SEDIMENTOLOGY AND TECTONIC SIGNIFICANCE OF THE COPPER BASIN FORMATION IN THE EASTERN WHIPPLE MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geology

by
Derrick Brehm Teel
Spring 1983
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Approved by:

[Signatures]

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[Date]
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Cenozoic tectonic activity in southeastern California and western Arizona is characterized by the development of a system of regionally extensive, low-angle normal faults or detachment faults during mid-Tertiary time. These faults appear to have developed coevally with major antiforms and synforms which occur on a variety of scales, from outcrop to regional anticlinorium size. Formation of these crustal highs and lows appears to be genetically related to the distribution and facies patterns of mid-Tertiary clastic and volcanic rocks. Because detachment faulting and upper-crustal folding appear to have occurred over at least a ten-million-year period (approximately 26 to 16 m.y.B.P.), their development is recorded by the stratigraphic record that accumulated during this time interval. By examining this stratigraphic record, the development of detachment-related deformation and sedimentation can be interrelated and collectively deciphered.

This study is concerned with the examination of the Copper Basin Formation which is located in the eastern Whipple Mountains of southeastern California. This
particular unit possesses an excellent synorogenic record of the Miocene tectonic development of this region. The stratigraphy, depositional environments, paleocurrent directions, petrography, and history of the formation are all directly related to the tectonics of the Whipple Mountains area.

**Regional Setting**

The Whipple Mountains, which are located in San Bernardino County, California, are an east-west elongate range located near the western margin of an extensive enigmatic tectonic terrane frequently referred to as the Mojave-Sonoran detachment terrane. This terrane is characterized by large-scale, low-angle normal faults termed detachment faults. Detachment faulting is considered to be a result of a mid-Tertiary extensional event that reflects the passage of the mid-Tertiary magmatic arc through this region (Crittenden and others, 1980). The terrane extends south-southeastward from the Las Vegas-Lake Mead Shear Zone in southernmost Nevada, across central and southern Arizona, down an unknown distance into Sonora, Mexico (Anderson, 1971, 1973, 1977, 1978; Shackelford, 1976, 1980; Crittenden and others, 1980; Carr and Dickey, 1975, 1976, 1977, 1980; Carr and others, 1980; Carr, 1981; Coney, 1980; Coney and Reynolds, 1977; Davis and others, 1977, 1979a, 1979b, 1980a,
1980b; Davis, 1975, 1979, 1980; Davis and Coney, 1979; Anderson and others, 1979a; Frost, 1979, 1981a, 1981b; Dickey and others, 1980; Martin and others, 1981; Rehrig and Reynolds, 1977, 1980; Rehrig, 1981, 1982; Reynolds, 1980; Otton, 1981a, 1981b, 1982; Lucchitta and Suneson, 1977a, 1977b, 1978, 1980, 1981; Cameron and others, 1981). The lateral extent of this terrane is ambiguous as well. To the west, extensional features recognized in the proximity of the San Andreas fault zone suggest that detachment faulting is present from Arizona, west to the San Andreas, and also west of the post-detachment strike-slip fault (Frost, 1981c; Frost and others, 1981, 1982b; Wallace, 1982; Wallace and English, 1982). To the east, detachment faulting appears to extend into the Rio Grande Rift region, although its full relationship to extension in the Rio Grande Rift has not been well documented (Figure 1). The Mojave-Sonoran detachment terrane along the Colorado River has been the object of intensive study. This portion of the terrane is characterized by numerous isolated mountain ranges that are considered to be a regionally coextensive Tertiary detachment fault complex. The Whipple Mountains are an integral part of this low-angle fault complex (Davis and others, 1979a, 1980a, 1980b).
Figure 1. Regional tectonic map illustrating present recognized extent of mid-Tertiary detachment faulting in the Mojave-Sonoran detachment terrane.
Local Geologic and Geographic Setting

The Whipple Mountains of southeastern California are situated adjacent to Lake Havasu, a reservoir created by Parker Dam, a hydroelectric facility on the lower Colorado River. The range occupies approximately 550 km$^2$ within a pronounced eastward salient of the Colorado-Arizona border. The immediately adjacent Buckskin Mountains of west-central Arizona are considered structurally and lithologically related to the Whipple Mountains (Davis and others, 1977, 1979a, 1979b, 1980a, 1980b; Frost, 1979, 1981a, 1981b, 1983) and are separated only by the Colorado River and the concordant interstate boundary (Figure 2).

The rocks of the Whipple Mountains and those of the coextensive detachment terranes of the Buckskin and Rawhide Mountains to the southeast are divisible into three basic units (Shackelford, 1976; Davis and others, 1980a; Frost, 1981b, 1983). The oldest rock unit consists predominantly of both mylonitic and nonmylonitic, quartzo-feldspathic gneiss of Precambrian age. These rocks are separated from overlying units by a low-angle detachment surface and are regarded as occupying an autochthonous lower-plate position relative to overlying rocks. The rocks overlying the detachment surface are referred to as upper-plate rocks and are considered to be allochthonous to varying degrees (Shackelford, 1975, 1976, 1977, 1980; Davis and others,
Figure 2. Index map of the Whipple Mountains. Enclosed region is shown in Figure 3.
The older of the two remaining upper-plate units is composed predominantly of Precambrian, nonmylonitic, quartzo-feldspathic gneisses; a Precambrian granite porphyry; and a variety of synkinematic Mesozoic and Tertiary intrusive rocks (Anderson and others, 1979b; Davis and others, 1979a, 1980a; Anderson and Krass, 1980; Anderson and Rowley, 1981). The younger upper-plate units that nonconformably and, locally, tectonically overlie the crystalline basement complex are composed of Oligo-Miocene sedimentary and volcanic strata that include the Gene Canyon, Copper Basin, and Osborne Wash Formations (Figure 3).

Previous Geologic Studies

Some of the earliest geologic studies completed on the Whipple Mountains were those of Ransome (1931, 1933), a consulting geologist for the Metropolitan Water District of Southern California (MWD). Ransome described the presence of a low-angle fault in the Bowmans Wash area of the southeastern Whipple Mountains. He speculated that this fault was probably a thrust fault. Ransome (1931) is responsible for naming the basic lithologic units in the Whipple Mountains and is possibly the first geologist to recognize the presence of low-angle faults in the Colorado River trough (Davis and others, 1979a, 1980a).
Figure 3. Generalized geologic map of the central and eastern Whipple Mountains, San Bernardino County, California. From Davis and others (1980a).
Shortly thereafter, Kemnitzer (1937), intrigued by Ransome's findings, mapped the eastern half of the Whipple Mountains as his doctoral dissertation. Kemnitzer's interpretations differed from those of Ransome in that Kemnitzer believed that high-angle normal faulting and associated uplift were responsible for the existing structures. Although he recognized movement along some of the Tertiary-basement rock contacts, he dismissed them as unconformities. Kemnitzer regarded thrust faulting as an unlikely mechanism for the development of the Whipple Mountains (Davis and others, 1979a, 1980a).

Subsequently, for more than 30 years the Whipple Mountains received little geologic attention until Terry (1971, 1972) again recognized the presence of a low-angle fault surface. Terry, however, did not recognize the tectonic nature of the contact between Tertiary rocks and crystalline basement rocks. She, like Kemnitzer, interpreted these contacts as unconformities. Similar to Ransome, however, Terry regarded the low-angle fault contact between upper- and lower-plate crystalline rocks as a thrust fault of probable Mesozoic age.

Concurrent with Terry's (1971, 1972) work in the Whipple Mountains, Anderson (1971) first recognized that low-angle faulting in the Eldorado Mountains of southeastern Nevada was related to extensional tectonism rather than
compression. Anderson's conception of imbricate normal faults that flatten with depth and merge with a basal detachment surface provided the groundwork for forthcoming reinterpretation and remapping of much of the Colorado River region, including the Whipple Mountains.

Association of the low-angle fault with the high-angle normal faults was first made by Davis during reconnaissance mapping of the range for the Vidal nuclear power plant (1974). His work demonstrated that the same style of extensional faulting existed in the Whipples as that being studied in the nearby Rawhide Mountains by one of Davis' students, Terry Shackelford (1976). At that time, Davis proposed gravitational sliding as the mechanism responsible for the juxtaposition of younger strata over older crystalline rocks (Davis and others, 1977, 1979b). Since then, continued study by a number of Davis' students and associates (Lingrey and others, 1977; Anderson and others, 1979a, 1979b; Davis and others, 1977, 1979a, 1979b, 1980a, 1980b; Evans, 1979; Frost, 1979; Lingrey, 1979; Prodruski, 1979; Anderson and Krass, 1980; Anderson and Rowley, 1981; Lopez, 1978, 1981; Krass, 1980, 1982; Rowley, 1980; Thurn, 1982a, 1982b, Osborne, 1981; Woodward, 1981; Woodward and Osborne, 1980) has refined previous interpretations and has made a considerable contribution toward the understanding of the geology of the Whipple Mountains.
Purpose

Although a substantial amount of information has accumulated that describes the structural and petrologic aspects of the crystalline rocks in the Whipple Mountains and adjacent ranges, the Tertiary continental deposits of the upper plate have remained relatively unstudied from a sedimentologic and genetic standpoint. The significance of these rocks and their reflection of the geologic evolution of the Whipple Mountains and adjacent portions of west-central Arizona have been recognized by a number of workers (Eberly and Stanley, 1978; Davis and others, 1979a, 1980a; Frost, 1979, 1981a, 1983; Frost and Otton, 1981; Pridmore and Craig, 1982; Teel and Frost, 1982). The insight gained by the study of these and similar synorogenic deposits of the region may contribute significantly toward further understanding of the Tertiary structural evolution and stratigraphy of large parts of the Cordillera.

The Copper Basin Formation, which is so spectacularly exposed in the eastern portions of the Whipple Mountains, provides an excellent opportunity for examination of the complex interrelationships between detachment faulting, structural development of the Whipple range, and upper-plate normal faulting associated with mid-Tertiary extension.
The purpose of this investigation is three-fold: (1) to describe and define the sedimentologic features and depositional environment of the Copper Basin Formation; (2) to demonstrate the genetic relationships between detachment faulting, large-scale crustal folding, and syntectonic (growth-fault) development of the formation associated with upper-plate normal faulting in the Whipple Mountains; and (3) to propose a model for the development of these features during mid-Tertiary time.

Method

The study area includes the type section of the Copper Basin Formation which is located in the southeastern Whipple Mountains, south of Bandit Pass, immediately adjacent to the Copper Basin Reservoir. Additional reconnaissance and sampling was conducted in a second well-developed sedimentary section of the formation exposed adjacent to Gene Wash Reservoir, 5 km to the east of Copper Basin Reservoir (Plate I). The region is covered by the U.S. Geological Survey Gene Wash 7.5 minute quadrangle topographic map. Field investigation included examination of stratigraphic, sedimentologic, and structural features. Laboratory study consisted of petrographic description of thin sections sampled from both localities.
CHAPTER TWO

Tertiary Continental Deposits of the Upper Plate

General Statement

The mid-Tertiary Gene Canyon, Copper Basin, and Osborne Wash Formations compose the youngest upper-plate stratigraphic units in the Whipple Mountains. These units collectively record the mid-Tertiary continuum and subsequent termination of detachment-related deformation that affected this region during Oligo-Miocene time.

Gene Canyon Formation

The oldest of the three Tertiary sedimentary and volcanic units is the Gene Canyon Formation. These deposits nonconformably overlie the crystalline rocks of the upper plate. At its type locality, the Gene Canyon Formation is composed of 526 meters of red to buff-colored, coarse sandstone, fanglomerate, and intercalated breccia composed of metamorphic and volcanic fragments (Kemnitzer, 1937). Ash-flow tuffs, andesitic volcanic flows, and lacustrine beds are observable at other outcrop localities (Frost, 1983).

Stratigraphically, the formation displays progressively higher energy deposits up-section, indicating that
an active tectonic environment became increasingly influential during its deposition. Lower portions of the unit are characterized by lacustrine beds, pebbly mudstones, and grus deposits. These deposits coarsen upward into debris flow, landslide, and coarse fanglomerate deposits characteristic of middle and upper parts of the formation. Finally, the presence of andesitic flows and ash flow tuffs may be suggestive of a proximally located calderan complex (Frost, 1983).

The age of the Gene Canyon Formation is not easily demonstrable. A single Artiodactyl (giant pig) track discovered by Kemnitzer (1937) suggests a late Oligocene to early Miocene age. Isotopic study of volcanic flows near the base of the Gene Canyon Formation has yielded ages ranging from $25.7 \pm 1.7$ m.y.B.P. ($\text{K}/\text{Ar}$, biotite) to $31.8 \pm 3.2$ m.y.B.P. ($\text{K}/\text{Ar}$, biotite) or late Oligocene (Martin and others, 1980; Davis and others, 1982). Basal volcanic flows of the overlying Copper Basin Formation have yielded age dates ranging from $17.1 \pm 0.8$ m.y.B.P. ($\text{K}/\text{Ar}$, whole rock) to $18.7 \pm 0.6$ m.y.B.P. ($\text{K}/\text{Ar}$, whole rock) or mid Miocene (Martin and others, 1980; Davis and others, 1982). The age of the Gene Canyon Formation can, therefore, be bracketed to be older than about 18 m.y. and younger than about 32 m.y. Dates extracted from the correlative Artillery Formation in the Rawhide and Buckskin Mountains to the southeast
are compatible with these age determinations (Lasky and Webber, 1949; Eberly and Stanley, 1978; Lucchitta and Suneson, 1980).

**Copper Basin Formation**

The mid-Miocene Copper Basin Formation is the best exposed and preserved Tertiary unit in the eastern Whipple Mountains. In some areas, the formation overlies the Gene Canyon Formation above a pronounced angular unconformity, whereas in other areas the two formations are conformable. In many portions of the Whipples, the Copper Basin Formation lies directly on upper-plate crystalline rocks with no intervening Gene Canyon rocks (Figures 4 and 5). The unit is composed of interbedded, brick red to reddish-brown sandstone, fanglomerate, and volcanic rocks. The Copper Basin Formation in its type locality is composed exclusively of coarse- to fine-grained clastic material suggestive of a proximal, tectonically active source area.

**Osborne Wash Formation**

The Osborne Wash Formation unconformably overlies the Gene Canyon and Copper Basin Formations, as well as upper- and lower-plate crystalline rocks in both the southern Whipple and western Buckskin Mountains. The formation is composed of olivine-bearing basalt flows, agglomerate, tuff, and alluvial debris that were deposited after mid-
Figure 4. Angular unconformity between the Gene Canyon Formation and the overlying Copper Basin Formation in Gene Canyon in the southeastern Whipple Mountains.
Figure 5. Ground view to the northwest of Copper Basin showing the nonconformable contact between upper-plate crystalline rocks (light) and overlying Copper Basin Formation volcanic rocks (dark).
Miocene detachment-related deformation. These deposits are largely undeformed but dip slightly to the southwest as a result of normal faulting associated with Pliocene basin-range type extension (Davis and others, 1979a, 1980a; Davis and Anderson, 1982).

The age of the base of the Osborne Wash Formation has been determined isotopically to be between 15.9 ± 2.8 m.y.B.P. (K/Ar, plagioclase) and 13.5 ± 1.0 m.y.B.P. (K/Ar, whole rock), or mid to late Miocene (Kuniyoshi and Freeman, 1974; Martin and others, 1980). Similar ages have been extracted from presumably correlative basaltic flows to the west of the Rawhide Mountains (Eberly and Stanley, 1978; Suneson and Lucchitta, 1979). These studies effectively document both the upper limit of Copper Basin Formation deposition and the termination of detachment-related deformation in the Whipple-Buckskin-Rawhide terrane (Davis and others, 1979a, 1980a).

The Osborne Wash Formation reflects the inception of fundamentally basaltic volcanism in the region. Chemical parameters of the formation indicate a deep mantle origin for the volcanic material, indicating a transition from andesitic, magmatic arc related volcanism of the Copper Basin and Gene Canyon Formations to post-subduction mafic volcanism associated with a changing plate tectonic configuration (Suneson, 1980).
CHAPTER THREE
Copper Basin Formation

Nomenclature and History

The Copper Basin Formation was first recognized and named by Ransome (1931, 1933) in his reports to the Metropolitan Water District concerning the Colorado River Aqueduct Project. Both the Gene Canyon Formation and the Copper Basin Formation were named after the areas where they are best exposed—in Gene Canyon and Copper Basin, respectively—although a specific type section or formal stratigraphic definition was never established for these two units. Despite the fact that the Copper Basin Formation has become an accepted lithostratigraphic unit in the Whipple Mountains by some authors, no formal entry into the U.S. Geological Survey Lexicon of geologic names has been made.

During his study of the overall structure and geology of the Whipples, Kemnitzer (1937) briefly described the Copper Basin Formation, its internal structures and stratigraphic relationships to adjoining units. Kemnitzer (1937) recognized the nature and extent of the unconformity between the Copper Basin Formation and underlying units. He also recognized that the same deformational scheme that
had affected the Gene Canyon Formation prior to the deposition of the Copper Basin Formation had continued to deform the younger Tertiary unit as well.

Kemnitzer (1937, p. 25) described the rocks of the Copper Basin Formation as "... a series of red and reddish-brown sandstones and conglomerates, with hard shales, lava flows and volcanic breccia, presumably Tertiary in age."

Age and Regional Correlation

The age of the Copper Basin Formation cannot be precisely determined from paleontological evidence. Kemnitzer (1937) discovered carnivore tracks that suggest a Miocene age for the formation, as did Gassaway (1972, 1977) for correlative units to the east. Subsequent isotopic studies have provided age constraints for the deposition of the formation. The basal volcanic flow of the formation has been dated at 18.7 ± 0.6 m.y. (Martin and others, 1980). This same flow located on the high klippe in the central Whipples has yielded age dates of 17.1 ± 0.8 m.y. and 18.0 ± 0.8 m.y. (Martin and others, 1980). Volcanic flows of the Copper Basin Formation are locally intruded by a distinctive "turkey-track" or "jackstraw" andesite that has been dated at 17.1 ± 0.5 m.y. and 17.9 ± 0.7 m.y. (Martin and others, 1980). Clastic rocks of the formation are locally overlain by volcanic flows of the Osborne Wash
Formation, previously described. These flows in the southwestern Buckskin Mountains have yielded ages of $13.5 \pm 1.0$ m.y., $12.9 \pm 0.6$ m.y., and $15.9 \pm 2.8$ m.y. (Marvin and Dobson, 1979; Dickey and others, 1980; Martin and others, 1980). These dates effectively bracket the deposition of the Copper Basin Formation to be between approximately 18 and at least 16 m.y.B.P.

In addition, conglomeratic clasts derived from basal and interbedded volcanic flows within the Copper Basin Formation are incorporated within the sediments, indicating that erosion and redeposition of these clasts as detritus of the formation must have occurred after 18 m.y. and prior to the deposition of the Osborne Wash Formation.

Alluvial deposits similar to the Copper Basin Formation have been described in a number of ranges throughout much of southeastern California and southwestern Arizona. These presumably synorogenic deposits have been extensively studied by a number of workers including Lasky and Webber (1949), Gassaway (1972, 1977), Shackelford (1976, 1980), Lucchitta and Suneson (1977a, 1977b, 1978, 1980), Scarborough and Wilt (1979), Suneson (1980), Osborne (1981), Otton (1981a, 1981b, 1982), Woodward (1981), Woodward and Osborne (1980), and Heidrick and Wilkins (1980). Where most of these authors studied Copper Basin Formation correlative sediments, the unit is termed the Chapin Wash
Formation after exposures in Chapin Wash in the Artillery Peak area (Lasky and Webber, 1949). Perhaps the best studied of these areas of western Arizona are the deposits of the Date Creek Basin (Sherbourne and others, 1979; Otton, 1981b; Scarborough and Wilt, 1979). In this region, the Chapin Wash Formation was deposited in northeast/southwest-trending basins that developed coevally with the uplift of the Harcuvar and Buckskin Mountains (J. K. Otton, 1981b, pers. comm., 1982). Deposits such as these, reflecting Tertiary Cordilleran tectonic evolution, have been described as far north as northeastern Washington (Gager, 1981) and as far south as the Baker Peaks in Arizona, near the U.S.-Mexico border (Pridmore and Craig, 1982).

**Lithologic Descriptions**

**General Statement**

The Copper Basin Formation is a mixture of alluvial clastic rocks and contemporaneously deposited volcanic and volcanioclastic rocks of mid-Miocene age. The east-central portion of the range is characterized by predominantly volcanic and volcanioclastic rocks, while the south and southeastern portions contain mostly sedimentary rocks (Davis and others, 1979a, 1980a).
Volcanic Facies and Associated Rocks

The volcanic and volcaniclastic rocks of the Copper Basin Formation are best exposed in the east central Whipple Mountains in the vicinities of Whipple and Bowmans Washes. At these localities, the volcanic rocks are in the form of massive flows of variable thicknesses (3-75 m), which commonly form large, resistant cliffs (Davis and others, 1979a, 1980a; Frost, 1983). These volcanic rocks are predominantly andesitic(?) in composition. Cavernous voids and a dark, red-brown coloration are characteristic weathering features of these rocks (Figure 5).

In addition to volcanic flows, there are hypabyssal rocks that have intruded into the upper-plate crystalline and Tertiary sedimentary units. Their composition is probably andesitic also, and they possess a distinctive texture characterized by lath-like plagioclase phenocrysts suspended in a darker, fine-grained groundmass (Frost, 1983). These rocks are termed "turkey-track" or "jackstraw" andesite and are frequently found as conglomeratic clasts within the sedimentary facies of the Copper Basin Formation. Although these rocks form well-developed, intrusive relationships in some areas such as lower Whipple Wash and the Aubrey Hills, the "jackstraw" unit forms extrusive flows in other parts of the Whipples.
Sedimentary Facies

In the southeastern portion of the range, the Copper Basin Formation is composed of coarse- to fine-grained, alluvial clastic rocks which overlie and interfinger with the volcanic rocks. In the Whipple Mountains, the formation is preserved as part of numerous irregular, fault-bounded blocks (Figures 3 and 6). The two best exposures of the sedimentary facies are in the southernmost parts of the two easternmost fault blocks: the Copper block, and the Gene block. The Copper block and the Gene block are situated adjacent to Metropolitan Water District's Copper Basin and Gene Wash reservoirs, respectively. The Copper Basin Formation, at its type locality in the southern portion of the Copper block, is composed of approximately 1,000 meters of interbedded fanglomerate, sandstone, siltstone, and mudstone. Despite the considerable thickness of this section, a complete stratigraphic section of the unit is not preserved because of extensive post-depositional erosion (Figure 7).

The sedimentary strata of the formation possess a heavy desert varnish, commonly half a centimeter or more in thickness, that imparts a uniform, dark brick-red color to the rocks, making their distinction from Copper Basin volcanic units, and sometimes bedrock, difficult to make
Figure 6. Aerial view to the southwest across the eastern Whipple Mountains showing the lithologic contacts between the Copper Basin Formation (dark), and the upper-plate crystalline rocks (light) of the area. Note the linear configuration of the consecutive topographic ridges, formed by the repetition of the same sequence. Lake Havasu in foreground. Photo courtesy of John S. Shelton.
Figure 7. Aerial view to the southeast across Copper Basin Reservoir. Type section of Copper Basin Formation on far side of reservoir. Note stratigraphically lower portions of the unit (to the left) dip more steeply than upper portions (to the right).
from a distance. Cavernous voids up to several meters across are also a characteristic weathering phenomenon of these rocks. The formation, in general, is highly indurated, although vertical and lateral changes in resistance are observable. Depositionally, the sedimentary facies of the Copper Basin Formation represent sedimentation by an alluvial fan system, as indicated by the rhythmic stratification of the formation and development of characteristic sedimentary structures and facies.

Stratification and Sedimentary Structures

A variety of stratification types and sedimentary structures are preserved in the Copper Basin Formation sedimentary facies. Sedimentary structures that have been recognized include planar cross-stratification and lamination (McKee and Weir, 1953), poorly defined current ripple and associated ripple cross-lamination, load features, and stream scour troughs with associated lag gravels. Desiccation cracks in fine-grained rocks are also relatively commonly preserved (Figures 8, 9, 10, 11, and 12).

Characteristic of stratification in both the Gene and Copper blocks is the extensive sheet-like character of bedding. At its type locality, Copper Basin Formation sedimentary strata possess extraordinarily regular and continuous stratification. Individual beds can be traced
Figure 8. Planar-based, medium-scale, cross stratification in pebbly, coarse-grained sandstone.
Figure 9. Planar-based, cross lamination in pebbly, coarse sandstone. Laminae are the result of numerous sheet-flood episodes.
Figure 10. Asymmetrical ripple marks in fine-grained sandstone overlain by pebbly, coarse-grained sandstone layer. Note normally-graded nature of rippled layer.
Figure 11. Injection structures in coarse sandstone.
Figure 12. Stream channel filled with lag gravel. Note bedding at margin of channel has been erosionally truncated by channel scour.
out laterally for several hundreds of meters and often for a kilometer or more (Figure 13). The full extent of the stratified sheets cannot be determined because faulting has truncated bedding at the eastern margin of the Copper block. The type section is composed of interbedded fanglomerate, sandstone, and siltstone-mudstone. Stream channel deposits are randomly dispersed throughout the section.

**Conglomerate Lithofacies**

Conglomeratic deposits compose between 20 and 25 percent of the Copper Basin Formation sedimentary section at its type locality. The conglomerates of the unit are both matrix-supported fanglomerates of debris flow deposits (paraconglomerate) and clast-supported stream channel deposits (orthoconglomerate) (see Depositional Environments, Processes, and Facies Development section). In both the paraconglomerate and orthoconglomerate deposits, sedimentary structures are absent, and clast imbrication and grading is localized and rare. Beds of paraconglomerate typically range from 20 or 30 cm to a meter or so in thickness. Clast sizes within the formation range from pebbles a centimeter in diameter to boulders in excess of a meter in diameter.
Figure 13. View along strike of the type section of the Copper Basin Formation. Note lit-par-lit layering and lateral continuity of strata.
Sandstone Lithofacies

Sandstone occurs both as beds and as the matrix of fanglomeratic units. Sandstone is the predominant clastic rock type in the Copper Basin Formation sedimentary facies, composing about 70 percent of the unit at the type locality. Like the conglomerate beds, the sandstone beds range from about 20 cm to a meter or more in thickness. Sandstone bodies are commonly tabular and reflect deposition by numerous sheet-flood episodes. In the sandstone, planar cross-stratification is the dominant primary sedimentary structure. Medium and small-scale (2-50 cm) cross-stratification are both locally observable. Horizontal and inclined planar stratification are also relatively common and many apparently structureless sandstone beds are probably horizontally stratified. Frequently observable are normal, reverse, or reverse to normal grading (Figures 14 and 15).

Siltstone Lithofacies

The fine-grained rocks of the Copper Basin Formation compose the smallest percentage of the sedimentary strata (5 to 10%). The siltstone and mudstone are rhythmically intercalated with the coarser clastic lithofacies, indicating the waning phases of ephemeral water flooding on the fan when competency was sufficient to transport only
Figure 14. Normal grading in sandstone bed.
Figure 15. Reverse-to-normal grading in sandstone layer.
fine-grained material following deposition of coarser clastic deposits. The fine-grained rocks are horizontally laminated, but internal lamination is commonly indistinct. The siltstone and mudstone laminae are generally a centimeter or so in thickness and commonly display desiccation cracks, indicating deposition in an arid subaerial environment. The thickness of some of the siltstone and mudstone layers, the presence of normal grading, and the lack of internal structure suggest that deposition from suspension may have been a key factor in their development.

Distal alluvial-fan facies are recognized to overlap with playa lake environments in modern analogs. Sheet-flood discharge into such an environment would result in turbid water conditions and consequent deposition of fine-grained material by settling. Subsequent evaporation of the playa would result in desiccation of the fine-grained sediments. A non-erosive contact between siltstone-mudstone layers and superjacent beds is indicated by the preservation of up-turned desiccated mud curls that ordinarily remain completely intact and in situ (Figure 16).

Discussion

Tectonic deformation coeval with sedimentation has resulted in the development of a distinctive stratigraphic
Figure 16. Upturned mud curls in thin mudstone layer. Note that sand has filled in the desiccation cracks, but the fragile mud flakes remain preserved.
geometry for the Copper Basin Formation. Copper Basin strata in the eastern Whipple Mountains are preserved as part of elongate fault-bounded blocks that have been rotated in some places in excess of $90^\circ$ to the southwest. The Copper Basin Formation, as well as a portion of the underlying Gene Canyon Formation, exhibit a growth-fault character demonstrated by a progressive decrease in dip of individual strata up-section (Figure 17). Basal strata of the Copper Basin Formation at its type locality dip at approximately $60^\circ$ to the southwest, while beds close to the top of the section dip at about $20-30^\circ$, indicating that the formation has been rotated through a vertical arc of at least $30^\circ$ during its deposition (Figure 7). This unique geometry requires that individual beds within the formation must progressively thicken to the southwest relative to northeastern portions of the unit.

Stratigraphic development of the sedimentary facies is characterized by autocyclically-generated, small-scale, fining-upward sequences. Each sequence records a sedimentation pulse on the fan whereby initial coarse clastic deposits are followed by progressively finer-grained, more fluidized deposits reflecting systematically decreasing transport energies on the fan. Plate II is a representative stratigraphic columnar section illustrating the stratigraphic development of the sedimentary facies and its
Figure 17. View in the east-central Whipples, near Whipple Wash, of the Gene Canyon Formation and the overlying Copper Basin Formation. Rocks of the Gene Canyon Formation are shown here dipping more steeply than the overlying Copper Basin volcanic rocks. The growth-fault development of this Tertiary section indicates that detachment faulting was active during most of the deposition of these units (26 m.y.B.P. to 16 m.y.B.P.)
associated sedimentary structures.

Stratigraphic correlation between the Copper and Gene block sections of the Copper Basin Formation was attempted, but tilting of the unit, significant erosion of intrablock strata, the generally homogeneous nature of the formation, and the lack of distinctive stratigraphic horizons rendered this impossible.

**Paleocurrents**

Despite an abundance of sedimentary structures within the Copper Basin Formation, sedimentary strata with suitably developed paleocurrent indicators are scarce and often tenuous. A total of 22 measurements, made at different localities within the type section of the formation, reflect a generally southward transport direction. To estimate the orientation of the preferred direction, or lines, of current movement, the resultant vectors for 16 unipolar indicators and average strike for 6 bipolar indicators were calculated from data represented on a circular histograms. The average strike of bidirectional current indicators is S 10°W, while vector resultant directions for unidirectional data average S 23°E. Modal directions were established at 30-degree intervals after Potter and Pettijohn (1977) (Plate I).

**Directional Current Features**

Unidirectional paleocurrent data include asymmetrical
ripple marks and ripple cross-lamination, cross bedding, and imbricated pebbles and cobbles. Bidirectional features are symmetrical ripple marks and channels (Plate I).

All of the paleocurrent features observed originated as a result of southward-flowing currents. The variation in azimuth of unidirectional data is attributable to the radial depositional characteristics of alluvial-fan deposits below the intersection point where incised ephemeral streams intersect the fan surface and shed clastic debris in sheet-like fashion as a result of the loss in confinement.

Many of the bipolar current indicators may be explained by southerly-flowing currents as well, since they infer no unique direction of transport and closely approximate the azimuthal distribution of unidirectional data. Ripple lamination, on the other hand, may have formed as a result of wind-generated currents in shallow ephemeral bodies of water and therefore bear no relationship to the overall basin paleogeography. Furthermore, structures examined by Nilsen (1969) that possess up-current dips suggestive of current flow opposite to that of the majority of orientations probably resulted from the preservation of antidune bedforms such as have been described by Harms and Fahnestock (1965).
Clast-Size Distribution

The significance of particle size distribution in alluvial-fan deposits has been recognized by various workers (Blissenbach, 1952; Bull, 1962; Passega, 1964). Maximum sizes of conglomerate clasts were measured at 35 localities in both the Copper and Gene blocks in the southeastern Whipple Mountains (Figure 18).

Clast sizes appear to be larger at the eastern extent of both the Copper and Gene blocks in the stratigraphically lowest parts of the sections. Westward and up-section, the clast size decreases. The irregular distribution of clast sizes, particularly within the type section, is attributable to at least two factors: (1) the northeast-facing fault scarps developing at the eastern margins of the fault blocks (associated with mid-Tertiary upper-plate extension) were supplying coarse clastic detritus to the coevally evolving alluvial fan system; and (2) the southwest tilting of the formation in both the Copper Basin and Gene Canyon sections results in only a limited northeast to southwest exposure (perpendicular to strike) of individual beds.

Depositional Environments, Processes and Facies Development

The sedimentary rocks of the Copper Basin Formation are far removed and clearly unassociated with any known
Figure 18. Map of Copper Basin and Gene Canyon sections showing maximum conglomerate clast size distributions.
Miocene marine deposits. Fossils, although virtually non-existent, are all terrestrial vertebrates (Kemnitzer, 1937; Gassaway, 1972, 1977). Rocks of widely ranging grain sizes are present as continuous sheet-like strata with rapid changes in lithofacies. An alluvial environment of deposition is indicated for the formation, based on the presence of distinctive facies and sedimentary structures. The coarse grain size of some of the rocks and the abrupt facies changes suggest that high gradient streams were important.

The sedimentary portion of the Copper Basin Formation exposed at its type locality, and in adjacent areas to the southeast, is composed of debris-flow deposits, sheetflood deposits, and stream channel deposits.

Debris-Flow Deposits

Debris flow deposits compose about 15-20 percent of the Copper Basin sedimentary section at its type locality. Debris flows were deposited as wide sheets which were usually less than one meter thick. The sedimentary rocks have mostly bimodal grain-size populations with a high degree of variability, poor sorting, and matrix-supported clasts (Figure 19). The maximum observed clast size is about 2 meters. Ordinarily, clasts do not display imbrication or orientation parallel to bedding. The debris flows commonly smoothed out, but did not erode, the underlying surface
Figure 19. Debris-flow deposited, matrix-supported fan­glomerate (paraconglomerate). Clasts are derived primarily from upper-plate crystalline sources. Note random orientation of clasts.
during deposition. Thicknesses of debris flows often decrease in a down-dip direction, and pinching out of individual flows laterally along strike is frequently observed.

The basal unit of the sedimentary facies at the type locality is a paraconglomerate unit approximately 60 meters thick. The massive unit displays no bedding, imbrication, or other sedimentary structures. Its genesis is interpreted to be the result of deposition by numerous debris flows. In this basal unit, poorly sorted and rounded plutonic and metamorphic clasts are suspended in a medium- to coarse-grained sandstone matrix (see Table 1, CC-1). Volcanic clasts are rare. Above this basal unit, fanglomerates are sequentially interbedded with sandstone and fine-grained rocks, and clasts are predominantly angular Copper Basin Formation-equivalent andesitic(?) fragments. Subordinate subangular to rounded plutonic, metamorphic, and varietal clast assemblages are present as well (Table 1).

Sheetflood Deposits

Sheetflood deposits compose approximately 70 percent of Copper Basin sedimentary rocks in their type locality. These deposits are stratigraphically similar to the debris flows deposited as thin, sheet-like beds parallel to one another. Sheetflood deposits are composed of poorly sorted, gravelly sandstone, sandstone, or siltstone and are cross-
stratified, laminated or structureless (Figures 8, 9, and 20). Thicknesses of flows are variable, ranging from several centimeters for coarser-grained flows to less than a centimeter for fine-grained flows. Water flow is interpreted to have been shallow, and mostly upper flow regime conditions prevailed, as indicated by the preservation of probable antidunes with associated backset lamination and lower upper flow regime plane beds. Finer-grained sheetflood sedimentary rocks imperceptibly grade into more viscous mud-slurry and mud-flow deposits.

**Stream Channel Deposits**

Stream channel deposits compose a relatively small quantity (10-15%) of the sedimentary strata in the Copper Basin Formation. Channels are generally asymmetrical in outline and often contain a lag gravel at the bottom. Most channels are erosionally truncated oblique to their axes so that it is not possible to determine their original shape. The occasional preservation of channels with undercut cutbanks suggests that some streams possessed a sinuous character indicative of low gradient on distal portions of the fan. The deposits are lenticular-shaped, poorly sorted conglomerates and sandstones. Trough cross-stratification and pebble imbrication are probably present but not observable because of poor exposures. Stream channels are generally less than a meter across and range
Figure 20. Planar-based, small-scale (10 cm) cross stratification in medium-to-coarse sandstone. Above and below the cross-stratified layer are structureless, homogeneous sandstone layers. Arrow indicates direction of transport.
from 25 cm to a meter in depth (Figures 12 and 21).

Discussion

On modern alluvial fans and alluvial plains, coarse sediment accumulates rapidly where confined streams emerge from relatively high source areas. Aggradation can be caused by a decrease in gradient in the basin floor, but it also can take place on a nearly uniform gradient where depth and velocity decrease as stream width increases at the mountain front (Bull, 1964).

The Copper Basin Formation sedimentary strata in the southeastern Whipple Mountains are composed almost exclusively of alluvial fan-associated deposits. At the type locality, the preponderance of sheetflood-deposited sediment and paucity of fanglomerate and stream channel deposits strongly suggest deposition below the intersection point on an alluvial fan or bajada. Extensive sheet-like stratigraphy of the formation and sedimentary structures indicative of shallow, fast-moving water support this interpretation.

Both proximal and distal alluvial fan facies are preserved in the Whipple Mountains. Proximal facies are preserved in the Whipple Wash area of the east-central portion of the range where coarse fanglomerate debris-flow deposits overlie Copper Basin Formation equivalent andesitic(?) volcanic flows. In the proximal portions of
Figure 21. Stream channel deposit. Note clast-supported conglomerate and gravels. Deposit is roughly 2 meters across and 1 meter deep.
the unit, in Whipple Wash, abundant clasts of lower-plate mylonitic gneiss are preserved. Conversely, clasts of mylonitic rocks are relatively scarce in distal deposits of the formation in other parts of the range. This contrast suggests that the Copper Basin Formation represents an unroofing sequence of the range, whereby lower-plate rocks became increasingly important sediment contributors as erosional denudation of the Whipple Mountains continued through mid-Miocene time.

Facies development within the fault blocks suggests multiple source areas were contributing sediment to the formation. In the type section, although distal facies predominate, the relative abundance of coarse debris flow deposits suggests that a secondary local source may also have contributed detritus to the unit. The absence of large-scale fining- or coarsening-upward megacycles in the formation suggests a lack of retrogradational or progradational facies development, respectively. This indicates that autocyclic and allocyclic mechanisms remained relatively static and in equilibrium with respect to one another throughout deposition of the unit.

**Paleoclimate**

Fossils are extremely rare in the Copper Basin Formation. Large carnivore tracks have been found in the formation (Kemnitzer, 1937; Gassaway, 1972, 1977), but
little is known of the paleoecological conditions indicated by them. Environmentally distinctive fossils have not been found in the formation, and, moreover, the coarse-grained, oxidized deposits probably are not favorable for their preservation.

Caliche development within the Copper Basin Formation sedimentary strata may be used to infer paleoclimatic conditions during the mid-Miocene. The caliche is preserved as indurated crusts that formed between depositional episodes on the fan. Caliche deposits range from less than a centimeter to several centimeters in thickness and possess a sharp contact with underlying detrital sedimentary rocks. The caliche is interpreted to have developed as a result of a combination of pedogenic and hydrologic processes (Reeves, 1976). Caliche probably initially represents the development of calcium carbonate-rich layers in ancient soil horizons that developed on the fan. Subsequent remobilization of the carbonate minerals by ground and surficial waters redistributed the calcareous material as fracture fillings and as thin crusts that accreted at the sediment-water interface in shallow ephemeral ponds occupying low spots on distal portions of the fan. Subsequent drying of these ponds resulted in desiccation of the calcareous deposits and formation of polygonal cracks that penetrate not only the caliche but the underlying clastic deposits
as well (Figure 22). The presence of such an inferred evaporative regime would indicate an arid to semi-arid desert environment for this region during the mid-Tertiary, similar to present day.
Figure 22. Polygonal desiccation cracks in caliche layer. Cracks not only penetrate the caliche but the underlying clastic sediments as well.
CHAPTER FOUR

Petrography of the Copper Basin Formation

Texture

Much of the Copper Basin Formation consists of clastic sedimentary rocks. Sedimentary rock types range from conglomerate to claystone, and there is a full gradation of intermediate sizes. Terminology used here for clastic rocks is from Wentworth (1922) and Picard (1971). Sandstone is the most abundant sedimentary rock type in the type locality of the formation, comprising about 70 percent of the unit. Conglomerate and fine-grained rocks are less abundant and constitute about 20 and 10 percent of the formation, respectively. Although fine-grained rocks are not uncommon, fissility is generally poor, and shale is rare. Sorting is poor, and detrital grains are angular in all sedimentary rocks of the Copper Basin Formation. In conglomerate, grain-size distributions are generally bimodal, and sandy matrix material is abundant. Much of the coarse-grained rocks are so poorly sorted that framework clasts are not in contact. Sandstone is also poorly sorted. Authigenic cements constitute between 10 and 30 percent of most sandstones, and apparently nearly all of the
interstitial matrix material has either altered to hematite cement or been replaced by carbonate.

Fine-grained rocks consist largely of common varieties, especially silty sandstones, silty claystone, and sandy mudstone. Poor sorting, mud cracks, and horizontal lamination are typical of most fine-grained rocks in the Copper Basin Formation.

**Composition**

The composition of framework constituents is described by Folk (1968). Compositional terms are modified and are applied to clastic rocks of all grain sizes. Figure 23 illustrates the compositions of 21 clastic rocks studied and shows the difference in composition of rocks of different grain size. The sedimentary rocks of the formation range from arkosic to lithic in composition. Conglomerate generally contains a higher proportion of rock fragments than other lithofacies, and a higher percentage of quartz is found in fine-grained rocks. Petrographic descriptions, point count analyses, and thin-section sample localities are presented in Appendices I, II, and III.

**Quartz**

Quartz grains are grouped according to optical properties into monocrystalline grains with undulatory or nonundulatory extinction, polycrystalline grains, and beta
Figure 23. Compositions of framework constituents of 21 clastic rocks of Copper Basin Formation. Q - quartz; F - feldspars; R - rock fragments. Classifications modified from Folk (1968). Conglomerate contains a significantly higher proportion of rock fragments than do finer-grained rocks.
quartz (Blatt and Christie, 1963). Metaquartzite fragments from the late Oligocene to early Miocene Gene Canyon Formation are observable in coarse-grained rocks and are counted with polycrystalline quartz. Chert is extremely rare in the formation and is considered a rock fragment. In general, percent nonundulatory of monocrystalline quartz is less in coarse-grained rocks than in finer-grained rocks. Percent monocrystalline of total quartz is relatively high and progressively increases with decreasing grain size. In conglomerate, a somewhat smaller proportion of quartz is monocrystalline. Decreases in the amount of undulatory and monocrystalline quartz with decreasing grain size has been observed in fresh detritus weathered from massive plutonic and metamorphic rocks, and unstable quartz types apparently are selectively destroyed during size reduction (Blatt, 1967).

**Feldspar**

Feldspar is abundant in the sedimentary facies of the formation, constituting between 15 and 60 percent of detritus in the unit. In the samples studied the order of abundance is microcline > orthoclase > plagioclase. Plagioclase grains are relatively scarce and are largely oligoclase (An$_{20-30}$) exhibiting well-developed albite twin lamellae. Zoned plagioclase, microperthite, myrmekite, and
sanidine are quite rare but observable in thin section.

**Rock Fragments**

Rock fragments consist of detrital material that was derived from both the upper-and lower-plate crystalline basement complex of the eastern Whipple Mountains and from the eroded Gene Canyon Formation and Copper Basin Formation volcanic strata. Rock fragments include many types of polycrystalline and monocrystalline grains other than quartz and feldspar, such as granitic and argillaceous fragments, detrital carbonate, schist, phyllite, and gneiss fragments and pyroclastic debris.

**Accessory and Clay Minerals**

Clay minerals are relatively uncommon in Copper Basin Formation sedimentary strata. Primary clays are generally not preserved as a result of alteration or replacement by carbonate and/or hematite. Amorphous material, possibly authigenic clays, associated with diagenetic alteration of iron-bearing detrital grains composes some of the matrix material observed in thin section.

Accessory minerals present in the sedimentary rocks include muscovite, biotite, hornblende, chlorite, pyroxene, zircon, sphene, apatite, epidote, and a variety of opaque minerals including magnetite, ilmenite, and leucoxene. Accessory minerals are not abundant, although their presence
is very important in the diagenetic development of the red pigmentation characteristic of the unit.

Cementation

Authigenic silica, carbonate, and hematite are cementing agents in the sedimentary facies of the Copper Basin Formation. Cement generally comprises between 10 and 30 percent of the sedimentary rocks, although cement in claystone and mudstone is difficult to resolve microscopically.

Silica cement is minor in the formation, and most of the cementing material is carbonate or hematite. Silica cement is early stage syntaxial overgrowths, which occur both on isolated grains lacking an interlocking framework and on detrital grains exhibiting interlocking euhedral terminations of the overgrowths. The former feature indicates that second-cycle sediment probably derived from the underlying Gene Canyon Formation strata is an important constituent in the detritus of the Copper Basin Formation, while the latter feature indicates that quartz overgrowth cementation was active in the Copper Basin sedimentary rocks themselves. Petrographic relationships indicate that silica cement was the first cement to form, followed by at least one generation of calcite cement. Some of the red pigment in the rocks predates even the earliest cement.
Silica cement was deposited over and around stained grain boundaries (Figure 24). During subsequent carbonate cementation, much red pigment from detrital rock fragments and grains of opaque oxides was mobilized and further oxidized. Cement of this stage is generally stained a pale reddish color and, in places, has replaced portions of quartz and feldspar framework grains. In some samples, a younger poikilotopic carbonate cement, representing a second stage of cementation, is free of red pigment (Figure 25).

**Diagenesis**

The origin of red hematite pigment in sedimentary rocks has been a subject of controversy among geologists for many years. Two major conflicting hypotheses have been used to explain the origin of the hematite. One hypothesis contends that hematite forms in lateritic soil horizons in humid, tropical climates and subsequent erosion and transportation of the material to desert basins results in the deposition of primary redbeds; i.e., the hematite is detrital and the sediments are red when deposited (Krynine, 1949). The opposing hypothesis contends that hematite is diagenetic forming *in situ* by progressive alteration of detrital ferromagnesian silicate minerals (Walker, 1967, 1976).

The former hypothesis that paleoclimatic significance can be attributed to the formation of redbeds. Walker
Figure 24. Photomicrograph of lithic arkose from the Copper Basin Formation showing well-developed syntaxial overgrowths on quartz framework grains. Note dark red hematite dust rim surrounding grains. Crossed nicols; FOV is approximately 2 mm across.
Figure 25. Photomicrograph of arkose from the Copper Basin Formation showing relationship between hematite-stained calcite cement (dark) and later-stage poikilotopic calcite cement (light). Detrital grains are fragments of microcline, quartz, and orthoclase. Crossed nicols; FOV is approximately 2 mm across.
(1967, 1976), however, provides convincing evidence that redbeds can form in hot, arid climates and that seasonally high rainfall or prior lateritization are not prerequisites for their formation. Therefore, the occurrence of ferric oxides in redbeds indicates that they formed under oxidizing conditions but is not of paleoclimatic significance because redbeds are known to form in both arid and moist tropical climates (Turner, 1980).

The Copper Basin Formation contains detritus derived from the crystalline basement of the interior portions of the range as well as from the underlying Gene Canyon Formation. The Gene Canyon Formation is composed, in part, of continental redbed deposits. Clearly, erosion and redeposition of these sediments as second-cycle detritus in the Copper Basin Formation would contribute detrital (primary) hematite to the formation. However, petrographic evidence indicates that the presence of detrital hematite is minor in comparison to post-depositional pigment development.

The diagenetic processes leading to the formation of redbeds in a desert alluvial environment are described by Walker and others (1978). They depend heavily on groundwater circulation patterns typical of desert basins. Owing to the high permeability of marginal alluvial fans, the water-table gradients at the basin margin are low, and the surface
drainage pattern is influent. Whenever surface runoff occurs, water flows into the alluvium. Effluent seepage only occurs near the center of the basin where the saturated zone lies nearer to the surface and groundwater is lost by evapotranspiration. These conditions perpetuate groundwater migration toward the center of the basin.

Walker and others (1978) have recognized two types of diagenetic processes that lead to the reddening of desert alluvial deposits. These are referred to as "early" and "late" diagenetic reddening.

"Early" diagenetic reddening results from infiltration of clay caused by influent groundwater seepage. The clay coats detrital grains, and continual exposure to oxygenated groundwater results in oxidation of the clay mineral lattice. "Early" diagenetic reddening is thought to be responsible for the reddish coloration of relatively young deposits (Plio-Pleistocene) but presumably was important during the early diagenetic history of ancient deposits as well.

In older (Miocene) desert alluvial deposits, "late" diagenetic reddening is considered to be the primary source of authigenic hematite. According to Walker and others (1978), when unstable framework silicates are in prolonged contact with oxygenated groundwater, they are susceptible to alteration by hydrolysis. The alteration process
involves the formation of dissolution voids and the replacement of framework grains by mixed layer illite-montmorillonite. Iron-bearing silicates such as hornblende, biotite, and pyroxene can be seen in various stages of alteration, and studies show that the replacement clay contains iron-oxide which is diffusing outward, away from the decomposing grain. This process causes the release of a variety of ions (including sodium, potassium, calcium, magnesium, aluminum, silicon, and iron) into the circulating groundwater. As groundwater moves through the sediment, its composition is modified, and wherever ions are in sufficient concentrations, authigenic mineral phases, especially hematite, are precipitated into the pore spaces. It is the microcrystalline authigenic hematite formed by this "late" diagenetic process that gives the Copper Basin Formation sedimentary rocks their distinctive brick-red coloration.
CHAPTER FIVE

Provenance of the Copper Basin Formation

One of the fundamental factors controlling the nature of a sedimentary rock unit is the composition of the source material from which the sediment was derived. The Copper Basin Formation sedimentary rocks are interpreted to have been derived from several sources, including the crystalline basement complex of the range, underlying late Oligocene-early Miocene Gene Canyon strata, and volcanic strata of the Copper Basin Formation itself.

Quartz

Types of quartz grains historically have been used to interpret the provenance of sandstone. "Unstrained" or nonundulatory quartz was thought to be indicative of plutonic igneous source rocks, while "strained" (undulatory) and polycrystalline quartz were thought to be associated with metamorphic source rocks (Krynine, 1946). Blatt (1967), however, demonstrated that undulatory and polycrystalline quartz are abundant in plutonic igneous rocks as well as metamorphic rocks.

In the Copper Basin Formation sedimentary rocks, quartz grains are about 13 percent nonundulatory, 53 percent
undulatory, and 33 percent polycrystalline. Beta quartz associated with volcanic source rocks is rare. Quartz grains, in general, are angular, poorly sorted, and frequently exhibit vacuoles, bubble trains, and/or micro­lites. The abundance of relatively unstable undulose and polycrystalline grains and their textural immaturity indicate that quartz grains in the Copper Basin Formation sedimentary rocks are overwhelmingly derived from nearby crystalline source rocks.

Feldspar

Feldspars in the Copper Basin Formation sedimentary rocks are abundant. Feldspar grains are about 13 percent plagioclase, 22 percent orthoclase, and 61 percent microcline; the remaining 4 percent is composed of sanidine, myrmekite, and microperthitic grains. The preponderance of relatively unstable microcline grains in the sediments is indicative of relatively local source rocks rich in alkali feldspars.

The crystalline basement of the eastern Whipple Mountains is composed of a variety of plutonic and metamorphic rock assemblages (Davis and others, 1979a, 1980a; Anderson and Frost, 1981) (Figure 26). Two spatially and volumetrically important rock types compose the majority of the crystalline basement in the eastern portions of the
Figure 26. Geologic map of the upper-plate crystalline terrane in the Gene block, eastern Whipple Mountains, Gene Wash 7½ minute quadrangle.
range: a Precambrian granite porphyry (rapakivi granite) containing between 34 and 70 percent alkali feldspar phenocrysts; and a foliated, metasedimentary quartzofeldspathic gneiss also of Precambrian age, containing up to nearly 50 percent alkali feldspar (Anderson and Frost, 1981). These lithologies are probable sources for Copper Basin Formation detritus.

**Origin and Distribution of Clast Types**

In this study, six representative conglomerate clast counts were conducted to determine the number of lithologic varieties present and their statistical distribution in an attempt to determine the source of the clasts. Random counts of 300 or more clasts were catalogued at random intervals throughout the stratigraphic section at the type locality of the Copper Basin Formation. Clast count localities are shown in Appendix III.

Fifteen lithologic varieties were identified through hand-sample analysis. Detailed petrographic descriptions and chemical analyses of most of plutonic and metamorphic lithologies are available in Anderson and Frost (1981). The distribution of lithologic varieties is outlined in Table 1. The clast populations in the conglomerate lithofacies of the unit consists of a variety of crystalline, sedimentary, and volcanic rocks derived from both the upper
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and lower plates of the Whipple Mountain detachment terrane.

Plutonic clast lithologies represented include adamellite, diabase, granite porphyry, and quartz monzodiorite. Metamorphic clast varieties include amphibolite, metasedimentary gneiss, and mylonitic gneiss derived from the lower plate. Volcanic rocks include clasts of andesite (?) derived from the Copper Basin Formation-equivalent volcanic flows, and porphyritic rhyolite and vesicular basalt derived from the Gene Canyon Formation. Clasts of hypabyssal intrusive rocks are characterized by a distinctively textured "jackstraw" or "turkey track" andesite. Sedimentary rock fragments include clasts of brecciated metaquartzite, clastic rock, and non-marine carbonate derived from the Gene Canyon Formation.

An interesting textural inversion is present in the conglomerate clast population. Crystalline clasts are generally subrounded to rounded, while less resistant volcanic clasts are subangular to angular. This feature probably indicates a multicyclic depositional history of the crystalline clasts. These clasts likely were deposited as fanglomeratic clasts of the Gene Canyon Formation and subsequently re-eroded, transported, and redeposited as detritus of the Copper Basin Formation. An alternative hypothesis is that the clasts were derived from a distant crystalline source and underwent rounding during transport.
However, considering the overall textural and mineralogical immaturity of the sediments and the proximity of lithologically equivalent basement rock, the former hypothesis appears more plausible.

Discussion

Figure 27 is a plot of sandstone compositions as they are related to provenance regions determined by Dickinson and Suczek (1979). Clearly the sandstone compositions plot in and around the field identified by Dickinson and Suczek (1979) as magmatic arc and continental block provenances. Sandstone of the formation is typically arkosic to lithic arkosic in composition (Figure 23). According to Dickinson and Suczek (1979), sandstone of this lithology represents a transitional provenance reflecting influence by both the magmatic arc and continental block provenances. Typical arkosic compositions reflect erosional denudation of uplifted crystalline sources, while more lithic sands reflect partial derivation from volcanic and sedimentary cover that partly mask or shield basement gneisses and granites. This provenance interpretation is consistent with the general geologic setting in the Whipple Mountains where arc-related volcanic strata of the Miocene Copper Basin Formation partially overlie uplifted crystalline basement rocks.
Figure 27. Ternary QFR plot of point-counted framework grains for sandstone samples of Copper Basin Formation. Q = quartz; F = feldspars; R = rock fragments. Provenance fields from Dickinson and Suczek (1979).
CHAPTER SIX
Tectonic Significance of the Copper Basin Formation

Structural Setting

Structurally the Whipple Mountains are expressed as two northeast-trending, doubly-plunging, antiformal basement flexures. Three well-developed synforms separate and flank the antiforms on either side (Figure 28). The antiforms are unequal in size and are markedly asymmetrical in shape (Figure 29). The larger of the two structures, the Whipple Peak antiform, possesses an axial length in excess of 25 km, while the smaller, the Bowmans Wash antiform, is approximately 15 km long. Developed orthogonally to the northeast-trending foldset is a second foldset. This north-to northwest-trending foldset is expressed as a broad crustal upwarp of smaller amplitude and longer wavelength than the primary foldset. Development of these antiforms and attendant synforms is characteristic of the structural setting of many of the mountain ranges in southeastern California and adjacent portions of Arizona, Nevada, and Sonora (Cameron and Frost, 1981; Cameron and others, 1981; Frost and others, 1982a; Frost and Martin, 1982).

The most extraordinary structural feature exposed in
Figure 28. Geologic map of the central and eastern Whipple Mountains, San Bernardino County, California. Note position of the antiformal highs and adjacent synformal lows. Modified from Davis and others (1980a).
Figure 29. Structure contour map of the Whipple detachment fault showing the northeast trend and asymmetric shape of the antiforms and synforms.
the Whipple Mountains is the major detachment fault itself. This detachment fault nearly encircles the core of the range, although it is not well exposed on the northwestern portion of the range (Figure 28). The fault separates upper-plate crystalline units, volcanic and sedimentary sequences from lower-plate mylonitic and nonmylonitic crystalline assemblages.

The presence of a conspicuous mylonitic gneiss possessing a well-developed mylonitic foliation and northeast-trending lineation within the lower plate of the Whipples, and many other ranges of the detachment terrane, has received much attention from workers studying the geology of the area. The close spatial association of mylonitization and associated detachment fault-related structure has led some workers to suggest a cogenetic relationship between the two (Davis and Coney, 1979; Rehrig and Reynolds, 1980; Lister and Davis, in press; Davis and others, in press). However, the validity of this association is questionable since the lower plates of many of the ranges within the detachment terrane are largely devoid of a mylonitic fabric (such as the Newberry Mountains, Nevada, and Chemehuevi, Big Maria, and Riverside Mountains, California). In addition, isotopic studies suggest that the mylonitic gneisses developed during Late Cretaceous to early Tertiary time, probably as a result of widespread
compressional tectonics (Martin and others, 1980, 1982).

An alternative explanation for lower-plate thinning and extension has been suggested by Adams and others (in press). They interpret lower-plate extension to be accommodated by a system of stacked, low-angle, anastomosing shear zones and document the presence of such fault geometries in numerous ranges within the detachment terrane, including the Whipple Mountains. Mylonitization and lineation formation as expressed in presently exposed rocks thus appear to be genetically unrelated to detachment faulting. The relationship between mylonitization and detachment faulting remains unresolved in terms of a consensus among workers in the area.

**Development of Upper-Plate Faults**

Tectonic transport of the upper-plate rocks is accommodated by numerous northwest-striking (N45° ± 15°W), northeast-dipping, planar normal faults. These faults reflect upper-crustal extension by fragmentation of the upper plate into discrete, rotated blocks. The strike of these faults is roughly orthogonal to the axes of the antiforms and is thereby demonstrative that transport of upper-plate was not radially off lower-plate structural highs, as would be expected in a gravity-slide complex, but approximately perpendicular to the strike of the faults.
Transport is, in fact, unidirectionally to the northeast (N50° ± 10°E) as is kinematically indicated by the southwestward rotation of the fault blocks (Davis and others, 1979a, 1980a).

Initially, the normal faults were conceived as being listric in nature, i.e., flattening with depth and tangentially merging with the major detachment surface (Frost, 1979; Davis and others, 1979a, 1980a). Further study has indicated that the majority of these faults remain planar to depth where they abruptly intersect, but do not offset, the major detachment surface or lower-plate rocks (Frost, 1983). Such a fault geometry requires the development of an extremely complex network of intrablock faulting (Gross and Hillemeyer, 1982).

**Relationship Between Crustal Extension and Upper-Plate Sedimentation**

Incorporated as part of the rotated fault blocks of the upper plate are the Tertiary continental sedimentary and volcanic units. Both the Gene Canyon Formation and Copper Basin Formation can be used to document the coeval and, therefore, the presumably cogenetic tripartite relationship between detachment faulting, upper-plate normal faulting, and development of the antiforms and synforms (Frost, 1979, 1981a; Frost and Otton, 1981; Teel and Frost, 1982). Together these units record an approximately
10 m.y. episode (26 m.y.B.P. to 16 m.y.B.P.) of deformation and concurrent sedimentation in the Whipple Mountains.

Lithologically, both the Gene Canyon and Copper Basin Formations reflect a tectonically active setting indicated by the preponderance of fanglomerates and immature (texturally and mineralogically) clastic sediments. Clearly, basement rocks were exposed and actively eroded during Oligo-Miocene time.

Despite the unfossiliferous nature of these formations, isotopically datable volcanic flows underlie and interfinger with both formations. These volcanic flows provide important temporal constraints that facilitate paleogeographic reconstruction of the Whipple Mountain area from late Oligocene through mid-Miocene time.

The synchronous relationship between upper-plate normal faulting and generation of the antiforms is initially exhibited in the Gene Canyon Formation. Preservation of the Gene Canyon Formation in the Whipple Mountains is restricted to the synformal troughs. Preservation only in the synforms and not on the antiforms suggests that uplift of the range occurred synchronously or after deposition of the unit. Stratigraphic relationships observed by Frost (1981b, 1983), however, indicate that only lower parts of that unit were deposited prior to deformation and were then subsequently folded as uplift commenced. Furthermore, lower
portions of the formation do not display growth-fault stratigraphy suggesting that upper-plate extension related to detachment faulting had not begun prior to late Oligocene time (Figure 30a). The ca 32 m.y. age obtained from a basal Gene Canyon Formation volcanic flow, considered in conjunction with the structural evidence, suggests that uplift and detachment faulting had not begun until sometime shortly after this time period. The actual time of initiation of detachment faulting is almost completely unconstrained. Presumably the coeval development of crustal folding, detachment faulting, and upper-plate normal faulting indicates a cogenetic association between the three. Paleocurrent studies on the Gene Canyon Formation have not been done. However, such a study conducted within the synforms might indicate increasing influence from the structural highs forming on either side, as well as from northeast-facing fault scarps that were developing during late Oligocene-early Miocene time (Figure 30b). Such a study would be an independent test of the model proposed here.

The Copper Basin Formation volcanic and sedimentary strata record deformation throughout the depositional history of the unit, from about 18 m.y.B.P. until approximately 16 m.y.B.P. During this 2 m.y. time span Copper Basin Formation rocks have been rotated, in some
Figure 30. Interpretive paleogeographic reconstrucive model of the Whipple Mountains region from late Oligocene through Miocene time.
Figure 30a. Late Oligocene pre-deformational stage of the Whipple Mountains area prior to (?) the major development of the antiforms/synforms and normal faults.
Figure 30b. Early formational stage of the Whipple Mountains region during late Oligocene-early Miocene time. Tectonic highs and lows created by the concomitant development of antiforms/synforms and normal faults established an alluvial fan sedimentation regime during this time period.
Figure 30c. Whipple Mountains region during Miocene time. Continued faulting, uplift, and erosion have generated maximum relief, resulting in thick accumulations of clastic sediments (Copper Basin Formation) in fault-bounded catchment troughs.
places, in excess of 60° to the southwest as a result of upper-plate normal faulting. During the deposition of the unit, relief in the area was probably at a maximum. Well developed tectonic highs and lows provided for the development of an alluvial fan depositional regime. Normal faulting occurring simultaneously with the developing Whipple Mountains antiforms resulted in the generation of numerous northwest-trending, sub-parallel sediment catchment troughs (Figures 30b and 30c). Clastic debris shed into these troughs from both the eroding antiforms and fault scarps resulted in the accumulation of thick sections of alluvial sediments. Uplift of the antiforms, faulting, and erosion appear to have kept pace with one another as indicated by the lack of progradational or retrogradational facies development.

Unlike the Gene Canyon Formation, the Copper Basin Formation is preserved both on the structural highs where it nonconformably overlies the upper-plate crystalline basement complex, and in the synformal lows where it overlies the Gene Canyon Formation. This feature indicates that the period of erosion between the deposition of the two formations was extensive and complete, removing all of the Gene Canyon Formation from the antiforms. Conversely, preservation of the Copper Basin Formation on these structures suggests that earlier deposited portions of the
unit mantled the antiforms as they were being actively uplifted.

In the Whipples, local unroofing of the mylonitic rocks by erosion occurred prior to 18 m.y., as is indicated by the presence of clasts of mylonitic gneiss within the Gene Canyon section. However, not until sometime after Gene Canyon Formation deposition, during the mid-Miocene, did the lower plate become extensively exposed to erosion (Figure 30c). This feature is demonstrated by the presentation of clasts of lower-plate rocks in the proximal facies of the Copper Basin Formation.

Proximal facies of the formation are exposed in the east-central Whipple Mountains and in the immediately adjacent portions of the western Buckskin Mountains, across the Colorado River in Arizona. The intervening Colorado River synform structurally separates the two ranges and is, in part, infilled by distal portions of the unit. In the vicinity of lower Whipple Wash the proximal facies of the Copper Basin Formation contain abundant clasts of mylonitic gneiss reflecting considerable clastic input from the lower plate of the range. In the western Buckskin Mountains, especially in the vicinity of Red Mountain, proximal facies of the formation possess abundant clasts of non-mylonitic rock derived from the lower plate of that range. This feature indicates that detritus of the Copper Basin
Formation was derived not only from the erosional denudation of the Whipple Mountains but from the western Buckskin Mountains as well. The resulting sediments were shed into the intervening synformal trough that separates the two ranges (Figure 28).

Distal facies of the formation are preserved in the south and southeastern portions of the Whipples, which includes the type section. These sediments reflect primarily an upper-plate source, as indicated by the paucity of lower-plate derived clasts and abundance of alkali feldspars derived from local basement lithologies. The unroofing sequence in distal portions of the formation has been largely obliterated by an extensive erosional episode.

Regionally, the Copper Basin Formation reflects clastic input from at least several major sources, including the Whipple Mountains antiforms, western Buckskin Mountains, and eroded local basement rocks that were associated with upper-plate normal faulting.

**Discussion**

The synchronicity between detachment faulting and development of the antiforms and synforms is a critical, and not completely resolved, component of the model presented here.

Frost and Martin (1982) suggest that Savahia Peak, in
the western Whipple Mountains, exemplifies the relationship between large-scale folding and relative transport of the upper plate. Savahia Peak is an outlier composed of southeastward-tilted Miocene (Gene Canyon and Copper Basin Formations equivalent?) volcanic strata which tectonically overlie the Whipple detachment fault. The detachment fault, in this region, dips to the southwest because of the domal form of the range. According to Frost and Martin (1982), the geometric configuration of the tilted strata and the detachment fault could suggest that development of the antiforms and synforms was post-detachment, or that both detachment faulting and large-scale folding are the result of regional crustal extension.

Belief that uplift of the range occurred relatively late in the deformation continuum is problematical. Such a viewpoint leaves the source area for the Copper Basin and Gene Canyon Formations partially unaccounted for. Paleo-current data suggests a southerly transport direction. Distal alluvial fan facies are developed at the type locality, while to the north, in the vicinity of Whipple Wash, more proximal facies are preserved. If the source for the Copper Basin sedimentary strata was exclusively nearby upper-plate, normal fault scarps, eastward-flowing paleocurrents should predominate. Furthermore, proximal fan facies should be well developed adjacent to the scarps
regardless of location within the fault blocks. Although
this feature may be partially obscured due to rotation of
the fault blocks, it is not observable in distal portions
of the unit in the Whipple Mountains, including the type
locality. Realization that a considerable volume of
material has been removed from the antiforms is an important
consideration, as well. It is unreasonable to suggest that
the detritus derived from the antiforms accumulated as
unit(s) other than the Gene Canyon and Copper Basin
Formations, especially considering the absence of other
alluvial units in the region. Clearly, syndepositional
faulting and sedimentologic features of the Copper Basin
Formation as well as the Gene Canyon Formation suggest a
coeval and, therefore, cogenetic association between uplift
of the Whipple Mountains and regional detachment faulting.
CHAPTER SEVEN
Summary and Recommendations

The Copper Basin Formation of the eastern Whipple Mountains reflects significant tectonic events in that area during Miocene time. The internal stratigraphy of the unit reflects a rhythmically stratified sedimentary sequence that is indicative of an alluvial-fan environment. These alluvial fans appear to have developed in response to the rise of the antiformal folds in the Whipple Mountains region. Progressive development of these folds provided both the source area and catchment basins for the unit. Coeval offset along normal faults associated with the regional detachment faults further complicated the basin morphology and resulted in a growth fault type character of Tertiary sedimentation and tectonics. The result of this concomitant normal faulting and sedimentation was the growth of a thick alluvial fan sequence that is tilted and extended. Thick sequences of tilted redbed and volcanic rocks appear to be a signature of mid-Tertiary detachment faulting and related crustal folding. The presence of such stratigraphic and deformational indicators may provide a powerful clue for determining the overall extent of detachment-related deformation and, ultimately, its cause. The genetic
relationship between sedimentation and extensional tectonics may also prove to be a powerful tool for deciphering the basin history of terranes containing hydrocarbon accumulation. Further study of the Copper Basin and Gene Canyon Formations and regionally correlative units will contribute significantly toward the understanding of Tertiary Cordilleran tectonic evolution.
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REFERENCES CITED


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APPENDIX I

Detailed Point-Count Analyses
Table 2. Detailed point count analyses. Sample localities shown in Appendix III.

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    - 38 10.6
    - 50 14.8
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    - 4 1.5
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  - 17 4.8
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- orthoclase
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**Lithic Fragments:**
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- 79 29.4
- 64 18.0
- 51 15.1

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APPENDIX II

Thin-Section Sample Descriptions
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Arkose (Q27.2 F65.5 R7.3 : F79.9 M1.7 C18.4 P0): hematite and calcite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; granular coarse to medium sandstone.

Tcbs-Cb-2
Arkose lutite (Q50 F40 R10 : F75 M2 C23 P0): hematite and minor calcite cement; submature, i.e., less than 5% matrix, moderately sorted, angular; siltstone.

Tcbs-Cb-3
Arkose (Q21.6 F62.3 R16.1 : F85.6 M0.9 C10.9 P2.6): hematite and minor calcite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; granular coarse to medium sandstone.

Tcbs-Cb-4
Feldspathic volcanic lithrudite (Q21.9 F23.8 R54.2 : F75.4 M3.2 C19.4 P2.0): hematite and calcite cement; submature, i.e., less than 5% matrix, very poorly sorted, angular; sandy pebble granule conglomerate.

Tcbs-Cb-5
Arkose (Q32.9 F51.9 R15.2 : F80.6 M1.6 C16.5 P1.3): calcite and minor hematite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; laminated; micaceous; silty fine to very fine sandstone.

Tcbs-Cb-6
Mixed volcanic-plutonic lithic arkose (Q35.8 F32.9 R31.2 : F78.6 M0 C21.4 P0): minor hematite and poikilotopic calcite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; coarse sandstone. Caliche development at surface of sample with sharp contact separating caliche from underlying clastic sediments.

Tcbs-Cb-7
Feldspathic volcanic lithrudite (Q15.9 F26.1 R58.0 : F83.0 M3.2 C13.0 P0.7): hematite and calcite cement; submature, i.e., less than 5% matrix, very poorly sorted, angular; micaceous; sandy pebble granule conglomerate.

Tcbs-Cb-8
Arkose (Q25.4 F57.4 R17.2 : F77.2 M3.1 C19.2 P0.6): hematite and microcrystalline/patchy poikilotopic calcite cement; submature, i.e., less than 5% matrix, moderately sorted, angular; coarse sandstone.
Tcbs-Cb-9
Volcanic lithrudite (Q12.0 F16.0 R72.0 : F84.2 M2.8 C12.9 Po): hematite and minor calcite cement; submature, i.e., less than 5% matrix, very poorly sorted, very angular; sandy pebble granule conglomerate.

Tcbs-Cb-10
Arkose (Q38.9 F51.3 R9.8 : F82.4 M2.6 C15.0 Po): early stage quartz overgrowth cement, microcrystalline/patchy poikilotopic calcite cement, and minor hematite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; coarse to fine sandstone.

Tcbs-Cb-11
Volcanic lithic arkose (Q27.8 F47.9 R24.3 : F68.4 M2.2 C29.4 Po): calcite and minor hematite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; fine to very fine sandstone. Caliche development at surface of sample with sharp contact separating caliche from underlying clastic sediments.

Tcbs-Cb-12
Arkosic lutite (Q45 F50 R5 : F65 M20 C10 P5): patchy poikilotopic/microcrystalline calcite cement and minor hematite cement; immature, i.e., less than 5% matrix, poorly sorted, angular; micaceous; sandy stilstone.

Tcbs-Cb-13
Arkose (Q29.6 F53.5 R16.9 : F80.9 M0.3 C18.0 P0.8): hematite and microcrystalline/poikilotopic calcite cement; submature, i.e., less than 5% matrix, moderately sorted, angular; medium to fine sandstone.

Tcbs-Cb-14
Volcanic lithic arkose (Q32.8 F48.8 R18.4 : F83.1 M1.2 C15.1 P0.6): hematite and microcrystalline/poikilotopic calcite cement; submature, i.e., less than 5% matrix, moderately sorted, angular; medium to fine sandstone.

Tcbs-Gb-1
Volcanic lithic arkose (Q23.8 F53.1 R23.0 : F75.2 M0.8 C24.0 P0.6): calcite and minor hematite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; micaceous; silty fine sandstone.

Tcbs-Gb-2
Volcanic lithrudite (Q15.8 F11.8 R72.4 : F75.8 M3.3 C20.2 P0.6): hematite and microcrystalline/patchy poikilotopic calcite cement; submature, i.e., less than 5% matrix, very poorly sorted, angular; sandy pebble granule conglomerate.
Tcbs-Gb-3
Volcanic lithic arkose (Q27.2 F44.1 R28.6 : F76.0 M1.3 C22.8 P0): poikilotopic/microcrystalline calcite cement, and minor hematite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; granular medium to fine sandstone. Caliche laminations developed at surface of sample with sharp contact separating caliche from underlying clastic sediments.

Tcbs-Gb-4
Mixed volcanic-plutonic lithrudite (Q17.1 F18.8 R64.1 : F81.6 M1.9 C16.5 P0): hematite and calcite cement; submature, i.e., less than 5% matrix, very poorly sorted, angular; sandy pebble granule conglomerate.

Tcbs-Gb-5
Arkose (Q19.5 F63.7 R16.7 : F78.6 M0.3 C19.9 P1.2): calcite and minor hematite cement; submature, i.e., less than 5% matrix, poorly sorted, angular; silty medium to fine sandstone.

Tcbs-Gb-6
Mixed lithic arkose (Q33.0 F43.8 R23.2 : F80.6 M1.9 C16.9 P0.6): early stage quartz overgrowth cement, microcrystalline/patchy poikilotopic calcite cement, and minor hematite cement; submature, i.e., less than 5% matrix, moderately sorted, angular; fine to very fine sandstone.

Tcbs-Gb-7
Arkosic lutite (Q60 F40 R0 : F65 M20 C15 P0): calcite and hematite cement; immature, i.e., less than 5% matrix, poorly sorted, angular; micaceous; laminated; deformed; sandy mudstone.
APPENDIX III

Thin-Section Sample and Clast-Count Localities
Figure 31. Map of southern Copper and Gene blocks showing thin-section sample and clast-count localities.
ABSTRACT
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The Copper Basin Formation in the eastern Whipple Mountains provides a synorogenic stratigraphic record of the mid-Miocene tectonic development of that region. Genesis of the Whipple Mountain antiforms and normal faults associated with a system of regional, low-angle detachment faults probably reflect the passage of the mid-Tertiary magmatic arc through this region. This deformational episode resulted in the establishment of relatively high sediment source areas and numerous linear depositional basins during late Oligocene through mid-Miocene time. The Copper Basin Formation at its type locality is composed of interbedded arkosic sandstone, siltstone-mudstone, and fanglomerate that exhibit distal alluvial fan facies development. Paleocurrent analyses indicate sediment transport was generally to the south, off the developing structural/topographic highs. Petrographic evidence indicates a local, mixed plutonic-metamorphic-volcanic source terrane for the Copper Basin Formation sedimentary rocks. Faulting occurring simultaneously with sedimentation has resulted in a distinctive, fan-like stratigraphic geometry for the unit. This feature indicates tectonic transport of the upper-plate occurred synchronously with uplift and
sedimentation. Stratigraphic and structural features developed in the underlying Gene Canyon Formation support this interpretation, as well. Radiometrically dated volcanic flows, interbedded with both formations, provide temporal constraints that facilitate paleogeographic reconstruction of the region during Oligo-Miocene time.
Plate I GEOLGY OF A PORTION OF THE SOUTHEASTERN WHITTLE MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

LEGEND

AREA NOT MAPPED

SEDIMENTOLOGY AND TECTONIC SIGNIFICANCE OF THE COPPER BASIN FORMATION IN THE EASTERN WHITTLE MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

by

Derrick B. Teel

1983
### Plate II

**DETAILED REPRESENTATIVE STRATIGRAPHIC COLUMNAR SECTION OF THE COPPER BASIN FORMATION SEDIMENTARY FACIES**

<table>
<thead>
<tr>
<th>METERS</th>
<th>Lithofacies Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Uniform cgl. (Continues above)</td>
</tr>
<tr>
<td>9</td>
<td>Thin siltstone/mudstone layer.</td>
</tr>
<tr>
<td>8</td>
<td>Mudcracks at top of siltstone/mudstone layer. Pebby medium-coarse ss. w/fining upward cycles, cross-strata, ripple and graded bedding.</td>
</tr>
<tr>
<td>7</td>
<td>Shallow asymmetric stream channel w/lag gravel at base. Thick uniform cgl. Repeated thin fining upward cycles within thicker cycle, cross-strata towards top. Shallow asymmetric stream channel w/lag gravels and undercut bank. scour truncates bedding at channel margins. Uniform cgl. Generally flat-beded pebbly medium-coarse ss. w/fining upward cycles, cross-strata, ripple and graded bedding. Flame structures at upper bedding surface of siltstone/mudstone layer. Shallow asymmetric stream channel w/lag gravels at base. Thick cgl. ss. siltstone/mudstone fining upward cycle. Note angular rote. clasts (dark) and rounded crystalline clasts (light). 1 cm - 2 m in diam.</td>
</tr>
<tr>
<td>6</td>
<td>Conglomerate Lithofacies: Typically structureless tabular paraconglomerate units and channelized orthoconglomerate deposits; 20 cm to 1 m in thickness. Deposits generally lack imbrication and grading. Matrix of paraconglomerate is poorly sorted granular medium to coarse-grained arkose to lithic arkosic sandstone. Conglomerate clasts are predominantly sub-rounded to rounded metamorphic/plutonic clasts and subangular to angular andesitic volcanic fragments; 1 cm to 2 m in diameter. Weathering out of clasts results in cavernous structures. Sandstone Lithofacies: Structureless or medium to small-scale planar or cross-stratified or laminated (30 cm - 1 cm) tabular units; 20 cm to 1 m in thickness. Typically poorly sorted pebbly medium to coarse-grained, dark reddish-brown, arkose to lithic arkosic sandstone; crystalline and volcanic pebbles and cobbles are randomly dispersed throughout the sandstone units. Normal, reverse, and reverse to normal grading are common. Stream scour/channeling are locally observable. Siltstone / Mudstone Lithofacies: Laminated or structureless, dark red, silty to very fine-grained sandy mudstone or very fine-grained sandy siltstone; 0.5 cm to 5 cm in thickness. Layers frequently display normal grading; negative weathering profile. Contact with overlying clastic units is usually sharp but non-erosive. Mudcracks and less frequently ripple marks and flame structures are preserved on upper bedding surfaces.</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

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