the values may pass below an economic mining limit the structure continues. The same is true in following the ore at depth. Hence, the structure at any rate may be regarded as persistent.

The influence of fracturing on ore deposition is very important. Equally noteworthy is the close relationship between fracturing and rock type. Where a major fault traverses granite or quartz monzonite, the rock remains unfractured. On the other hand, a major fault in the metamorphic rocks or in quartz diorite shatters the rock. Though numerous prospects and even mines have been started on promising veins in the granite and in the quartz monzonite, none of these has ever proved valuable. Every mine in the district which has produced or is now producing gold on an economic basis occurs in metamorphics or quartz diorite. This influence of fractured country rock is brought

out strikingly in the case of the Cargo Muchacho mine, in which the vein was exceedingly rich wherever it lay in quartz diorite. Where the structure passed southeastward into the quartz monzonite, however, the values disappeared.

A low-angle fault, whether it be hanging wall or footwall, generally forms one limit to the ore. The other limit is usually determined by assay rather than by any structural feature. Nevertheless, the values seem to be concentrated in a definitely bounded zone. These zones are abundantly fractured, although often the fractures are microscopic. The amount of ore occurring as fissure filling is negligible. Almost all of the ore appears to have been deposited by replacement, although, of course, the ore-bearing solutions entered along definite fracture channels.

ORE SHOOTS

In most of the mines in the district the ore shoots appear to trend roughly northward, or northeastward as in the case of the American Girl mine. The shoots are broadly related to zones of approximately northward-trending fractures.

ORES

Two main types of ore are known from the Cargo Muchacho district. In the more common and more extensively worked, the gold is free milling. In the second and less common type, the gold is included in disseminated pyrite.

COMPOSITION AND VALUE

Gold (and its included silver) and copper are the only minerals extracted from the Cargo Muchacho district ores. In the mines from which free milling gold is obtained the values run from $15.00 to $150.00 per ton. The gold content of the sulfide ores, on the other hand, averages only $5.00 to $20.00 per ton. The copper content in this sulfide ore normally more than pays for freight and smelting charges on the concentrate.

MINERALIZATION

Mineralogy

Mineral species which occur, or are associated with, the metallic ore deposits of the Cargo Muchacho district are listed below. Brief mention of their occurrence is also given:

Gold: native gold

Silver: native silver

Copper: chalcopyrite
covellite
chalcocite
malachite
azurite
chrysocolla
cuprite
native copper

Iron: pyrite
magnetite
hematite
limonite

Lead: galena

Zinc: sphalerite

Gangue: quartz
calcite
sericite
biotite
chlorite
fluorite

Gold occurs (1) as microscopic grains disseminated through the country rock; (2) as wire gold and grains in quartz veins; (3) as microscopic grains in disseminated pyrite; and (4) as placer nuggets, grains, and colors. All of this gold contains some silver.

The only *silver* in the district occurs alloyed with gold.

Chalcopyrite, the most abundant of the copper-bearing minerals, occurs sparingly in the American Girl mine. It was probably the primary source for most of the oxidized copper which can be seen in scattered outcrops all over the district.

Among the supergene *copper* minerals are covellite, chalcocite, malachite, azurite, chrysocolla, cuprite, and copper, all in minor amounts.

Pyrite is the most abundant sulfide in the region. It occurs as a primary mineral in veins and in disseminated deposits.

Magnetite has been found occurring as a primary vein mineral in very small amounts at several isolated spots in the workings of the American Girl mine.

Hematite has been collected as shiny gray mirror-like plates from a number of mineralized veins throughout the whole district. It is most commonly found penetrating calcite crystals along their cleavage planes.

Limonite occurs in the oxidized zone wherever there has been mineralization.

Galena and small amounts of *sphalerite* have been identified as occurring along with chalcopyrite in the ores of the American Girl mine.

Quartz is the most abundant gangue mineral of the whole district. It forms the bulk of most of the vein deposits and is an important constituent in all disseminated deposits.

Calcite, and much less commonly *fluorite*, occur in minor amounts as gangue minerals in conjunction with most of the mineralization in the area.

Sericite and *biotite* occur in mineralized zones as small, fresh-looking crystals with subparallel orientation. They also occur in large micaceous lenticular masses locally along the main fault of the American Girl mine.

Chlorite is generally found in the mineralized zone in veinlets with calcite or quartz, though some of it appears disseminated.

The best opportunity to study the mineralization was provided by the American Girl mine. Consequently, the remarks in the following few pages are strictly applicable to that mine only, although they apply in general to the other prospects and mines.

Wall-Rock Alteration

The country rock in the American Girl mine has undergone considerable alteration by mineralizing solutions. The country rock has been somewhat sheared but the extent to which this shearing brought about mineralogical changes is not great, except perhaps in the close proximity of the shears themselves. This general but weak dynamic metamorphism may be observed persistently throughout the mine.

Locally, especially along the main fault, shearing stresses acting in combination with a small amount of introduced material succeeded in producing nonpersistent lenses of sericite.

To a later phase belong the solutions which produced the major alterations and metallization. Chloritization and sericitization are the most important types of alteration, particularly in the metamorphic rocks. Feldspars and some quartz have also been introduced into the arkosite. Areas of alteration of quartz diorite are rare.

The typical barren wall rock throughout most of the American Girl mine is green-gray, generally fine-grained but occasionally porphyritic, containing large gray to pink crystals of feldspar. The porphyritic variety of alteration is best observed in the footwall drift of the 500 level of the mine. In the hand specimen (C. M. No. 43) the nature and origin of the rock remain highly uncertain. In thin-section under the microscope, however, this wall rock is really identified.

Principal minerals:

Orthoclase, 35 percent, occurs in roughly rounded grains of small to medium size. It is partly altered to kaolin and in places very small flakes of sericite have developed in the crystals.

Microcline, 16 percent, small to medium-sized gray grains which are distinct from the large pink metacrysts described under alteration minerals.

Andesine, 3 percent, appears as small, rounded grains scattered throughout the groundmass.

Quartz, 30 percent, most commonly occurs as small rounded grains. Quartz also occurs to a very small extent as an alteration mineral.

Accessory minerals:

Include zircon, apatite, sphene, and topaz.

Alteration minerals:

Chlorite, 8 percent, is the only important dark mineral in the rock. Characterized by its ultra-blue abnormal interference color, it probably represents the variety penninite.

Microcline, 4 percent, occurs as large pink metacrysts which replace the earlier mineral grains indiscriminately. The metacrysts often bear inclusions of quartz and occasionally of the less common minerals.

Quartz occurs in one or two small veinlets penetrating the microcline metacrysts.

Calcite and pyrite are present as a few grains replacing the country rock.

Sericite and kaolin are developed to a small extent in the feldspars.

The rock was derived from an arkosic sediment, probably identical with Tumco arkosite. Hydrothermal alteration has changed the megascopic appearance of the rock considerably with little effect on its chemical composition and structure. Original dark minerals (probably mostly biotite) have been entirely chloritized. Microcline has been introduced or reworked in place to form medium to large-sized pink metacrysts. Minor amounts of quartz likewise have been introduced or reworked. A few grains of pyrite and calcite give evidence of the actual infiltration of mineralizing solutions. The sericitization of the feldspars may have occurred at the time of this later mineralization. (There is no proof of the time of sericitization in the wall rock under discussion. For evidence that sericitization may have been closely related to ore deposition, see below.) Kaolin in the feldspars may have been developed either by the action of supergene ground waters

or by hydrothermal action. Chloritized rock of the type described above is common in all of the workings of the mine whether in rich ore or barren waste, whether in hanging wall or in foot wall. The degree of intensity of chloritization decreases with increased distance from the ore-bearing area.

In contrast to the widespread weak chloritization of the wall rock is a localized and intensive alteration to sericite and biotite. This sericite-biotite alteration occurs in the American Girl mine only in areas in close proximity to the main fault or to minor subparallel faults. All of the wall rock which was altered in this manner constituted economically profitable ore. Perhaps almost half of the total ore of the mine was derived from these heavily metallized sericite-biotite alteration zones.

In the hand specimen (C. M. No. 45) the ore appears to consist of abundant euhedral pyrite crystals in a very fine-grained, dark-gray, indistinctive groundmass. Numerous fine stringers cut the rock. Under the microscope, it appears that none of the original minerals of the rock have been left unaltered, except perhaps apatite.

Accessory minerals:

Apatite, 1 percent, occurs in small, rounded grains, and is scattered all through the rock.

Alteration minerals:

Sericite, 57 percent, makes up the bulk of the groundmass. It is very fine grained and almost completely lacking in any crystal alignment.

Biotite, 30 percent, occurs in small, fresh-looking crystals with subparallel orientation. They are very rarely replaced or altered in any way.

Quartz, 2 percent, calcite, 4 percent, and chlorite occur in veinlets and also disseminated throughout the rock.

Magnetite occurs as a dust disseminated through the rock.

Pyrite, 5 percent, forms large euhedral crystals which cut across the other minerals, replacing rather than displacing them.

The magnetite as well as apatite may have been an original rock mineral, but it must have suffered recrystallization. All of the other minerals are the products of wall-rock alteration. From the nature of this highly altered specimen (C. M. No. 45) there is no clue to the original character of this ore-bearing rock.

Veins

In addition to the quartz, calcite, and chlorite veinlets which penetrate the wall rock, several strong veins occur in the American Girl mine. All of these major veins follow faults along which the wall rock is shattered on either side. The dominant vein mineral is quartz. Pyrite, chalcopyrite, galena, and magnetite have been observed in these veins. Vein pyrite is rarely in euhedral crystals, in contrast to euhedral pyrite in the altered wall rocks. Perhaps the sphalerite and pyrrhotite reported in the concentrates were also derived from these metal-bearing quartz veins. Pink orthoclase and deep purple fluorite have been occasionally noted in vein quartz. Most commonly the veins are massive and single, but occasionally they occur as composite veins or lodes. A few very thin veins have minor cavities and vugs lined with quartz and euhedral pyrite. Others contain calcite.

Metallization

Along with the wall-rock alteration there were introduced a number of metallic elements, mostly in the form of sulfides. All data on metallization was obtained from a report by the American Cyanamid Company.[26] The flotation concentrate includes pyrite, chalcopyrite, chalcocite, covellite, bornite, sphalerite, galena, pyrrhotite, magnetite, hematite, limonite, and gold.

TABLE 2

ASSAYS OF THE FLOTATION CONCENTRATE

	American Cyanamid Co.	Smelter
Gold	6.75 oz. per ton	6.88 oz. per ton
Silver		3.50 oz. per ton
Copper*	2.85%	3.05%
Iron	31.93%	30.50%
Sulphur	32.93%	32.50%
Lime		1.50%
Alumina		4.10%
Silica		20.60%
Insoluble	25.90%	

(* The percentage of copper in both samples is lower than average. 5% copper is usual.)

Assays of the different mesh sizes after screen analysis reveal that most of the values fall into the minus 325-mesh group. The minus 325-mesh contained 54.74 percent of the total gold, 70.65 percent of the copper, 45.81 percent of the iron, and 27.81 percent of the insoluble material.

Examination of the flotation concentrate under the microscope showed that the metallic mineral constituents occurred in both free and locked mineral grains. Pyrite was the most abundant mineral constituent. Most of the pyrite occurred in apparently free mineral grains. An appreciable proportion of the pyrite contained inclusions of other mineral constituents, especially chalcopyrite, sphalerite, limonite, and quartz.

Of the copper-bearing minerals, about 66 percent were chalcopyrite and about 34 percent were chalcocite, along with a little covellite and bornite. About 76 percent of the copper metal content occurred in apparently free mineral grains and about 24 percent occurred in locked mineral particles, especially as minute inclusions of chalcopyrite in pyrite.

Occurrences of gold were noted in free mineral grains and in locked particles. Locked gold particles 1 to 30 microns in diameter were most common in pyrite and chalcopyrite. Gold was also found both in limonite and quartz. The limonite was generally pseudomorphous after pyrite.

Four panner products and a slime product were obtained from a sample of the concentrate on a Haultain super-panner. These products were all assayed for gold, copper, iron, and insoluble material. Of the

[26] American Cyanamid Company. Ore Dressing Laboratory. Microscopical examination of a flotation concentrate from the American Girl Mine. Private Report. 1938.

gold, 21.94 percent was panned out as free gold. The panner iron concentrate assayed 6.04 oz. of gold per ton and carried 38.40 percent of the gold. The panner copper concentrate assayed 10.24 oz. of gold per ton and carried 17.82 percent of the gold. The panner tailing contained 4.10 percent of the gold, and assayed 1.32 oz. of gold per ton. In the slime portion of the sample was 17.74 percent of the gold. The slimes assayed 5.28 oz. of gold per ton.

The study of the ore minerals has not been carried far enough to permit detailed discussion of the paragenesis of the ore minerals. Since most of the gold occurs as minute locked particles in the pyrite and chalcopyrite, the interpretation that is placed upon these relationships (whether inclusion or replacement) will determine in a large measure the nature of any hypothesis of paragenesis.

A series of drawings made from photographs of polished sections of the concentrates[26] illustrates the nature of the occurrence of the metallic minerals and their relationships to each other (Fig. 15).

Omitting for lack of evidence any statement regarding the paragenetic relationships of gold and quartz, these drawings seem to show the following mineral paragenesis:

Earliest: pyrite
chalcopyrite
Latest: sphalerite

Relationship Between Wall-Rock Alteration, Veins, and Metallization

Surrounding the main fault and some of the minor faults of the American Girl mine lies an aureole of chloritized and feldspathized country rock. Bodies of rock highly altered to dense, fine-grained masses of sericite and biotite crystals occur in shoots and lenticular deposits in close association with the breaks. Almost all of the alteration took place in the arkosite wall-rock to the west of the American Girl shaft. Nothing beyond a little chloritization occurred in the quartz diorite which lies to the east.

Whether these two types of alteration represent successive stages or different phases of the same stage of mineralization, the metallization occurs dominantly with the sericite and biotite. Massive quartz veins, which occasionally carry inclusions of sericite-biotite ore, were deposited during the next stage. More pyrite and gold, along with the less common sulfide minerals and fluorite were deposited in the quartz veins. The exact time of deposition of the relatively unimportant calcite stringers was not determined, though it is suggested that they followed the period of metallization.

Origin of the Ores

While some of the materials involved may have been derived from the decomposition of the country rock, most of the chemical elements were introduced. Furthermore, the source of these introduced elements was probably a cooling magma. Sericitization, which represents the most intensive type of alteration, is considered to be indicative of the alkalinity of the solution.[27]

[26] American Cyanamid Company, *op. cit.* 1938.

[27] Graton, L. C. Nature of the ore-forming fluid. Econ. Geol., vol. 35, supplement to No. 2, pp. 197-358. 1940.

The metallization, wall rock alteration, and vein structure, as discussed above are typical of mesothermal ore deposits.

Age of Mineralization

Mineralization in the American Girl mine was obviously controlled by the main fault and its subsidiary faults. In every case, wall-rock alteration and metallization decreases with increasing distance from these breaks. Hence the mineralization is post-faulting. In several places in the footwall in the American Girl mine small sulfide-bearing veins have been found cutting pegmatite dikes. Hence, the ore mineralization occurred after the pegmatites intruded. In the Sovereign East mine of Tumco Valley the pegmatite dikes are seen to be offset by the main thrust fault in the mine.

From these structural relationships it is concluded that the ore is post-faulting and the faulting is post-pegmatite. The pegmatites are known to be the youngest of the coarsely crystalline rocks. Hence the ore mineralization is younger than the main period of intrusion. Though at present there is no apparent means of telling how much younger, it is believed that these mesothermal gold-bearing quartz veins, like those of southern Yuma County, Arizona,[28] may be of late Mesozoic age.

GOLD PLACERS

Distribution

The alluvial gravels of Jackson Gulch and the Padre Madre Valley are reported to have yielded rich returns in placer gold. Pits and dump piles testify that these two alluvial areas were thoroughly explored and exploited. At the present time there is very little gravel left which has not been worked at least once.

Gold Content

Rumor has it that these placer deposits were very rich. However, no estimate can be made of their total yield. In Jackson Gulch the writer witnessed the dry washing of about half a cubic yard of previously undisturbed gravel. This gravel yielded approximately $5.00 in gold, most of which was in the form of small, relatively unworn nuggets. The preponderance of larger pieces was probably due to the loss of the fine colors in the dry washing.

TAILINGS

The three major tailings piles of the district have all been reworked to a greater or less degree. The Tumco tailings are being cyanided in a small scale operation.[29] Old tailings and dumps of the American Girl were extensively milled and concentrated by O'Brien Mines, Inc. Cargo Muchacho tailings have been reworked more than once. Holmes and Nicholson were the last to operate on them.

[28] Wilson, E. D. Geology and mineral deposits of southern Yuma County, Arizona. Univ. of Arizona, Ariz. Bur. of Mines Bull. 134, p. 46. 1933.

[29] Calif. State Mineralogist's Report, vol. 34, p. 9. 1938.

METAL MINES

MINES IN THE LEUCOGRANITE

Mineralized zones occur on faults in or near metamorphic inclusions. The attitude of the faults is parallel to the relic structure of the inclusions. The mineralization consists essentially of quartz veins bearing pyrite, a little chalcopyrite, specular hematite and gold.

La Colorada mine (Plate II, no. 1) consists of nine claims owned by Mr. and Mrs. Mike Muller and Earl Goff of Calexico, California. The vein strikes eastward and dips 30 to 35 degrees.

Golden Queen prospect (Plate II, no. 2) is owned by a Mr. Miller. The vein lies on a flat-lying fault of variable strike, which averages roughly NW, while the dip is less than 20 degrees SW.

MINES IN THE TUMCO ARKOSITE OF TUMCO VALLEY

Mineralized zones occur on and near faults parallel to the regional structure. Perpendicular transverse faults form a minor ore control, as in the Golden Cross mine. Drag folds in the hanging wall also localized the deposition of the ore, *e.g.* the large-scale drag-folds in the 450 stope and 700 stope of the Golden Queen mine. The mineralization consists of quartz, pyrite, chalcopyrite, and gold. In the past, some of these mines were operated on a very large scale.

Coffee Pot prospect (Plate II, no. 3) consists of six claims owned by Eddie Coffee, J. L. Hardy, Henry Stroud, Mike Olathe, Henry H. Austin, and Jose Davis. Vein attitude is (strike) N. 84°E., (dip) 34°S. A winze had been sunk 65 feet down the dip in January 1939.

King mine (Plate II, no. 4) differs from other mines in this group in its steep dip near the surface. The attitude of the main fault is N. 72° W., 52°S.

Golden Cross group of mines now under the control of Thomas L. Woodruff of Ogilby had a total production estimated at more than $3,000,000. All were large mines with inclined shafts extending down the dip of the main fault for more than 1,000 feet, and with many thousands of feet of workings. Ore occurred disseminated in the hanging wall. All were mined by shrinkage stoping.

Golden Queen mine (Plate II, no. 5). The attitude of the footwall is N. 52°E., 26°S. Pegmatite stringers in the hanging wall are shown in a picture of the shaft (Fig. 7).

Golden Cross mine (Plate II, no. 6). Footwall attitude is N. 57°E., 37°S.

Golden Crown mine (Plate II, no. 9). Footwall attitude is N. 86°W., 22°S.[30]

[30] California State Mineralogist's Reports, vol. 12, pp. 240-241. 1893-1894; vol. 13, pp. 331, 337-339. 1895-96; vol. 15, pp. 726-728. 1913-1914; vol. 22, pp. 257-258. 1926.

Draper, M. Private Report on the American Girl Mine. 1911.

U. S. Bureau of Mines. U. S. Department of Commerce. Mineral resources of the U. S. Washington. 1924-1931. Minerals yearbook-review. Washington. 1932-1933.

U. S. Bureau of Mines. U. S. Department of Interior. Minerals yearbook-reviews. Washington. 1933-1939.

U. S. Geological Survey. Mineral resources of the U. S. Washington. 1882-1923.

Sovereign mines, East and West (Plate II, nos. 7 and 8; also Fig. 11) owned by Thomas L. Woodruff. Total production for 1937-38 more than $50,000. The property is still being operated (1940). Ore occurs in the footwall under a fault of variable attitude; strike N. 72°-30°E., dip 20°-30°S. In the Sovereign East mine, workings extend more than 200 feet down the dip and over 350 feet along the strike. Free gold occurs in a quartz vein 20 to 70 inches thick and averages $10.00 to $15.00 per ton.[31]

Other properties in the Tumco arkosite include Banner mine, Delta prospect, and Desert King mine.[32]

AMERICAN GIRL MINE (Plate III)

This mine (Plate III, no. 12) is covered by 18 claims, which also include the American Boy mine (Plate II, no. 13). The American Girl was recently operated by O'Brien Mines, Inc. Early in 1939 these holdings were incorporated with properties controlled by Sidney B. Wood, Jr., to form Allied Mines Inc., with Mr. Wood as general manager. Operation of the mine ceased in the summer of 1939. An estimate of the total production of the American Girl mine from July 1936 to May 1, 1939 is 119,000 tons of ore mined, yielding $575,000 in gold, silver, and copper. Earlier production had yielded:

1892-1900	30,000 tons	$105,000 gold
1913-1916	20,000 tons	$131,000 gold

A well drilled in alluvium to the southwest of the range about 2.5 miles from the mine supplied water for the mine and mill (for analysis see Table 3). Water for domestic use was trucked from Irvin well in Ogilby.

The accompanying plan of the underground workings shows the extent of operations. The ore occurs on and near a thrust fault which dips 30°S. near the surface and 25°S. at depth. Minor cross faults which intersect the main thrust fault have locally shattered the wall rock and have determined to a considerable extent the localization of intense wall-rock alteration and metallization. The nature of the wall rock, wall-rock alteration, and metallization have been discussed above. The Tybo shaft of the mine is shown in (Fig. 8).[33]

The American Boy mine differs from the American Girl in distribution of wall-rock types. The entire hanging wall consists of quartz diorite; the footwall, of metamorphosed arkosite. The structure is similar to that of the American Girl, but wall rock alteration and metallization are not so intense.

Nearby properties similar in geology include the Ogilby group, the Mayata and Englewood claims, and the Yuma and Arizona claims.[34]

[31] California State Mineralogist's Report, vol. 34, p. 9. 1938. U. S. Bureau of Mines. U. S. Department of Interior. Minerals yearbook-reviews. 1938 and 1939.

[32] California State Mineralogist's Reports, vol. 13, pp. 331-332. 1895-96; vol. 14, p. 729. 1913-1914; vol. 22, pp. 255-256. 1926.

[33] California State Mineralogist's Reports, vol. 13, p. 331. 1895-96; vol. 14, pp. 728-729. 1913-14; vol. 22, p. 255. 1926; vol. 34, p. 9. 1938.
Draper, Marshall. Private report on the American Girl Mine. 1911.

[34] California State Mineralogist's Reports, vol. 14, p. 729. 1913-14; vol. 22, p. 259. 1926.

TABLE 3

ANALYSIS OF WATER FROM THE AMERICAN GIRL WELL

Dissolved Solids

Silica	1.30 grains per U. S. gal.	
Aluminum oxide	0.25	
Iron oxide	0.01	
Calcium	24.41	
Magnesium	0.90	
Sodium	82.64	
Sulphate	21.16	
Chlorine	156.52	
Carbonate	None	
Bicarbonate	2.14	
Total solids	289.36	
Total non-volatile solids		288.27
Total hardness as $CaCO_3$		64.74

Hypothetical Combinations

Silica	1.30 grains per U. S. gal.
Aluminum oxide	0.25
Iron oxide	0.01
Calcium bicarbonate	2.84
Calcium sulphate	29.98
Calcium chloride	41.30
Magnesium bicarbonate	None
Magnesium sulphate	None
Magnesium chloride	3.53
Sodium bicarbonate	None
Sodium carbonate	None
Sodium sulphate	None
Sodium chloride	210.15
Total solids	289.36

Determinations

Carbon dioxide uncombined in p.p.m.	2.0
Hydrogen sulphide in p.p.m.	None
Specific electric conductance	Not determined
Hydrogen Ion concentration	7.7
Boron in p.p.m.	0.4
Color (filtered)	None
Odor	None
Taste	Saline
Turbidity (filtered)	None

Smith-Emery Co. Chemical analysis of water from the American Girl well. Private report, March, 1936.

GUADALOUPE MINE

This mine, owned by Nat Kenison, is located near the east end of Obregon Valley (Plate II, no. 14). Disseminated pyrite occurs in a large quartzitic inclusion in quartz diorite along a fault which parallels the orientation of the inclusion. The fault strikes N. 7°W. and dips 52°E.[35]

[35] California State Mineralogist's Reports, vol. 14, p. 729. 1913-14; vol. 22, p. 255. 1926.

MINES IN QUARTZ DIORITE

Within this rock quartz veins occur along minor generally steep-dipping faults and shear zones. Wall-rock alteration in the form of chloritization is intense in the mines of Madre Valley, but is of limited extent elsewhere. Hematite is common. Gold occurs free or in pyrite. Although the values are generally spotty a few of these mines have been very productive.

Pasadena mine (Plate II, no. 24). An ore-bearing silicified shear zone, with an attitude of N. 30°E., 33°SE., has been prospected by five adits at different levels.[36]

Cargo Muchacho mine (Plate II, no. 23) was leased and worked by Holmes and Nicholson in 1936 and again in 1939. Quartz veins occur in a silicified shear zone 2 to 8 feet wide. Its attitude is approximately N. 4°E., 48°E. To the south the mineralized zone crosses the contact from the quartz diorite into quartz monzonite. Values occur only where quartz diorite is the wall rock.[37]

Blossom mine (Plate II, no. 18; also Fig. 9) is an old property which was re-opened in 1938-39 by a Mr. Stubbins. The quartz diorite country rock is abundantly sheared and highly chloritized. There are many small quartz stringers in the mine, but none of them is persistent. The 200-foot Valencia shaft and several hundred feet of drift explore a mineralized fault zone with an attitude of N. 15°-25°W., 50°SW.[38]

Padre and Madre mines (Plate II, nos. 19-21; also Figs. 10 and 12) are owned and operated by the Holmes and Nicholson Mining Company. The ore occurs in or near a dull-gray quartz vein which follows a fault of variable attitude. Its strike ranges from N. 50°W. to N. 50°E. Dip remains almost constant at approximately 24°S. A persistent breccia dike a few inches to a foot thick occurs generally in the footwall parallel to the vein.[39]

Other properties in the quartz diorite include Occidental mine, south of Pasadena mine; Gray Eagle prospect, east of Pasadena mine; and Little Bear prospect (Plate II, no. 22). Gray Eagle, owned by C. J. Creese has an attitude of N.57°E., 36°SE. Little Bear is owned by Roy Bennett and others of Yuma, Arizona. It is characterized by a zone of numerous small quartz stringers with an attitude of N. 60°E., 45°SE.

MINES IN QUARTZ MONZONITE

A number of prospects have been opened in quartz monzonite on small veins similar to those which occur in quartz diorite. None of them has developed into a mine.

[36] California State Mineralogist's Reports, vol. 11, p. 386. 1891-1892.; vol. 12, p. 242. 1893-1894; vol. 13, pp. 341 and 343. 1895-1896; vol. 14, p. 729. 1913-1914; vol. 22, p. 260. 1926.

[37] California State Mineralogist's Reports, vol. 6, p. 81, Pt. I. 1886; vol. 11, pp. 385-386. 1891-92; vol. 12, p. 239. 1893-1894; vol. 13, pp. 333-334. 1895-96; vol. 14, p. 729. 1913-1914; vol. 22, p. 255. 1926; vol. 34, p. 9. 1938.

[38] Calif. State Mineralogist's Reports, vol. 12, p. 238. 1893-94; vol. 13, p. 332. 1895-96; vol. 14, p. 729. 1913-14; vol. 22, p. 255. 1926.

[39] Register of Mines and Minerals. San Diego Co., p. 6. 1902.
Calif. State Mineralogist's Reports, vol. 12, p. 242. 1893-94; vol. 14, p. 729. 1913-14; vol. 22, p. 259. 1926. vol. 34, p. 9. 1938.

Whitecap prospect (Plate II, no. 15), five claims owned by J. D. Northcott, J. H. Williams, R. van Patten and B. J. Hanna. Vein attitude N. 33°W., 51°E.

Tee Wee prospect (Plate II, no. 16), three claims owned by Alex Crawford, may represent an extension of the Whitecap vein.

ECONOMIC GEOLOGY—NONMETALS

GENERAL DESCRIPTION

The non-metallic products of the Cargo Muchacho district consist of sericite and kyanite. Though both of these minerals have been mined extensively in the district, their production is sporadic and follows closely the demands of the market. Five sericite quarries have been opened up and two kyanite deposits have been worked. Most of the production has come from one sericite quarry and from one kyanite quarry.

The mineralogy and general geology and possible origin of these deposits have been discussed above.

NONMETAL MINES

SERICITE IN TUMCO FORMATION

Occasionally, near pegmatite dikes in the Tumco arkosite, the country rock is completely altered to sericite. This grades outward first into a sericite schist bearing large feldspar augen, then to a biotite-feldspar schist, and finally into normal Tumco arkosite.

A prospect pit in the bottom of an arroyo a few hundred feet north of the Golden Queen mine and a few sporadically active quarries (Plate II, no. 10) at the southwest end of Tumco Valley exemplify this type of occurrence.

SERICITE IN THE VITREFRAX FORMATION

This occurrence of sericite has been briefly described above. The largest and most active sericite quarry in the district is located on Micatale Hill (Plate II, no. 11). An open cut has been worked since about 1930 by Micatale Inc., under C. E. Allebrand of Los Angeles.

KYANITE IN THE VITREFRAX FORMATION

The geology of the kyanite deposits has been briefly discussed above.

Several small quarries have been worked on Micatale Hill and in its vicinity.

Ogilby kyanite deposits. 10 claims owned by Vitrefrax Corp., 5050 Pacific Boulevard, Los Angeles. A large open cut on Vitrefrax Hill (Plate II, no. 17) supplies an average of 100 tons per year of kyanite. The best ore in the mine averages 40 percent kyanite. The kyanite is separated from the quartz by crushing and screening in the Micatale mill (Fig. 13.)[40]

[40] California State Mineralogist's Reports, vol. 13, p. 333. 1895-1896; vol. 22, pp. 268-270. 1926; vol. 27, pp. 451-452, 455-457. 1931.
California State Div. of Mines Bull. 99, pp. 87, 121-122. 1928.
Riddle, F. H. Minerals of the sillimanite group. Eng. and Mining Jour., vol. 133, no. 3, p. 141. 1932.