MESOZOIC GEOLOGY AND TECTONICS OF THE BIG MARIA MOUNTAINS REGION, SOUTHEASTERN CALIFORNIA

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ABSTRACT

Southeastern California was part of the North American craton during Paleozoic time, and a platform Paleozoic section like that of the western Grand Canyon was deposited on a basement of Proterozoic granites and gneisses. Platform conditions continued with deposition of Triassic clastic strata and subordinate volcanic rocks and evaporites, and ended after deposition of Early Jurassic eolian strata. Cratonic conditions were interrupted in the southwest part of the region by Late Triassic granitic and volcanic magmatism and uplift. During later Jurassic time granites and ignimbrites were emplaced widely throughout the region. Next, the very thick basinal Late Jurassic(?) and Cretaceous fluvial McCoy Mountains Formation was deposited. Late in Late Cretaceous time, the base of the continental plate was eroded tectonically against oceanic materials being subducted beneath it, and those materials are exposed, as the Orocopia Schist, beneath the truncated base of the continental plate. Metamorphic dehydration of the schist may have released hot water into the crust to trigger synchronous metamorphism and severe deformation, accompanied by intrusion of leucogranites. The region was extended during middle Tertiary time and detachment faults are widely exposed.

Popular speculations in favor of a cryptic Jurassic or Cretaceous megashear or suture through this region are disproved by the presence of the same cratonic section of Cambrian through Jurassic strata north and south of the hypothetical structures.

INTRODUCTION

The lowest rainfall and best exposure in the desert Southwest are in the Death Valley region of east-central California and in far southeastern California. The latter region, the subject of this essay, was part of the North American craton until middle Mesozoic time, and since then has been the site of diverse deformation, metamorphism, and magmatism reflecting continental-margin plate interactions. The cratonic pre-tectonic framework and superb exposures permit uncommon constraints on both structural styles and regional reconstructions.

BIG MARIA MOUNTAINS

The Big Maria Mountains display the results of extreme Late Cretaceous ductile deformation, synchronous with greenschist- and amphibolite-facies metamorphism, of Proterozoic basement rocks, Paleozoic and lower Mesozoic cratonic sedimentary rocks overlain by Jurassic volcanic rocks, and Jurassic granitic rocks. The metamorphosed stratified rocks are present in a crossfolded syncline trending irregularly northwestward through the range, flanked by metamorphosed Jurassic and Proterozoic granites, and in a screen between metagranites, mostly of Jurassic age, in the northwest (Fig. 2; Hamilton, 1982, 1984).

Paleozoic Stratigraphy

The metamorphosed Mesozoic strata of the Big Maria Mountains lie concordantly above metamorphosed Paleozoic cratonic strata (Hamilton, 1982, 1984). The Mesozoic rocks are mostly greenish-gray schists; distinctions between formations often are not obvious until the rocks are examined closely. The Paleozoic rocks, by contrast, comprise strikingly recognizable units; despite their complex isoclinal intercalations and their tectonic attenuations to less than 1 percent of stratigraphic thicknesses, formations are continuous through structures of extreme ductile deformation. The Mesozoic strata have undergone the same metamorphism and deformation as have the Paleozoic ones, but their structure and stratigraphy would have been difficult to decipher without an understanding of the structure and stratigraphy of the Paleozoic rocks.

The section of metamorphosed Paleozoic cratonic strata in the Big Maria Mountains begins with the Cambrian Tapeats Quartzite, which is overlain by Bright Angel Schist, and that by calcitic Muav Marble. The clastic rocks tend to be recessive and are easily overlooked in severely attenuated sections. Thick cliff-forming dolomite marble comes next; Upper Cambrian, Ordovician, and Lower Devonian formations are present in unmetamorphosed sections to the north but cannot be discriminated in the metadolomite. Next comes white calcite marble, which certainly includes the Mississippian and so is designated Redwall Marble, although Upper Devonian and Pennsylvanian rocks likely are present in it also. Metadolomite and Redwall are white on fresh breaks, as is much Muav; but Redwall is also white where weathered, whereas Muav and dolomite are typically yellow buff. Above the Redwall are metamorphosed calcareous redbeds, now mostly calc-silicate rocks, of the Upper Pennsylvanian and Lower Permian Supai Formation, which forms cliffs with darkly varnished surfaces. Above the Supai come the Permian calc-silicate, recessive-weathering Hermit Schist, fine-grained eolian Coconino Quartzite, and chert-rich, mostly calcitic, cliff-forming varicolored Kaibab and Toroweap Marbles (here termed Kaibab). A three-part lithologic division can be made within the Kaibab, for the middle part is richest in metachert. A field guide to these units is given by Hamilton and others (1987, Day 1).

This Big Maria section has provided the regional reference section for metamorphosed Paleozoic formations and has been found to have continuity in southeastern California and southwestern Arizona (Stone and others, 1983). Complete sections that are only slightly metamorphosed are known in the New Water Mountains (Miller, 1970; Miller and McKee, 1971) and southeast of the Granite Wash Mountains (Richard, 1982). Stratigraphic thickness is about 1500 m. The lithologic succession of the Big Maria section is strikingly similar to that of the cratonic section of the westernmost Grand Canyon and southeastern Nevada, 250 km to the north, and less like that of southeastern Arizona, 350 km to the east. The Big Maria section is very different from miogeoclinal sections farther west in Nevada and California.

The distinctive cratonic section is now known also in southwesternmost Arizona and northwesternmost Sonora, as discussed in sequel because of its importance as disproof of conjectural sutures and megashears in that region.

Structural Style

The nine distinctive Paleozoic lithologic units are recognizable at all degrees of deformation and metamorphism and I have mapped them throughout the range at a scale of 1:24,000, although only a generalized map has been published

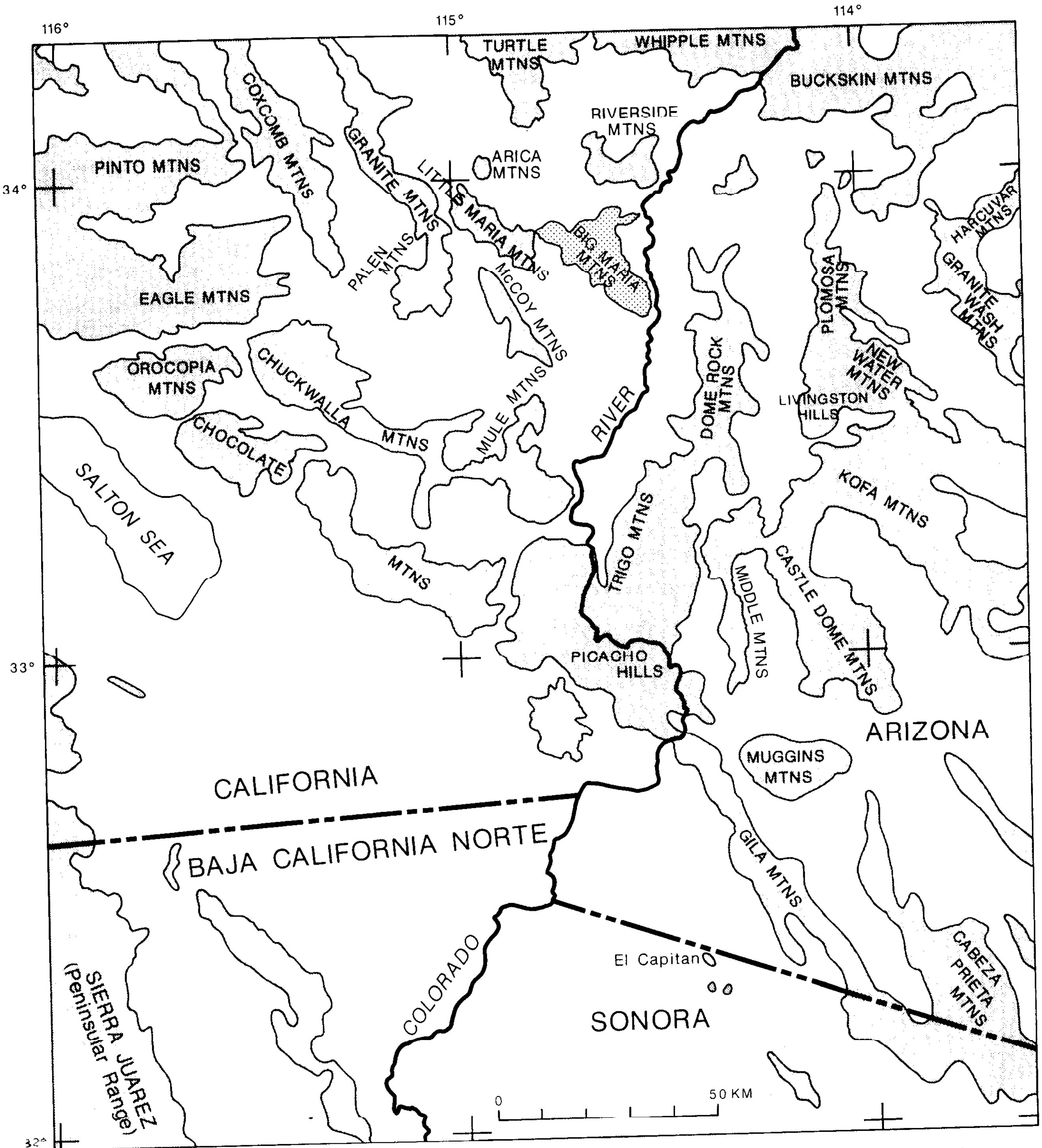


Figure 1. Index map of southeastern California and vicinity. Most outcrop areas are dominated by Proterozoic, Jurassic and Cretaceous granites and gneisses. Metamorphosed cratonic Cambrian to Lower Jurassic strata occur in the Palen, Big and Little Maria, and New Water Mountains; in many ranges north and east of those; and in the Gila Mountains and El Capitan. Overlying Jurassic metavolcanic rocks are succeeded by the very thick Upper Jurassic(?) and Cretaceous McCoy Mountains Formation, best known in the Coxcomb, Palen, McCoy, and Dome Rock Mountains and Livingston Hills. Orocopia Schist--accretionary-wedge material subducted in Late Cretaceous time--crops out beneath continental plutonic rocks in the Orocopia and Chocolate Mountains, Picacho Hills, and southern Trigo, Middle, and Castle Dome Mountains. Middle Tertiary volcanic and sedimentary rocks, mostly above detachment faults, are widespread and dominate the Picacho-Trigo-Castle Dome-Kofa Mountains region.

(Hamilton, 1984). Strains that include attenuations of the total section to 1 percent of its stratigraphic thickness while retaining all formations in correct sequence and normal metamorphic lithology are recorded clearly. A field guide to this deformation is given in Hamilton and others (1987). Mesozoic units display comparable deformation but as they are much less distinctive it is appropriate to here discuss the structural style before describing those units.

The major structure involving the metasedimentary and metavolcanic rocks of the Big Maria Mountains is a large tight to isoclinal syncline that trends generally northwestward through the range and is flanked by metamorphosed Proterozoic and Jurassic granitic rocks (Figs. 2, 3). The syncline is crossfolded by many tight recumbent folds. Local dips tend to be gentle to either the northeast or southwest, depending on which limbs of crossfolds are exposed. Dramatic attenuations occur in short distances along continuous outcrop belts both around these crossfolds and along single limbs. Such attenuations can involve some parts of the section or even single formations much more than others but tend to affect the entire section in the same sense. The greatest present thicknesses of units are less than half their initial thicknesses. As such apparently thick sections are isoclinally folded internally, the thicknesses represent balances between flattening and thickening by folding. Small synmetamorphic folds define by their S and Z configurations northeastward overfolding throughout the range (Figs. 6, 7, 8), regardless of position relative to either the main syncline or its crossfolds. As gentle northeast dips are dominant over gentle southwest ones within the metasedimentary rocks (but not within the range as a whole), the overfolding is more often down the local dip than up it. Recumbent folding is pervasive and sections are almost as often inverted as upright. Sense of vergence is not proved by facing directions of formations within folds because the crossfolding affected successions that had initial steep dips, not horizontal ones. (Ellis, 1982, overlooked this when she asserted that the structures were south-verging.)

Despite the plane-parallel boundaries of formations within limbs of large crossfolds, the units display internal polyphase-isoclinal folding. Isoclinal folds and the shredded remnants of such folds are folded and refolded by other synmetamorphic folds. This deformation must be the product of combined pure and simple shear: superimposed folds were produced in a continuum of flow subparallel to lithologic boundaries. A similar explanation is in my view applicable to many metamorphic terrains commonly regarded as recording superimposed periods of diversely oriented shortening.

The crossfolds fully affect the Jurassic metagranites as well as all older rocks, and belong to the Late Cretaceous episode of synmetamorphic deformation. Although the Jurassic plutons must have caused severe deformation and metamorphism of their wallrocks, no minor structures, and only rare contact-metamorphic minerals, are known to have survived from that early event. Perhaps the main syncline was itself produced between rising Jurassic plutons; if so, early attenuation of wallrocks would have been accomplished primarily by subvertical stretching. Upon the effect of such synmagmatic deformation was superimposed the Cretaceous flattening which accompanied recumbent folding and regional metamorphism. A screen of metamorphosed sedimentary, volcanic, and basement rocks is present between metamorphosed Jurassic granites in the northwestern part of the range, and this complex also was recumbently crossfolded during the Cretaceous event.

The Mesozoic units are dominantly grayish-green schists, and thus much less distinctive than the Paleozoic units, but detailed mapping demonstrates them to behave in the same structural fashion as do the Paleozoic units. Tectonic attenuations of nearby Paleozoic and Mesozoic sections commonly fluctuate in concert (Fig. 3), and even the thickest present sections are greatly attenuated from initial thicknesses. Small-scale folding commonly is inconspicuous in slabby hillside outcrops of the Mesozoic rocks, but in clean outcrops their deformation can be seen to be comparable to that of the Paleozoic units.

The conversion of Proterozoic and Jurassic granitic rocks to augen gneisses in most of the range also records extreme deformation. Except in the lowest-grade terrain, contacts of the Jurassic metagranites with the metasedimentary and metavolcanic rocks are now parallel to foliation and internal contacts; dikes and crosscutting contacts have been flattened and transposed. Proterozoic augen gneiss--now almost phyllonitic--in several places forms sheets, kilometers long but only 2-50 m thick, between severely attenuated Tapeats Quartzite and Jurassic augen gneiss. Such configurations likely record tectonic thinning of much greater initial thicknesses of Proterozoic rocks along contacts of the Jurassic plutons. The Jurassic granites are in contact with all Paleozoic and Mesozoic units in various parts of the range, whereas with rare exceptions the Proterozoic rocks are in contact only with Tapeats Quartzite.

Mesozoic Stratigraphy

Metasedimentary and metavolcanic rocks that lie stratigraphically above the Permian Kaibab Marble and are intruded by granitic rocks of Middle or Late Jurassic age are widespread. I have mapped these metamorphic rocks as three units, with local subdivisions. The lower unit consists dominantly of metamorphosed clastic sedimentary rocks, assigned a Triassic age because rocks in this position in distant fossiliferous sections are mostly Triassic, but the unit may contain rocks of Late Permian and Early Jurassic ages also. The middle unit is an impure, fine-grained quartzite, the correlative for which in unmetamorphosed sections is the Aztec Sandstone, at least largely of Early Jurassic age. The upper unit consists of silicic metavolcanic rocks, correlative with metavolcanic rocks dated as Jurassic in nearby ranges, and older than the 160 Ma granites that here intrude them.

The Mesozoic and Paleozoic strata belong to a cratonic succession that is preserved discontinuously from the western Grand Canyon and southeastern Nevada to northern Sonora. The best-preserved Mesozoic sections yet studied near the Big Maria mountains are in the Buckskin Mountains (Reynolds, Spencer, and DeWitt, this volume; Spencer and others, 1986) and Palen Mountains (discussed in sequel).

Triassic Strata

The metasedimentary rocks that lie between Kaibab Marble and Aztec Quartzite likely include the equivalents of Triassic redbed formations. J. D. Walker (this volume) infers from regional stratigraphic relationships that at least the lower part of this section in the Big Maria region is of Early Triassic age. The present thickness of the section in the Big Maria Mountains varies from 2 to 100 m; the premetamorphic thickness likely was about 500 m.

The basal part of the Big Maria post-Kaibab section is dominated by richly epidotic, bright green metasedimentary schists. The rest of the presumably Triassic section consists of metaconglomerate, metasandstone, calc-silicate metashales, and probable metatuffs (Figs. 4, 5). All of these rocks are schists, most of them greenish gray. The upper part of the pre-Aztec section typically consists of coarse conglomerate (Figs. 4, 6). Most metaconglomerate is dominated by clasts of quartzite but includes abundant clasts of other Paleozoic units and of the Proterozoic basement, and the matrix commonly is arkosic. Primary clasts were subrounded but have been flattened severely.

Informative outcrops of metaconglomerate are present at fieldtrip Stop 1-2B of Hamilton and others (1987) in the southeastern Big Maria Mountains where metamorphism was relatively slight. Initial boulders were as large as 0.5 m. Distinctive Proterozoic megacrystic potassic granite--a common basement rock type in the region--and all Paleozoic formations are represented. The Paleozoic section is preserved in nearby ranges in a complete arc from west (Little Maria and Palen Mountains) through north (Arica and Riverside Mountains) to east-southeast (Plomosa and New Water Mountains), so presumably the boulders came from the south or southwest, perhaps from the region of Triassic granitic magmatism in the Mule Mountains (R. M. Tosdal in Hamilton and others, 1987) although no clasts of the Triassic granites have been recognized in the conglomerate.

Severity of flattening of cobbles in the conglomerates increases both with metamorphic grade and with intensity of attenuation of the local stratigraphic section. In the least-deformed localities, large boulders of granite and dolomite tend to be flattened only to triaxial ratios of approximately 3:2:1, whereas limestone clasts (now calcite marble) are flattened to 50:1; most clasts remain coherent. Clasts in more deformed tracts have been transposed and shredded into thin layers and laminae and conglomeratic origins may be apparent only in stream-polished outcrops. Flattened cobbles are crossfolded, torn apart, and transposed into new layers parallel to the new foliation (Fig. 6).

Aztec Quartzite (Lower Jurassic)

Quartzite which I presume to be the metamorphosed equivalent of the Lower Jurassic Aztec Sandstone comprises the medial part of the Mesozoic section throughout the Big Maria Mountains. Stratigraphy, sedimentology, and age of the Aztec Sandstone and equivalent units in regions to the north and east have been discussed by Marzolf (1983) and Stewart and others (1986).

Primary structure in the Aztec has everywhere been obliterated in the Big Maria Mountains. The formation consists of fine-grained and generally impure quartzite that varies in aspect because of the metamorphic behavior of feldspar sand (much of it now muscovite) and of interstitial iron oxide and calcite in the protolith sandstone. White vitreous quartzite is present erratically. Some contains considerable muscovite (Fig. 7) and disintegrates to small schistose plates. Some magnetite-bearing quartzite is white where fresh but weathers to mottled red, gray, and white colors; this lithology tends to stand as cliffs, although the formation otherwise commonly makes slopes (Fig. 3). Other magnetite-bearing quartzite is shear-laminated in white and gray. Much of the quartzite contains altered grains of clastic feldspar plus a few percent of epidote and other metamorphic minerals, and is a buff or pale greenish-gray granular schist.

The Aztec Quartzite seldom resembles the Permian Coconino Quartzite, which is a fine-grained vitreous quartzite that weathers to sharply angular chips and shards. Tapeats Quartzite is strikingly different from both Aztec and Coconino, for it is highly variable in grain size--much of the protolith was grit or arkose, or was silty.

Odd variants of the Aztec in a small area in the southeastern Big Maria Mountains are laminated mica-quartz and hematite-tourmaline-muscovite-kyanite-quartz rocks cut by pods of quartz and kyanite. The syndeformational minerals record Late Cretaceous metamorphism. The aluminous character of the rocks presumably records metasomatism, likely accompanying intrusion of an adjacent small pluton of Jurassic quartz monzonite which was itself metasomatized and is now schistose. Most of the outcrops of kyanitic rock were removed recently in the course of quarrying the metagranite for dam riprap, but blocks and a few outcrops of dark kyanite quartzite remain near the quarry at Stop 1-2B of Hamilton and others (1987).

The present thickness of the Aztec Quartzite varies from about 150 m (thus perhaps half the initial stratigraphic thickness) to less than one meter because of the great variations in attenuation and of internal isoclinal folding. That entire thickness range is displayed over distances of only a few kilometers along strike in belts of continuous exposure of the unit in several parts of the Big Maria Mountains, yet only in short segments is the formation missing altogether.

Figure 2 (Facing page and below). Generalized geologic map of the Big Maria Mountains and the south edge of the Riverside Mountains, after Hamilton (1982, Fig. 2).

EXPLANATION

Q Quaternary sediments, locally also Pliocene strata

Tr Oligocene or Miocene intrusive rhyolite

Tb Oligocene sedimentary breccias and clastic strata

Metamorphosed Late or Middle Jurassic plutonic rocks

- **Jg** Granodiorite, quartz monzonite, and alaskite
- **Jd** Diorite
- **Jgb** Hornblende gabbro
- **Jm** Migmatized Mesozoic and Proterozoic gneiss, much injected by unit Jg

Mz Metamorphosed Middle Jurassic volcanic rocks and Lower Jurassic and Triassic clastic sedimentary rocks

Pz Metamorphosed Paleozoic cratonic strata--Kaibab Marble through Tapeats Quartzite

Metamorphosed Proterozoic basement rocks

- **Pg** Megacrystic potassic granite
- **Pu** Upper-plate fine-grained gneiss and granite

Faults--Dotted where concealed

Strike-slip, post-detachment

Normal, post-detachment

Detachment (low-angle extensional fault)

Type unspecified

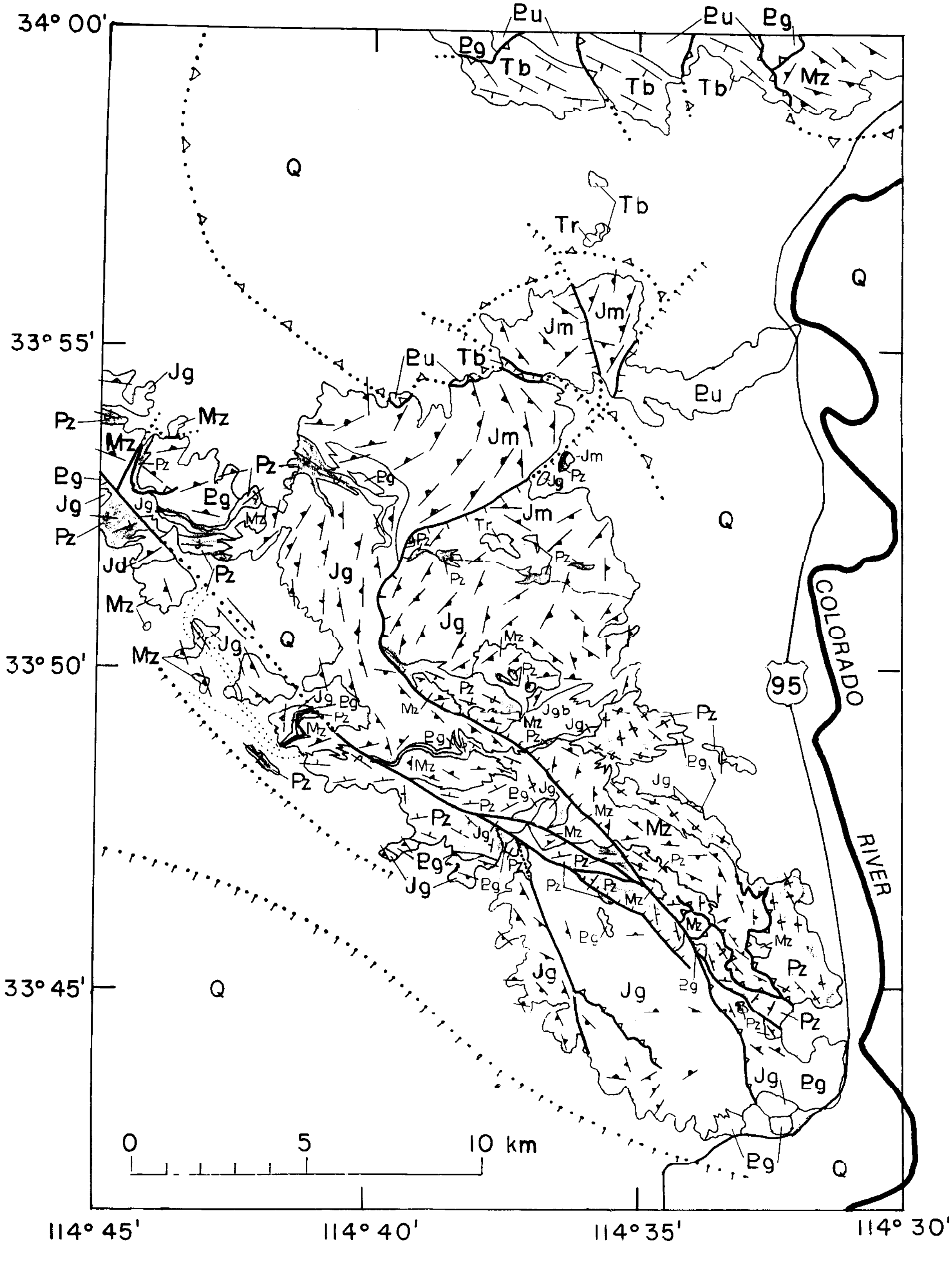
Attitudes

Foliation

Layering--in unit Tb, bedding dipping steeply to moderately; in unit Pz, showing generally upright or inverted sequence, dips mostly gentle

Meta-Ignimbrite (Jurassic)

Silicic metavolcanic schist of Jurassic age is the youngest unit in the premetamorphic stratified succession. The platy, greenish-gray schist is of monotonous aspect in weathered hillside outcrops, but in stream-polished exposures it is seen to be extremely transposed and to be complexly lenticular, isoclinal, layered, and laminated parallel to foliation (Fig. 8). Such structures can be seen at Stop 1-6B of Hamilton and others (1987) and in the main wash that drains east to the quarry at Stop 1-2B. Only where least transposed are obvious clasts of diverse-textured silicic volcanic rocks preserved as indicators of the tuffaceous, and locally breccious, nature of the protolith. Elsewhere, it is not generally obvious to what extent long, thin lenses represent flattened clasts and to what extent they represent layering disrupted and mixed by shear and flattening. Outcrop appearance is replicated throughout progressive attenuation (Fig. 8). The metavolcanic rocks typically crop out as bluffs and steep slopes (Fig. 3).


34° 00'
33° 55'
33° 50'
33° 45'
114° 45'
114° 40'
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0
5
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COLORADO
RIVER
95
Q
Tb
Tr
Jm
Jg
Jd
Jgb
Mz
Pz
Pu
Pg

The lower part of the section is of metarhyodacite that is darker than the upper part of meta-quartz latite. The boundary between the two types is sharp although locally there is tectonic intercalation across it. The present thickness of the lower unit varies from about 2 to 50 m, and of the upper from about 50 to 300 m.

The common greenschist-facies metavolcanic rocks are laminated fine-grained muscovite-epidote-biotite-quartz-albite schists. Biotite is pleochroic in olive green. Amphibolite-facies schists contain oligoclase and often minor hornblende. Small augen, preserved primarily in greenschist-facies rocks, represent initial phenocrysts which had a maximum size of about 5 mm. Augen of sutured quartz represent quartz phenocrysts; augen of albite with abundant inclusions of muscovite, calcite, and epidote, initial crystals of plagioclase; augen dominated by muscovite and quartz, alkali feldspar; and epidote-rich micro-augen perhaps represent initial clinopyroxene phenocrysts. The proportions of such relic phenocrysts vary widely but were dominantly of plagioclase in the metarhyodacite, plagioclase and alkali feldspar in the meta-quartz latite, and some rocks were crystal-rich. Widespread microlenticular fabrics in the least-metamorphosed rocks likely include relics of ignimbritic textures. Fine-grained biotite-granodiorite gneisses in the north-central part of the range may represent metavolcanic rocks in a migmatitic terrain.

Meta-ignimbrite sharing the same structural and stratigraphic constraints in varying combinations--underlain by Aztec Quartzite, intruded by Middle or Late Jurassic granitic rocks, overlain by McCoy Mountains Formation, and metamorphosed during Late Cretaceous time--is widespread through southeastern Arizona and southwestern California (Tosdal and others, 1987). Published radiometric ages from the formation are Jurassic but are imprecise.

Jurassic Granitic Rocks

Large plutons of granodiorite, quartz monzonite, and alaskite, and smaller ones of diorite and hornblende gabbro, were intruded into all older rocks of the range during Jurassic time and were metamorphosed with them during Late Cretaceous time. These rocks are much recrystallized but little foliated in most of the greenschist-facies southern part of the range, whereas elsewhere they are augen gneisses with amphibolite-facies mineralogy. The least metamorphosed granodiorite and quartz monzonite are characterized by sparse, stubby-rectangular phenocrysts of potassic feldspar, commonly purplish gray with rims of white oligoclase, in a matrix of medium-grained quartz, plagioclase, white potassic feldspar, biotite, and hornblende. Contacts between quartz monzonite and granodiorite in the little-deformed terrain are sharp, and alaskite is in irregular masses--not dikes--up to about 1 km^2 in area; weak foliation cuts across the contacts.

In the highly deformed granitic rocks, internal and external contacts have been transposed parallel to foliation. The K-spar phenocrysts survive as equant augen in strongly foliated gneiss and tend to retain their purplish color through metamorphism of lower amphibolite facies but to have lost it at higher grade. The irregular alaskites have been flattened to sheets of fine-grained leucogneiss. Long, thin lenses and tongues of metagranitic rocks within metasedimentary and

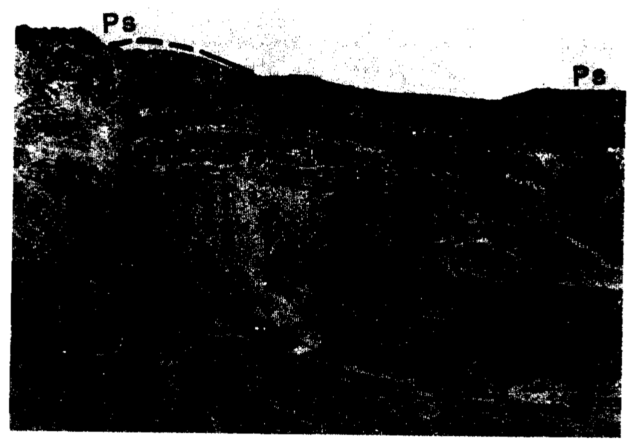

Figure 4. Inverted upper Paleozoic and lower Mesozoic section, southeastern Big Maria Mountains. **Ps**, Supai; **Phc**, Hermit and Coconino; **Pk**, Kaibab; **TR**, Triassic schist; **cg**, metaconglomerate; **Ja**, Aztec. Hill is 60 m high; tectonic attenuation is to about 5 percent of initial thickness.

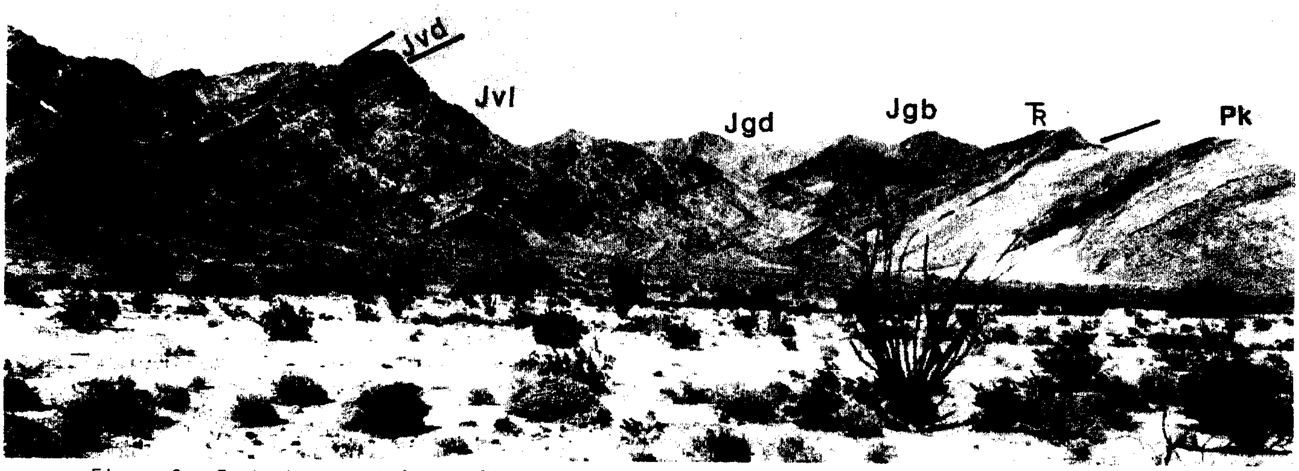

Figure 3. East at asymmetric syncline, west-central Big Maria Mountains. **Pk**, Kaibab; **TR**, Triassic; **Ja**, Aztec; **Jvd**, dark lower section of Jurassic metavolcanic rocks; **Jvl**, light upper section. Combined units in inverted sections, attenuated to 1 percent of stratigraphic thickness: **Pz**, complete Paleozoic section; **TR J**, units TR + Ja + Jvd, complete. Distant Jurassic rocks: **Jgb**, metagabbro; **Jgd**, metagranodiorite. Axis of large isoclinal syncline lies structurally high in unit Jvl. Note isoclinal interfold of units Pk and TR in right distance. Late Cretaceous pegmatites cut all rocks and structures. Metagranites of Proterozoic and Jurassic ages lie above unit Pz at top left.

metavolcanic rocks have been transposed from steeply crosscutting initial contacts.

Zircons from two specimens were dated by L. T. Silver (oral communication, 1978) by the U/Pb method as indicating magmatic crystallization at about 160-165 Ma, Middle-Late Jurassic boundary time. One sample was of recrystallized but nonfoliated quartz monzonite from the southern part of the range, the other of granodioritic augen gneiss from the west-central part.

Hornblende gabbro comprises a pluton in the east-central part of the range and shows metamorphism primarily by the hornblendic and chloritic schists around its margin.

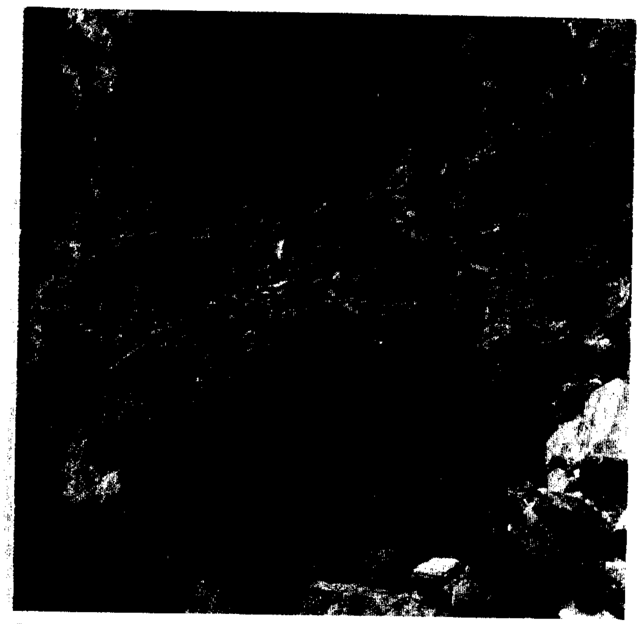

Figure 5. Northwest along axes of recumbent folds in Triassic epidote-biotite schist and metaconglomerate, cut by Late Cretaceous pegmatite (left), central Big Maria Mountains. Outcrop 12 m high.

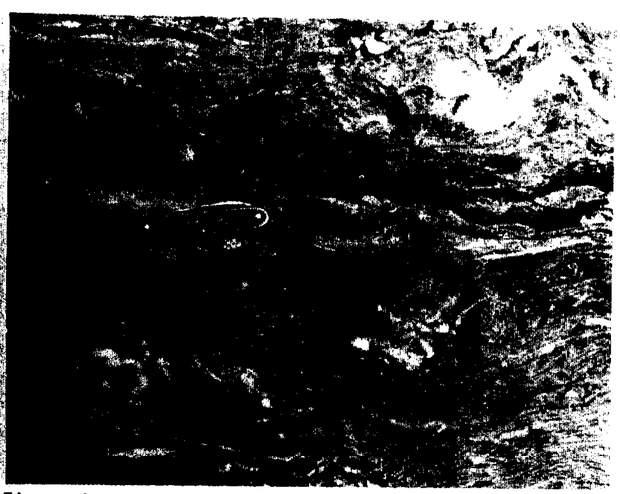

Figure 6. Triassic or Lower Jurassic metaconglomerate, viewed northwest along long axes of cobbles and axes of northeast-verging folds. Limestone cobbles are now contorted lenses of white marble; dolomite and quartzite are moderately flattened. Southeastern Big Maria Mountains.

The distinctive megacrystic Jurassic granites are widespread in southeastern California, southern Arizona, and northern Sonora. R. M. Tosdal (written communication, 1987) stated that granite of this type has an age near 165 Ma wherever it has been dated precisely, although Jurassic granites of other types have yielded U/Pb zircon ages between about 150 and 175 Ma (Anderson and Silver, 1979; Tosdal and others, 1987). Presumably the Jurassic ignimbrites and granites are correlative on a regional scale.

Metamorphism

The Jurassic granites and all older rocks were metamorphosed at upper greenschist to middle or upper amphibolite facies during very late Cretaceous time (Hamilton, 1982 and unpub.; Hoisch, 1987b; Hoisch and others, in press). The lowest-grade rocks are in the southern part of the range; biotite formed in metaclastic, metavolcanic, and metagranitic rocks, talc + tremolite in siliceous dolomites, and temperatures were near 440-500°C (Hoisch and others, in press). Peak metamorphic temperatures increased northwestward in the western part of the range, through 550°C (diopside-tremolite assemblages in metadolomite) to about 600°C (diopside-forsterite-tremolite; Hoisch and others, in

Figure 7. Vertically foliated micaceous Aztec Quartzite deformed by recumbent crossfolds verging northeast (right). Southeastern Big Maria Mountains.

Figure 8. West-northwest down mineral lineation and axes of northeast-verging folds in extremely attenuated Jurassic meta-ignimbrite, west-central Big Maria Mountains. Locality is in lower left part of view of Figure 3.

press). Higher temperatures may have been reached in the northern interior of the range, where high-grade rocks have not been studied in detail. Petrobarometric determinations indicate that metamorphism occurred at a depth of about 12 km (Hoisch, 1987b and oral communication, 1987; Hoisch and others, in press). Spectra of $^{40}Ar/^{39}Ar$ in two specimens indicate cooling through the argon-retention temperature of hornblende (near 500°C) about 75 Ma and of muscovite (near 350°C) about 60 Ma; as the peak metamorphic temperature of these specimens was about 550°C, the hornblende dates approximate the age of metamorphism (Hoisch and others, in press). Many K-Ar ages, mostly of partly separated biotite, from diverse rock types in the range show much scatter but are concentrated near 60 Ma (Martin and others, 1982) and presumably record postmetamorphic cooling toward equilibrium geotherms.

Metamorphism was synkinematic with the major deformation. Mineral alignments mostly parallel fold axes. Proterozoic and Jurassic granitic rocks were recrystallized but little deformed pervasively in the low-grade southern part of the range, and elsewhere are now augen gneisses.

Dikes of muscovite pegmatite form a great swarm in the northwestern and north-central part of the range and cut sharply across the highly deformed metamorphic rocks (Figs. 3, 5). The dikes are in part steep, with dominant northwest strikes, and in part, particularly in augen gneiss, semiconcordant to layering. These dikes comprise more than 20 percent of a large, irregular tract in the northwest interior of the range. The metamorphic temperatures determined by Hoisch increase irregularly toward the pegmatitic terrain so it is likely that the sources of heat for metamorphism and pegmatites were related. Hoisch (1987b) deduced from the widespread wollastonitite that the metamorphism required the passage of enormous volumes of water of amphibolite-facies temperatures. He proposed that this water came from oceanic sedimentary rocks then being subducted and metamorphosed at shallow depth beneath truncated continental lithosphere (see discussion of Orocopia suture), and that the pegmatites were another product of the water influx.

The emplacement of large plutons of Jurassic granitic rocks must have been accompanied by major contact metamorphism and associated deformation, but the effects of this were overprinted so severely by the Cretaceous metamorphism and deformation that they have yet to be discriminated except in the local survival of contact skarn. The kinematic indicators and mineral assemblages of the metamorphic rocks date almost wholly from the Cretaceous event.

In the north-central part of the Big Maria Mountains, the postkinematic pegmatite swarm is involved in mylonitization that increases in intensity upward, over a structural thickness of several hundred meters, toward the projection of a middle Tertiary detachment fault. Presumably this late retrograde metamorphism represents an early, deep-seated stage of Tertiary extensional deformation.

Tertiary Detachment Faulting

The crust of the region was extended during late Oligocene to middle Miocene time, and detachment faults are known in the Big Maria Mountains and many neighboring ranges. Extension of upper-plate rocks was at least 100 percent, and the mode in which this strain was transmitted through the lower plates is much disputed. Clearly, though, the detachment faults in general originated as ductile faults in the middle crust and rose toward the surface, with slip continuing in progressively more brittle modes, as upper-crustal material was stripped from them by tectonic denudation. One popular model (Wernicke, 1985) has detachments originating as gently dipping ramps cutting through the crust, and the lower plates rising isostatically as they are denuded tectonically; range-size upper-plate blocks are left perched and inactive on the faults as flattened and domed by such rise. Another model (Hamilton, 1982) postulates spreading in the middle crust by the sliding apart of lenses separated by ductile shear zones (an analog is the spreading of a pile of wet halibut); as the composite upper surface of the separating lenses increases in area, the brittle overlying crust is sundered into blocks that first rotate like dominos, then are carried passively apart. Good evidence supports both models; perhaps initial upper-crust deformation is largely in the ramp mode whereas middle-crust deformation may begin in the lens mode. Extensive ductile deformation of lower-plate rocks occurred in many detachment systems.

The detachment faults known in many ranges in this region mostly display slip in the top-to-the-northeast sense, and rotation of upper-plate rocks to southwest dips, regardless of the direction of dip of the locally underlying segment of a detachment fault. North-dipping detachment faults bound the northern Big Maria (Hamilton, 1982, 1984) and Little Maria Mountains, but it can not yet be proved whether the faults headwalled to the surface above the ranges or overlay them completely. Middle Tertiary detachment faults certainly overlay the entire lower-plate assemblages of the Arica and Riverside Mountains, and of many ranges to the northeast, east, southeast, and south of the Big Marias. Lower-plate rocks display comparable mid-crust levels of formation throughout this region: there is no consistent northeastward increase in depth of exposure as predicted by the ramp model. Both reflection profiles and surface mapping indicate the existence of crustal lenses separated by ductile shear zones beneath the detachment faults (Frost and Okaya, 1986; Hamilton, 1982). Detachment faults have not yet been identified with certainty to the southwest of the Big Marias, where nearly all rocks in nearby ranges are of mid-crust types to be expected in lower rather than upper plates. Farther southwest, in the Orocopia Mountains region, I infer from the presence of moderately dipping Tertiary strata against middle- and lower-crustal rocks that detachment faults are present although they have yet to be mapped. At the north end of the intervening McCoy Mountains, a cemented megabreccia of metagranite and metamorphosed Supai Formation lies with gently dipping contact atop Mesozoic metavolcanic rocks and is, I suspect, a remnant of middle Tertiary strata in the upper plate of a detachment fault; but the critical contact is covered by rubble.

Straight, steep dikes of intermediate composition and northwest strike cut pegmatites, mylonites, and all metamorphic rocks in the Big Maria Mountains and presumably belong to the period of middle Tertiary extension. These dikes show varying degrees of deuteric alteration to fine-grained minerals of low-greenschist facies. I infer that the dikes were emplaced and slowly cooled at mid-crustal depths early in the period of extension. The dikes are broken by brittle faults that in turn are injected by pods of unaltered, aphanitic rhyodacite. One of these rhyodacites yielded a K/Ar hornblende age of 22 Ma (Martin and others, 1982), so uplift to shallow levels likely had occurred by early Miocene time.

LITTLE MARIA MOUNTAINS

The Little Maria Mountains display on-strike continuations of Big Maria lithologic and structural assemblages. I have examined various parts of the range and have done local detailed mapping. The grade of Cretaceous metamorphism varies from upper greenschist to middle amphibolite facies (Hoisch, 1987a; Shklanka, 1963), and the rocks display extreme ductile deformation.

The southern Little Maria Mountains contain the westward continuation of the Big Maria syncline. Metamorphosed Paleozoic and Mesozoic strata, mapped by Shklanka (1963), lie between metagranites. In general, Shklanka's unit L1, micaceous quartzite and muscovite-biotite-quartz schist, is equivalent to Tapeats Quartzite plus Bright Angel Schist; his L2, marble, is largely the Muav and Redwall Marbles and intervening metadolomite; his L3, wollastonite and calc-silicate "hornfels", is mostly Supai Formation; his L4, micaceous quartzite and calc-silicate "hornfels", is mostly Coconino Quartzite plus Hermit Schist; and his marble and calc-silicate units M5 through M11 are Kaibab Marble. Most of the metagranite of the southern and western Little Maria Mountains is of Jurassic type, but a muscovite granite likely of Late Cretaceous age is present at the northwest tip of the range, and Proterozoic megacrystic metagranite lies beneath Tapeats Quartzite in the east-central part of the range.

The Mesozoic strata of the core of the syncline are equivalent to the Triassic section of the Big Maria Mountains. These rocks were assigned by Shklanka mostly to his units U-12 through U-15, designations which he applied also to some tracts of Paleozoic rocks. These rocks were described by Shklanka as dominantly quartzose metasedimentary rocks that contain widely varying amounts of biotite, muscovite, epidote, tremolite, and actinolite. Aztec Quartzite and Jurassic metavolcanic rocks have not been recognized in the syncline, but casual description by Emerson (1981) permits the inference that both are present in the northern part of the range.

The upper part of the Kaibab Marble and the basal overlying metashales contain anhydrite. The large gypsum quarries at Midland are in tectonically intercalated Kaibab and schist in which anhydrite was hydrated to gypsum beneath a Pliocene(?) pediment. Quarries, town, and plaster-board mill were abandoned when fresh anhydrite was reached, although small-scale quarrying has been resumed in lesser deposits.

RIVERSIDE MOUNTAINS

The Riverside Mountains contain a broad tract of metamorphosed Mesozoic stratified rocks. Although I have mapped most of the range in detail, I have not yet been able to carry a consistent stratigraphy through the Mesozoic package. The Riverside Mountains expose both upper and lower plates of a detachment-fault system (Carr and Dickey, 1980; Hamilton, 1964, 1984; Lyle, 1982, presented a map adapted from Carr and Dickey, 1980, and my early reconnaissance map, now obsolete, as generalized by Bishop, 1964). The western part of the range consists of upper-plate materials--Proterozoic gneiss and granite, Cretaceous granodiorite, and steep middle Tertiary redbeds, breccias, and subordinate mafic and silicic volcanic rocks. The high eastern part of the range lies structurally beneath the undulating detachment fault and consists of Proterozoic gneiss and granite, the complete metamorphosed Paleozoic cratonic section, metamorphosed stratified Mesozoic rocks, and metagranite intrusive into the Paleozoic rocks but of a type that I do not recognize as diagnostic of either the Jurassic or Cretaceous suites of the region. My mapping in the Riverside Mountains is unpublished except for early reconnaissance at the south end of the range (Hamilton, 1964).

All the lower-plate rocks were highly deformed and metamorphosed at low greenschist facies, presumably during Late Cretaceous time. Mylonites are common and some large tracts are pervasively mylonitic; it is not yet clear how much of this late deformation is a product of the middle Tertiary extensional deformation which culminated in detachment faulting (Power, 1986; Hamilton, unpublished). The Paleozoic metasedimentary rocks are in part deformed with ductile continuity but in part have been dismembered--sections are disrupted and ductile folds shredded--by the superimposed effects of the two deformations. The mostly clastic Mesozoic lithologic units are in discontinuous packages.

The basal unit of the post-Kaibab section consists of green anhydritic metashale, complexly interfingered tectonically with higher and lower units. This schist has few natural outcrops. The anhydrite is mostly hydrated to gypsum near the surface, the rock is disaggregated and expanded, and the unit forms rounded gray or greenish hills mantled by soft gypsiferous soil with tiny schist fragments; the hills resemble badlands eroded from unconsolidated clays. The adjacent upper part of the Kaibab Marble includes much anhydrite also, so it is possible that little time elapsed between deposition of limestone and shale, and hence that the anhydrite schist is also of Permian age.

The upper part of the Kaibab is anhydritic also in the far northwestern Big Maria Mountains, the southern Little Maria Mountains, and the northern Palen Mountains, and in the latter two areas the basal schist of the overlying clastic sequence also is anhydritic.

The south edge of the exposed Riverside Mountains lower plate exposes the structurally, and likely also stratigraphically, highest rocks, which are greenstone and greenschist derived from finely porphyritic undated rhyodacite (greenstone of Hamilton, 1964). Most of this unit is weakly foliated, and its outcrops are massive.

Between the anhydrite schist and the metarhyodacite is a dismembered section of metamorphosed clastic sediments (most of the "low-grade metamorphic rocks" of Hamilton, 1964). Thick roundstone conglomerates, strongly flattened with schistose matrixes, are conspicuous at various structural levels. Metasiltstones, now phyllites and schists, and fine- to coarse-grained metasandstones are widespread; metatuffs and impure metacarbonate rocks are present locally. I do not know the internal stratigraphy of this assemblage. Its rock types can be matched in the Triassic section, which is far more attenuated tectonically, of the Big Maria Mountains, and of the less deformed equivalent section of the northern Palen Mountains.

I infer the thick rhyodacite of the southernmost Riverside Mountains to be correlative with the Jurassic rhyodacite of neighboring ranges, although a Cretaceous age also appears possible in a regional context. No Aztec Quartzite lies against the Riverside Mountains rhyodacite, so I infer the rhyodacite to lie directly upon Triassic strata, the Aztec perhaps having been eroded away during deformation accompanying emplacement of Jurassic granites.

PALEN MOUNTAINS

The northern Palen Mountains expose the upper Paleozoic and lower Mesozoic cratonic section. Paul Stone (written communication, 1984) subdivided the presumably Triassic strata--the section lying between Kaibab Marble and Aztec Quartzite--into three units in his mapping. The lower unit consists of chloritic schist and fine-grained calcareous quartzite; the middle unit consists of calcareous quartzite and quartzite conglomerate; and the upper unit is of volcanic sandstone and of conglomerate containing clasts of granite, quartzite, and carbonate rocks. Aggregate thickness of these units is perhaps 500 m, and they are less deformed than those of the Big Maria Mountains. S. J. Reynolds and J. E. Spencer (oral communications, 1987) have also examined these units and regard them as correlative with units in southwestern Arizona. Much of the basal schist in the Palen Mountains bears anhydrite and is much disrupted by expansion upon surficial hydration to gypsum.

LeVeque (1981) and Pelka (1973) regarded these Palen Mountains units as overthrust from the north by the Paleozoic metasedimentary rocks, but Stone, Reynolds, Spencer, and I have all observed the section to be continuous and unfaulted from Kaibab Marble up through Triassic and younger rocks.

The Aztec Quartzite is present in the Palen Mountains between the Triassic metasedimentary rocks and Jurassic meta-ignimbrite. The Aztec is the Subarkose member of the Palen Formation of Pelka (1973); the Quartzose arenite member of LeVeque (1981), who recognized the Aztec correlation but who misapplied the same designation to a quartzite and conglomerate low in the Triassic sequence; and the Aztec Quartzite of Paul Stone (written communication, 1984). The unit is recrystallized but little foliated. LeVeque emphasized the "high-angle trough crossbeds", which I have seen also and infer to be eolian. LeVeque found some of the quartzite to contain considerable potassic feldspar.

Lying upon the Aztec in the Palen Mountains, and also forming the northern McCoy Mountains, are silicic Jurassic metavolcanic rocks which were divided by Pelka (1973) into various volcanic and hypabyssal units. (He mismapped surficial megabreccias of granite in the northern Palen Mountains, derived from the adjacent Granite Mountains, as intrusive masses.) The upper part of the metavolcanic section is more felsic than the lower part. Internal structure of the meta-igneous rocks is uncertain; their present thickness may be as much as several kilometers.

The meta-ignimbrite is overlain, with at least broad concordance, by the thick McCoy Mountains Formation.

MCCOY MOUNTAINS FORMATION LATE JURASSIC(?) AND CRETACEOUS

The McCoy and Palen Mountains consist largely of the McCoy Mountains Formation, a section, about 7 km thick, of coarse fluvial clastic strata, named by Miller (1944) and mapped and described by Pelka (1973). Harding (1982) added sedimentologic and paleomagnetic data. Paul Stone (in Hamilton and others, 1987, and Stone and others, 1985; also unpublished) has done further mapping in both ranges.

The formation is best known in an outcrop belt trending east-southeastward from the Coxcomb Mountains (Greene, 1968) through the Palen and McCoy Mountains (Harding, 1982; Pelka, 1973) to the Dome Rock Mountains, southern Plomosa Mountains, and Livingston Hills (Harding, 1982; Miller, 1970; Tosdal, 1986). Strata likely correlative are present elsewhere in southeastern California and southwestern Arizona (Dickinson and others, 1987). All known sections are metamorphosed.

The McCoy Mountains Formation lies in stratigraphic position upon Jurassic ignimbrite in the McCoy and Palen Mountains and is metamorphosed with it. Aluminous phyllite along the contact may represent a thick weathering zone (Paul Stone, in Hamilton and others, 1987). The formation consists mostly of metamorphosed roundstone conglomerate, sandstone, and siltstone. It was deposited by streams that flowed mostly southward and, in the far west, eastward (Harding, 1982; Pelka, 1973). Cobbles are of diverse volcanic, granitic, quartzitic, and carbonatic rocks. The formation has general gentle to moderate southward dips in the McCoy and Palen Mountains. The northern and central parts are but slightly metamorphosed and display a slaty to phyllitic cleavage that dips in general gently northward, and from the relationship of cleavage to bedding I infer that the vergence of synmetamorphic deformation was southward and that the southward dip of bedding represents subsequent rotation from a synmetamorphic dip that was gentle to the north (see Stone and others, 1987). The southern part of the unit in both ranges is also recrystallized only at low greenschist facies but is much more deformed, for it displays pervasive phyllitic or schistose cleavage, in general subparallel to bedding dipping gently southward, and severe flattening of conglomerate clasts. Large south-verging folds are present in the southern McCoy Mountains (Fig. 9). The northern rocks likely received their slaty cleavage at a temperature of 300-350°C whereas the foliated southern rocks record perhaps 400°C. If these temperatures represent ambient geothermal gradients, then the deformation occurred at a depth of about 15 km. Structurally higher recumbent-fold limbs of McCoy rocks may have provided the indicated overburden. A field guide to the formation, including its upper and lower contacts, is given by Stone (in Hamilton and others, 1987).

The McCoy Mountains Formation is intruded by granodiorite of late Late Cretaceous age in the Coxcomb Mountains (Calzia and others, 1986; Greene, 1968). A metarhyolite near the middle of the section in the Dome Rock Mountains has a discordant U-Pb age of about 78+/-8 Ma (R. M. Tosdal in Hamilton and others, 1987; Tosdal regards the metarhyolite as formed from a tuff, although alternatively it may have been a sill). Petrified logs high in the section in the Palen and McCoy Mountains have been identified as angiospermous and therefore no older than Albian, late Early Cretaceous, by several paleobotanists. The wood has been studied in the most detail by Virginia Page (in Stone and others, 1987) who assigned it to the Albian and younger genus Paraphyllanthoxylon of primitive angiosperm wood. The upper part of the section is thus of Cretaceous age; the lower part could be as old as Late Jurassic.

Harding and Coney (1985) and Harding and others (1983) noted that the paleomagnetic pole position defined by Harding (1982) from the formation, in its present orientation, is closer to that expected for Jurassic rocks than Cretaceous ones. The stable magnetization is held largely in synmetamorphic minerals. Harding and her associates argued accordingly that the formation and its deformation and metamorphism were wholly of Jurassic age. The fossil wood proves, however, that at least the upper part of the formation is no older than late Early Cretaceous. May (1985) showed that Harding's paleomagnetic data contain internal evidence for post-magnetization rotations, and Stone and others (1987) showed that the present paleomagnetic orientation can be explained as due to the rotations that are indicated independently by the observed structure of the formation from an initial Cretaceous magnetic orientation.

Harding and her co-authors asserted that the fossil wood in the McCoy Mountains Formation could be dismissed as an age constraint because the time of origin of angiosperms is disputed among paleobotanists. Although the evolution of proto-angiosperm fruiting structures is indeed debated, this has no bearing on the dating value of wood of clearly angiospermous character. Such wood first, and widely about the world, appears in Albian strata.

Regional stratigraphic relationships make it likely that the McCoy was deposited in the nonmarine northwest end of the trough or troughs which received the marine and nonmarine Bisbee Group and equivalent units in southern Arizona, New Mexico, and Chihuahua (Dickinson, 1981; Dickinson and others, 1986, 1987). This correlation makes an Early Cretaceous age likely for most of the McCoy. Detritus in the McCoy likely came mostly from the northwest end of the Mogollon highlands of Early Cretaceous age (Bilodeau, 1986; Dickinson, 1981).

ON MESOZOIC MEGASHEARS, SUTURES, AND THRUSTS

Various geologists have argued in recent years that either a great strike-slip fault or a suture between mainland North America and an exotic minicontinent to the southwest formed with northwest or west-northwest trend across southeastern California in Jurassic or Cretaceous time. Such speculations are in my view invalid.

Mojave-Sonora Megashear

Anderson and Silver (1979, 1981) argued that a strike-slip fault with about 800 km of Jurassic left slip trends northwestward through northwestern Sonora, southwestern-most Arizona, and southeastern California. They stated that their unpublished reconnaissance U-Pb geochronologic study of Proterozoic gneisses and granites of Sonora shows rocks yielding ages of about 1.1, 1.5, and 1.6-1.7 Ga to be scattered widely about Sonora, whereas the southwest part of northern Sonora contains rocks yielding those ages and also ages of about 1.75 Ga. They inferred that the terrain with those slightly older rocks was juxtaposed against the northeastern terrain on the proposed strike-slip fault. They and others have incorporated this cryptic Mojave-Sonora Megashear in much speculation regarding California, Mexico, and the Gulf of Mexico. The uppermost Proterozoic and Paleozoic miogeoclinal section of central Sonora is viewed by megashear proponents as having been offset from the similar section of the Death Valley-southwest Mojave region of

California and juxtaposed against the cratonic section of southeastern California, southern Arizona, and northeastern Sonora (Anderson and Silver, 1979; Stewart and others, 1984).

Facies of Paleozoic strata in Sonora.--The megashear concept requires that any Paleozoic rocks southwest of the proposed fault in the region of the California-Arizona-Sonora corner be of outer-shelf or oceanic facies. Dated Proterozoic rocks in the south ends of the Gila and Cabeza Prieta Mountains were assigned by Anderson and Silver (1979) to their southwestern province, so their hypothetical megashear must lie northeast of the Cabeza Prieta--but the cratonic Paleozoic and lower Mesozoic section of Maria Mountains type is present southwest of that range, so the megashear can not exist. The distinctive cratonic section from Tapeats Quartzite through Redwall Marble is preserved in the Gila Mountains (S. J. Reynolds, written communication, 1987). The cratonic formations of the upper Paleozoic and lower Mesozoic--Supai through fossiliferous Kaibab, and Triassic strata, Aztec Quartzite, and Jurassic ignimbrite--are exposed in El Capitan in northwesternmost Sonora (Leveille and Frost, 1984; R. G. Gastil, F. G. Poole, and J. H. Stewart, oral communications, 1986, 1987).

The cratonic section is known in northeast as well as northwest Sonora. The miogeoclinal section is known in the southeast and northwest parts of central Sonora (Peiffer-Rangin, 1979; Stewart and others, 1984) and in that part of eastern Baja California which was adjacent thereto prior to Neogene slip on the San Andreas fault (Gastil and Miller, 1983). Eugeoclinal rocks are known in turn south of the miogeoclinal rocks of Sonora and palinspastically adjacent Baja California (Gastil and Miller, 1983; Peiffer-Rangin, 1979; Poole and others, 1982). Facies boundaries trend approximately east-southeastward across Sonora, which represents the southwest edge of Paleozoic North America, not the displaced northwest edge as predicted by the megashear concept.

Orocopia Suture

During Late Cretaceous or Paleocene time, the base of the continental plate as exposed in southeastern California was truncated and oceanic sedimentary and crystalline rocks, metamorphosed mostly at lower amphibolite facies, were emplaced against it. Plutonic rocks formed in magmatic arcs 100 km or so above older subducting plates are now in direct contact with subducted rocks. Windows exposing the base of the continental plate and the structurally underlying oceanic rocks, the Orocopia Schist, are present in a zone trending southeastward and eastsoutheastward through the Orocopia and Chocolate Mountains, Picacho Hills, and the Trigo, Middle, and Castle Dome Mountains (Haxel and Dillon, 1978). In the eastern Chocolate Mountains and the Picacho Hills, the contact between oceanic and continental rocks is marked by a meter or so of greenschist-facies mylonite, and late deformation within a few tens of meters of the contact records northeast-verging deformation. Field guides to these features are given by Haxel and others (1986) and Haxel and Tosdal (in Hamilton and others, 1987).

Haxel and Dillon (1978), Haxel and Tosdal (1986), and Haxel and others (1986) assumed that the shear sense of subduction, which was accompanied by amphibolite-facies metamorphism, was the same as that of the greenschist-facies mylonitization, and hence that subduction was southwestward. They suggested that the Orocopia Schist protolith was deposited in an oceanic basin that was closed by subduction southwestward under a minicontinent that might have been either transported from some distant site or have been rifted a short distance away from North America and then collided back against it. Haxel and Tosdal (1986) and Haxel and others (1986) preferred the latter option and proposed that a small ocean basin had opened by transtension along the Jurassic Mojave-Sonora megashear.

The cratonic Paleozoic and Mesozoic sections of El Capitan and the Gila Mountains, noted previously, lie south of the hypothetical suture and thus disprove both the exotic-minicontinent and megashear-basin interpretations.

The truncated base of the continent is exposed also in other parts of southern California--in and near the central Transverse Ranges, the southern Sierra Nevada, and the north-central Mojave Desert--where the oceanic rocks are known as the Pelona and Rand Schists, and the structural base of the overlying continental plate is termed the Vincent and Rand thrusts. In these areas also, there is no evidence for a suture between mainland North America and a southwestern plate. In the San Gabriel Mountains, a kilometer-thick zone of mylonitic gneiss, representing the same metamorphic facies as the underlying oceanic rocks and thus in striking contrast to the thin retrograde mylonite in the Chocolate Mountains, marks the base of the continental plate, and the probable vergence direction, after allowance for Miocene rotation indicated by paleomagnetic data, was southwestward. In the Rand Mountains in the Mojave Desert, a middle Tertiary detachment fault has cut out the Cretaceous megathrust and now forms the contact between continental and oceanic rocks (Postlethwaite and Jacobson, 1987), as I infer to be the situation also in southeastern California.

The Chocolate Mountains region was subjected to severe middle Tertiary extension, recorded by detachment faults above which upper-plate rocks have been rotated to southwest dips. The sense of slip on these detachment faults, some of which occur less than a kilometer from, and parallel to, the thin mylonite zone that marks the present base of old continental crust, is top-to-the-northeast, the same as that in the mylonite zone. Mylonite in the contact zone has a middle Tertiary K-Ar age (Frost and others, 1982). I regard the truncation of the continental plate and the transport beneath it of oceanic rocks as best integrated with regional geology in terms of northeastward subduction under mainland North America, during the late Late Cretaceous period of rapid convergence of North American and Farallon plates (Engebretson and others, 1985), of oceanic rocks from a trench and accretionary-wedge complex at the southwest edge of the continent. Other unusual tectonic features developed at the same time--the Santa Rosa mylonites of the Peninsular Ranges, the Laramide crustal shortening of the craton to the northeast, and possibly the coastal California Sur-Nacimiento megathrust (the character and age of which are disputed)--can be explained as related to this event (Hamilton, in press; also Dickinson and Snyder, 1978, and others). I see the late-stage semiductile deformation documented by Haxel and his associates as representing middle Tertiary extensional deformation superimposed on the older structures, and the present contact between continent and schist in the Chocolate Mountains region as an extensional ductile fault that cuts out the older megathrust.

Synmetamorphic Thrust Faults

My mapping of the Big Maria Mountains has proceeded intermittently since 1958, and I am still learning from this spectacularly deformed terrain. I early recognized the general stratigraphic sequence of Paleozoic metasedimentary rocks, but not the phenomenal extent to which those rocks could be attenuated tectonically and intercalated by isoclinal folding. My early field maps show numerous layer-parallel thrust faults to account for what I took to be stratal omissions. As my mapping became more detailed, I learned that discrete pre-Tertiary faults are highly exceptional and that severely attenuated units in normal succession were present along most of the contacts which I had classed previously as faults. Thus, I early inferred that extensive thrust faults placed Paleozoic metadolomite (which crops out conspicuously even where attenuated to a meter or two) against Proterozoic metagranite; but in detailed remapping I found that almost invariably the Bright Angel Schist and Tapeats Quartzite intervene continuously, though each might be only a meter thick and largely covered by rubble.

Although such flattening of course represents extreme deformation, it is in a pervasively ductile mode.

Granites in the Big Maria Mountains underwent pervasive ductile deformation to augen gneisses in the central and northern parts of the range, where metamorphic conditions varied upward from highest greenschist or lowest amphibolite. Under the greenschist-facies conditions in the southern part of the range, metasedimentary and metavolcanic rocks flattened in ductile mode whereas granitic rocks were recrystallized but not in general highly strained; synmetamorphic faulting is nevertheless all but lacking there also, and Paleozoic and Mesozoic units preserve continuity, and Tapeats Quartzite remains in contact with Proterozoic basement rocks, except where Jurassic granites or Tertiary brittle or semibrittle faults disrupted the sequence.

In the Riverside Mountains, by contrast, cohesion was lost in many zones during deformation, which occurred under lower greenschist facies and mylonitic conditions. The extent to which disruptive Tertiary mylonitization has there been superimposed on the effects of more cohesive Cretaceous synmetamorphic flattening has not been established.

My early mistaken overemphasis of thrust faulting in synmetamorphic deformation is, I believe, being repeated by other geologists who infer the crystalline complexes to be dominated by great overthrust sheets. I regard their inferred structures which I have examined in the field as largely products of pervasive regional synmetamorphic ductile deformation rather than of discrete faulting.

I see synmetamorphic deformation as represented commonly by pervasive pure and simple shear. At low strain rates and at temperatures greater than about 400°C, most rocks deform by pervasive, ductile flow, not by brittle faulting and the development of great thrust sheets. Rocks are almost as likely to be inverted as upright in pervasively deformed assemblages, so superposition of basement on cover rocks is not proof of overthrusting. Pervasive deformation can result in extreme isoclinal interfolding and flattening of rocks that maintained cohesion, so it is essential when dealing with metasedimentary rocks that the stratigraphic section be understood and that it be recognized that sequences, not thicknesses, provide the key to the presence or absence of faults. Great slip can be distributed through severely deformed rocks without the presence of major discrete faults. Such faults are, of course, present in rocks deformed at low temperatures.

Mule Mountains Thrust System.--Metavolcanic and metasedimentary rocks at the south ends of the McCoy and Palen Mountains lie concordantly above equally metamorphosed conglomerate of the McCoy Mountains Formation. Pelka (1973), Harding (1982), Harding and Coney (1985), and Harding and others (1983) assumed the metavolcanic rocks to correlate with the Jurassic metavolcanic rocks that lie depositionally beneath the McCoy in the north parts of the ranges and inferred the southern contact to be a great north-directed thrust fault. Tosdal (1986) designated this supposed fault the north strand of the Mule Mountains thrust zone.

The contact in question as exposed in the McCoy Mountains is abrupt, separates uniformly metamorphosed rocks, and displays no evidence for faulting. The ductile deformation at and near the contact appears identical to that of all other rocks in the southern part of the range. The metavolcanic rocks above the contact are undated. Those of the southernmost McCoy Mountains bear a casual resemblance--no detailed study has been made--to the Jurassic rocks to the north, except that abundant metasedimentary rocks are intercalated in the southern section. The metavolcanic rocks of the southernmost Palen Mountains are mafic, quite unlike the proved Jurassic rocks to the north (Pelka, 1973) although possibly resembling known Jurassic rocks to the east in Arizona (Tosdal, in Hamilton and others, 1987).

Harding and her associates asserted that a north-verging drag syncline lies beneath the supposed fault in the Palen and McCoy Mountains. No such structure exists, for the rocks at issue display south-verging deformation (Fig. 9); nor is such a structure present in the Coxcomb Mountains (Greene, 1968). Tosdal (1986) argued for the presence of an unexposed drag syncline in the southern Dome Rock Mountains, but his rationale requires great stratigraphic facies changes between the hypothetical north and south limbs.

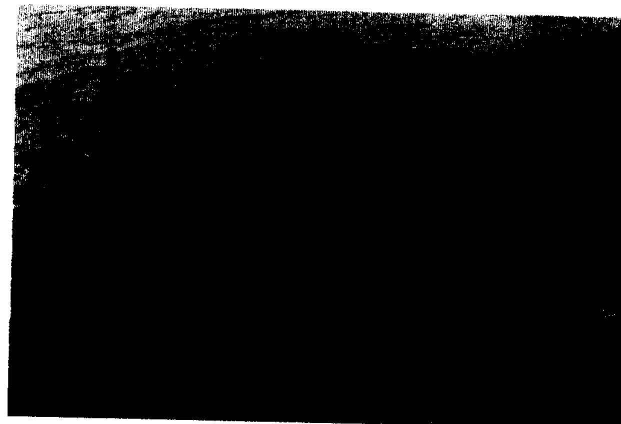

Figure 9. View southwest at southwest tip of McCoy Mountains, showing south-verging folds in metaconglomerate of McCoy Mountains Formation.

I suspect that the southern metavolcanic rocks lie stratigraphically above the McCoy Mountains Formation and are of Late Cretaceous age. If they do instead prove to be Jurassic, then severe ductile flattening of southern rocks of the McCoy will need to be incorporated in their explanation.

Tosdal (1986) placed the south strands of the "Mule Mountains thrust system" in the northern Mule Mountains. As Tosdal emphasized, the same Jurassic metagranitic and metavolcanic rocks occur on both sides of the supposed faults, which, like the south McCoy contact, are tight contacts within a regionally foliated terrain. I see no evidence for discrete faulting, although the foliation represents flattening and shear so that these metamorphic rocks, like all others in the region, might be regarded as vast zones of distributed thrusting. A field guide to exposures of the contacts is given by Tosdal (in Hamilton and others, 1987).

West-central Arizona.--Reynolds and others (1980, 1986) viewed the Cretaceous structures of west-central Arizona as dominated by thrust sheets. They depicted a Harquahala thrust as juxtaposing unlike terrains through much of the Harquahala Mountains. I have seen this proposed thrust in the White Marble Mine area, where it is the contact of Proterozoic metagranite atop Paleozoic metasedimentary rocks. The complete Paleozoic section is present, beginning with Tapeats Quartzite in unfaulted contact with the granite: the contact is an inverted unconformity. Paleozoic units are cut out against the granite contact farther west, but the fault so indicated need not be large.

Scarborough and others (1983) depicted a "Deadman thrust" of "stacked thrust plates" of metagranitic and metasedimentary rocks in the Plomosa Mountains. Reynolds and others (1986) incorporated the supposed thrust zone in regional synthesis. I have been over the area and found no faults. Scarborough and his associates overlooked isoclinal repetitions of upper Paleozoic and lower Mesozoic formations and misidentified various units; I found no out-of-sequence formations. Further, Scarborough and others (1983) assigned all of the metagranitic rocks to the Proterozoic, which if correct would require that any contact with upper Paleozoic metasedimentary rocks be a fault; but in fact the granite against such rocks is of Jurassic type, and skarn is present locally along contacts with Kaibab Marble.

S. J. Reynolds (written communication, 1987) reports that he now regards about half the aggregate length of previously designated thrust faults as representing instead pervasive flattening without discrete faulting.

McCoy Suture

Harding and Coney (1985) speculated that the McCoy Mountains Formation was deposited along what was then the southwest margin of North America and that it was accreted to the continent by being overthrust from the north by North American lithosphere and from the south by an exotic continental miniplate. The southern of these conjectural sutures is the contact, between metaconglomerate below and metavolcanic plus metasedimentary rocks above, at the south tips of the McCoy and Palen Mountains. As just discussed, I see no evidence for faulting there. Moreover, the cratonic Paleozoic and lower Mesozoic strata of El Capitan and the Gila Mountains lie southwest of the proposed suture but are like those to the northeast of it and so preclude the existence of a minicontinent unrelated to the rest of southeastern California.

Nor is the McCoy Mountains Formation overthrust from the north by North American lithosphere. In the northern Palen Mountains, there is, as described previously, a continuous, concordant section from the McCoy Mountains Formation down through the Jurassic meta-ignimbrite, Aztec Quartzite, and Triassic metaclastic rocks, to Kaibab Marble and underlying Paleozoic strata, all in stratigraphic order. The McCoy Mountains Formation was deposited on cratonic North America. McCoy rocks have been identified also within the cratonic terrain of the Granite Wash Mountains (Reynolds and others, 1986), north of the limit assigned them by Harding and associates.

MESOZOIC HISTORY

The rocks and structures discussed on these pages can be fitted into a history of southeastern California and adjacent areas. The Triassic and Early Jurassic were times primarily of cratonic sedimentation, but Late Triassic arc magmatism in the southwestern part of the region was accompanied by uplifts from which coarse clastic materials were shed northeastward. Intense arc magmatism in Middle and Late Jurassic time resulted in the emplacement of many granitic batholiths and the eruption of widespread ignimbrite sheets over the cratonic section. Although local deformation must have accompanied emplacement of the plutons, there was little regional deformation, for younger strata tend to lie upon the volcanic rocks rather than older units. Latest Jurassic(?) and Early Cretaceous rifting formed basins, the structural character of which is still undefined, that trended northwestward into the region from the Gulf of Mexico and were flanked on the northeast by highlands. The thick fluvial McCoy Mountains Formation was deposited in one such basin. There was intense arc magmatism farther southwest at this time, so the rifting was in a back-arc mode. When convergence between North American and Farallon plates accelerated in Late Cretaceous time, the subducting oceanic plate could no longer sink out of the way of the overriding continental plate, and the continental plate was eroded from beneath against oceanic materials that are now exposed as the Orocopia Schist. At about the same time, there was general midcrust metamorphism at elevated temperatures, accompanied by pervasive deformation and widespread formation of granites from hydrous magmas, in the Maria Mountains and elsewhere farther inland. Hot water from metamorphosing subducted oceanic rocks may have caused the crustal heating (Hoisch, 1987b), and drag against them may have contributed to the deformation.

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