Mesozoic Thrusting and Tertiary Detachment Faulting in the Moon Mountains, West-central Arizona

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Cover: Geologic map of Moon Mountain, Arizona.

Note: This report was originally released as Chapter 2 in Knapp’s Ph.D. dissertation, Structural development, thermal evolution, and tectonic significance of a Cordilleran basement thrust terrain, Maria fold and thrust belt, west-central Arizona, Mass. Inst. of Technol., Cambridge, MA, 1989.
CHAPTER 2

MESOZOIC THRUSTING AND TERTIARY DETACHMENT FAULTING IN THE MOON MOUNTAINS, WEST-CENTRAL ARIZONA

James H. Knapp

ABSTRACT

The rocks and structures exposed in the Moon Mountains of the Colorado River Indian Reservation, west-central Arizona, record Mesozoic thrusting within the Maria fold and thrust belt, and superimposed Tertiary detachment faulting related to the regional Whipple-Buckskin-Rawhide detachment system. The major structures of the Moon Mountains are (1) the Valenzuela thrust fault, (2) the Moon Mountain detachment fault, and (3) the Copper Peak detachment fault. Lithologies consist primarily of Mesozoic and Tertiary intrusive rocks and crystalline gneisses of Precambrian age, with minor but important exposures of deformed and metamorphosed sedimentary and volcanic rocks. A newly-described section of metamorphosed, lower Mesozoic sedimentary rocks, the Valenzuela metasedimentary section, is assigned to the Buckskin Formation (Reynolds et al., 1987) of western Arizona.

The Valenzuela thrust fault, exposed in the southern Moon Mountains, carries an assemblage of megacrystic, Jurassic quartz syenite and Precambrian gneisses and schists over the deformed Valenzuela metasedimentary sequence. Footwall structure suggests initial tectonic transport of the hanging wall to the south, whereas later fabrics in both the hanging wall and footwall indicate northward transport, suggesting a multi-stage
kinematic history for this Mesozoic structure. Fabrics associated with the thrust fault indicate that amphibolite facies metamorphism accompanied deformation. The Valenzuela thrust system is correlated with the Tyson thrust system of the northern Dome Rock Mountains, implying a regional extent for this structure.

The Moon Mountain detachment fault, exposed along the eastern side of Moon Mountain, places a section of faulted and tilted Tertiary sedimentary rocks above gneisses, schists, and amphibolites of the Moon Mountains crystalline assemblage. At least two fabrics are present in the footwall gneisses. Gneissic compositional layering is concordant with the detachment fault, but primarily represents a Mesozoic feature. Ductile shear fabrics of Tertiary age are variably developed in gneisses and granites of the footwall, and indicate a consistent top-to-the-east shear sense associated with the detachment system. Strata in the hanging wall of the detachment show tilting which is strongly oblique to the inferred direction of movement for the detachment fault.

The Copper Peak detachment fault, exposed in the Copper Peak area of the northeastern Moon Mountains, carries sedimentary and volcanic rocks of Paleozoic(?), Mesozoic, and Tertiary age over a ductilely deformed footwall consisting primarily of granitic intrusive rocks. Ductile footwall fabrics exhibit a consistent top-to-the-northeast sense of shear. The development of these ductile fabrics is constrained to post-date intrusion of the Copper Peak granite (of probable mid-Tertiary age), and largely pre-date the intrusion of a late- to post-tectonic biotite granite (Tmbg) which yields an early Miocene (20.8 ± 3.2 Ma) U-Pb zircon age. The Copper Peak detachment is correlated with the Moon Mountain detachment fault, from which it is offset by an inferred, high-angle fault. The lack of penetrative ductile fabrics in Paleozoic/Mesozoic sedimentary rocks in the hanging wall of this fault is distinctive in the western Arizona region, and may constrain reconstruction of the detachment system.

Regional relations dictate that the Moon Mountain and correlative Copper Peak detachment faults are the western exposed limit of the Whipple-Bucksin-Rawhide detachment system at the latitude of the Moon Mountains. The presence of Tertiary ductile fabrics in the footwalls of these structures implies that the rocks originated at depths and temperatures sufficient to produce well-developed mylonitic fabrics, and that the actual breakaway (original surface break) for the detachment system is not preserved in this area. In addition, these east-dipping mylonitic fabrics dip antithetically to a much deeper-seated, west-dipping mylonitic zone that has been seismically imaged (Hauser et al., 1987) and correlated with mylonites of the Whipple and Buckskin Mountains. This
relation suggests that either (1) Tertiary mylonitization was characterized by anastamosing shear zones within a large section of the crust, or that (2) different phases of Tertiary mylonitization are represented in the lower plate of the Whipple-Buckskin-Rawhide detachment system.

The generation of large magnitudes of extension in mid-Tertiary time may have been related to inheritance of a thickened crust from Mesozoic shortening, but accommodation of extensional strain in the detachment system did not take place primarily along pre-existing thrust faults. Preservation of dissected but intact Mesozoic structures, such as the Valenzuela thrust fault, are well-documented in western Arizona, and indicate that the geometry of the detachment fault and related structures was not controlled by pre-existing zones of weakness. Localization of strain was probably more a function of both the local and regional stress regime and the evolving thermal structure of the crust.

INTRODUCTION

LOCATION AND GEOLOGIC SETTING

The Moon Mountains of the Colorado River Indian Reservation in west-central Arizona are located Mojave-Sonoran Desert region within the southern Basin and Range province of the western U.S. Cordillera (Fig. 2.1). Rocks exposed in this region record a complex history involving major compressional deformation, probably during a number of episodes in Mesozoic time, and large-magnitude extensional tectonism during Tertiary time. The Moon Mountains are centrally located within the Maria fold and thrust belt (Reynolds et al., 1986), which extends from the Coxcomb Mountains of southeastern California, to the Harquahala Mountains of central Arizona (Fig. 2.1). In addition, the Moon Mountains area is situated within the westernmost exposures of the regional Whipple-Buckskin-Rawhide detachment system of mid-Tertiary age, a system associated with profound crustal extension in the Colorado River extensional corridor (Howard and John, 1987)

Rocks exposed in the Moon Mountains consist primarily of crystalline gneisses and granitic intrusive rocks, with lesser amounts of sedimentary and volcanic supracrustal lithologies. These rocks range in age from Precambrian to Tertiary, and record a
complicated history of repeated deformation, metamorphism, and magmatism which characterizes much of the Mojave-Sonoran Desert area of the southwestern Cordillera. Detailed field mapping, structural analysis, and geochronology are presented in this study which document the presence of Mesozoic thrusting and associated fabrics, as well as Tertiary detachment faulting and associated structural elements in the Moon Mountains area.

Some confusion surrounds the geographic nomenclature of the Moon Mountains area. Moon Mountain is variably referred to solely as the peak which bears this name, or the entire area composed of the two elongate ridges which define the northernmost Dome Rock Mountains, north of Tyson Wash. For the purpose of this report, Moon Mountain will be used to refer to the peak which bears this name, and Moon Mountains will refer to the entire area made up of the two elongate ridges (Plate 2-1; Fig. 2.2). Several informal names have been used to designate certain geographic areas or elements, for the sake of ease of reference. These names are indicated on the sketch map in Figure 2.2, and include (1) Detachment Wash, (2) the Valenzuela area, (3) El Diablo Peak, (4) the Mojave Paint Basin, and (5) Copper Peak. The Valenzuela area refers to the region near and to the south of the Valenzuela Mine, in the southeastern part of the Moon Mountains. El Diablo Peak is the name given to peak 1337' in the Valenzuela area.

**PREVIOUS WORK**

Previous work within the Moon Mountains area has largely revolved around the mining resources and potential of the Colorado River region. The area was heavily mined in the late 1800's and early 1900's for base and precious metals, and is now the site of gold production from the Copperstone Mine, an open pit operation just to the north of the Copper Peak area in the northeastern Moon Mountains (see Spencer et al., 1988). Wilson et al. (1969) showed the generalized distribution of rock types for the Moon Mountains area on the Arizona state geologic map, identifying the presence of crystalline gneisses and metamorphosed Mesozoic rocks. James Baker, from San Diego State University, produced a brief, unpublished, senior honors thesis report on the general location of the Moon Mountain detachment fault, and a brief treatment of the rock types of the western half of the Moon Mountains. Buising (1988) included outcrops of the upper Miocene to lower Pliocene Bouse Formation at Moon Mountain in her study of the proto-Gulf of California in western Arizona and southeastern California. Metzger (1968, 1973) also makes mention of Bouse Formation deposits in the area of the Moon Mountains in
reports on the hydrogeology of the lower Colorado River trough. The present study constitutes the first thorough compilation and discussion of the rocks and structures of the Moon Mountains, including the geologic map compiled at a scale of 1:24,000 (Knapp, in press).

DESCRIPTION OF ROCK UNITS

Rocks exposed in the Moon Mountains consist predominantly of crystalline gneisses and granitic intrusive rocks, with lesser amounts of sedimentary and volcanic lithologies. These rocks range in age from Precambrian to Tertiary and record successive periods of sedimentation, magmatism, deformation, and metamorphism. Detailed descriptions of the rock units are presented below, and are categorized by metamorphic, sedimentary, and igneous rock types. Within each of these divisions, units are discussed in order of decreasing age, as deduced from field relationships and U-Pb zircon geochronology.

The general distribution of rock units in the Moon Mountains is primarily influenced by the major structures present in the area (Plate 2-1, Fig. 2.2). The footwalls of both the Moon Mountain and Copper Peak detachment faults are predominated by crystalline gneisses and granitic intrusive rocks; the hanging walls of these structures are devoid of these lithologies, and carry either Tertiary sedimentary rocks (Moon Mountain detachment) or sedimentary and volcanic rocks of Tertiary, Mesozoic, and Paleozoic (?) age (Copper Peak detachment). Supracrustal rocks of Mesozoic age are restricted primarily to two areas. A newly recognized sequence of metasedimentary rocks, herein referred to as the Valenzuela metasedimentary sequence, occurs beneath the Valenzuela thrust fault in the southeastern Moon Mountains. Metavolcanic rocks of inferred Mesozoic age are concentrated in the area of the Mojave Paint Basin, where they are surrounded by younger granitic intrusive rocks.

METAMORPHIC ROCKS

Metamorphic rocks of the Moon Mountains consist of gneisses, schists, and amphibolites of presumed Precambrian age, and a sequence of metamorphosed sedimentary rocks, herein named the Valenzuela metasedimentary section. These lithologies comprise roughly 35% of the bedrock exposure, and record multiple phases of deformation and metamorphism.
Rocks of inferred Precambrian age in the Moon Mountains have been divided into two lithotectonic units based on general lithologic characteristics and geographic distribution. The Moon Mountain crystalline assemblage is designated as the collection of gneisses and amphibolites which underlie Moon Mountain, in the footwall of the Moon Mountain detachment fault in the northwestern Moon Mountains (Plate 2-1; Fig. 2.2). The name Valen crystalline assemblage is used here for the sequence of gneisses and schists which outcrop along the eastern arm of the Moon Mountains, in the footwall of the Copper Peak detachment. These rock units are inferred to be primarily of Precambrian age based on lithologic similarity with Precambrian rocks from surrounding ranges (e.g. Whipple Mountains, Orell, 1988; Podruski, 1979), and constitute the oldest units exposed in the Moon Mountains area.

MOON MOUNTAIN CRYSTALLINE ASSEMBLAGE (mx, a)

The Moon Mountain crystalline assemblage, named for the crystalline rocks which compose Moon Mountain itself, is exposed over an area of roughly four to five square kilometers in the northwestern Moon Mountains (Plate 2-1). These rocks display fabrics associated with intense deformation and amphibolite facies metamorphism. Five main lithologies have been identified within the Moon Mountain crystalline assemblage, defining a crude tectonic stratigraphy. These five divisions, in structurally ascending order, are: (1) a lower injection complex, composed mostly of sheared augen gneiss which has been extensively intruded by dikes of the structurally lower Tyson Peak granite, (2) thinly-banded gneiss, (3) quartz-mica schist (4) hornblende-biotite schist, and (5) medium- to coarse-grained augen gneiss. These five units form a continuous, layered stratigraphy over several kilometers within the highly deformed rocks of the Moon Mountain crystalline assemblage. The maximum exposed structural thickness of this sequence is ~120 m, in the vicinity northwest of the Apache Mine. Due to the regional northeast dip of the section, lower structural levels are not exposed at the north end of Moon Mountain, and the top of the section has been truncated by a splay of the Moon Mountain detachment fault.

VALEN CRYSTALLINE ASSEMBLAGE (vx)

The Valen crystalline assemblage is named for exposures of gneisses, schists, and amphibolites which underlie Valen Peak and surrounding areas in the eastern arm of the Moon Mountains (Fig. 2.2). This heterogeneous assemblage of crystalline rocks outcrops over an area of about three square kilometers, and is characterized by a variety
of lithologies, including megacrystic augen gneiss, banded-gneiss, quartzofeldspathic schist, and amphibolite, in order of decreasing abundance. All lithologies possess a metamorphic fabric, which varies from a crude foliation defined by aligned porphyroclasts and matrix minerals in the coarse-grained augen gneisses (Fig. 2.3), to a well-developed foliation and metamorphic mineral lineation in the schists and amphibolites. Fabrics do not exhibit a consistent orientation in these rocks; foliation is typically moderate- to shallow-dipping, but is disrupted on a local scale by folding. Metamorphic lineation is similarly variable. Petrographic analysis of these rocks indicates these fabrics were developed at amphibolite or epidote amphibolite facies conditions of metamorphism.

The Valen crystalline assemblage is intruded by several younger granitic bodies. Along the northern boundary of this unit, biotite-bearing granites of lower Miocene age intrude the Valen crystalline assemblage. The southern boundary of the crystalline complex is marked by an intrusive contact with a large body of quartz syenite of Jurassic age. The southernmost exposures of the Valen assemblage are fault bounded, and are carried in the hanging wall of the Valenzuela Thrust, where they overlie rocks of the Valenzuela metasedimentary section.

VALENZUELA METASEDIMENTARY SEQUENCE

A section of deformed and metamorphosed sedimentary rocks, exposed in the Valenzuela area of the southeastern Moon Mountains, has been informally named the Valenzuela metasedimentary section. These rocks consist of schist, marble, quartzite, and calc-silicate rocks which have been metamorphosed at lower amphibolite facies, and are beneath the Valenzuela thrust fault. Due to the internal deformation within this section, the original stratigraphic order of this sequence cannot be reconstructed with certainty. The structural ordering consists of: (1) a basal section of calc-silicate rocks with abundant, isoclinally folded quartzite lenses, (thought to be quartzite pebbles and cobbles), (2) a thin interval (2-4 m) of thinly-bedded quartzite, (3) a section of interbedded schists and quartzites, (4) a thick interval of orange- to brown-colored micaceous marble, (5) a second, thin, discontinuous interval of schists, (6) a second interval of thinly bedded quartzite which typically marks the overlying thrust contact, and (7) a second interval of calc-silicate rocks (see Figs. 2.4a and b). This structural sequence appears to define a repetition of the lithologies in a large, overturned synform, opening toward the south. Attenuation in the upper limb has resulted in thinning and omission of units directly beneath the Valenzuela thrust. Since the original stratigraphic
order of the Valenzuela section is unknown, it is impossible to determine whether this fold constitutes a large syncline, overturned to the south as in the neighboring Big Maria Mountains, or a synformal anticline.

**Calc-silicate Rocks (vc)**

The base of the Valenzuela metasedimentary sequence consists of 10-12 m of greyish green-weathering calc-silicate rocks that contain numerous quartzite lenses (Fig. 2.5). Since the base of this unit is not exposed, the structural thickness represents a minimum. The contact with the overlying quartzite is sheared, but appears to be an original stratigraphic boundary. These rocks are typically medium- to fine-grained schists which contain the assemblage quartz + potassium feldspar + biotite + plagioclase + calcite + chlorite + epidote, with minor muscovite. Preserved as rootless isoclinal fold hinges are abundant lenses of pure vitreous quartz. In thin section, these quartz lenses are medium- to coarse-grained with interlocking grain boundaries, suggesting a hydrothermal origin; however, in outcrop, the lenses take on the appearance of deformed quartzite clasts.

**Thinly-bedded Micaceous Quartzite (vq)**

An interval of thin- to very thin-bedded, micaceous quartzite occurs both near the base and at the top of the structural section. This quartzite outcrops as a resistant ledge, typically 3 to 4 m thick. It marks the thrust contact with the overlying quartz syenite along much of the length of the Valenzuela thrust fault, is exposed above the basal unit of calc-silicate rocks, and is exposed in a klippe of the metasedimentary rocks that lie above the Valen crystalline assemblage to the west of the Graveside fault (Plate 2-3). Despite intense recrystallization and internal deformation, the unit appears to retain certain aspects of its sedimentary origin. The quartzite is a thin- to very thin-bedded, light to medium grey-weathering, laminated, medium- to fine-grained, micaceous quartzite with thin micaceous partings. The rock consists almost exclusively of quartz (90-95%) and muscovite (4-5%), with a minor amount of potassium feldspar.

The unit displays intense internal deformation, typified by isoclinal folding (Fig.2.6); contacts with adjacent units are sheared, but relatively intact. Beneath the Valenzuela thrust fault, the outcrop pattern of this quartzite unit defines a large recumbent fold, opening toward the south, and cored by rocks of the interbedded schist, quartzite, and micaceous marble.
Interbedded Schist and Quartzite (vs)

An interval of thin- to medium-interbedded schist and quartzite makes up a significant part of the section. This unit outcrops as a slope of silvery-grey to brown-weathering schists, with more resistant, quartz-rich layers forming small continuous ridges (Fig. 2.4a). The maximum structural thickness of this unit is about 40-45 m, but probably represents an overestimate due to the internal folding and thickening evident in the outcrop.

Schists from this unit are composed largely of quartz and muscovite. One sample was found to contain numerous kyanite porphyroclasts, with a matrix assemblage of quartz + muscovite + sillimanite(?) + epidote ± opaques oxides. This assemblage is indicative of amphibolite facies metamorphism, and sillimanite has grown within the fabric.

Micaceous Marble (vm)

A very distinctive lithology within the Valenzuela metasedimentary section consists of an orange-weathering, micaceous calcite marble. This unit forms a prominent, resistant ledge in the upper part of the section. Contacts with both the underlying interbedded schist and quartzite unit and the overlying part of the section are sheared, and the base of the marble changes from a concordant contact to one which cuts with marked discordance across the underlying part of the section (Figs. 2.4a and b). The marble outcrops as a "medium-bedded", coarse-grained, orange- to brown-weathering, micaceous marble. Structural thickness of the unit varies considerably along strike due to thickening and attenuation of the unit, but ranges from ~2 to 10 m.

The marble contains the assemblage calcite + muscovite ± quartz. Some intervals are very micaceous, containing up to 10% muscovite. Due to the degree of recrystallization and internal deformation within this unit, essentially no primary features remain.

Stratigraphic Correlation

Stratigraphic correlation of the Valenzuela metasedimentary sequence with known stratigraphy from west-central Arizona and adjoining southeastern California suggests an early Mesozoic age for this section. A clear correlation can be made with the Tung Hill metasedimentary sequence (Yeats, 1985) of the northern Dome Rock Mountains, just to
the south of the exposures of the Valenzuela section. This correlation can be made on the basis of (1) the general succession of lithologies within the two sections, (2) similar structural position of these metasedimentary rocks beneath thrust faults which carry deformed augen gneiss in the hanging wall, and (3) the geographic proximity of the two sections, which are separated by no more than ~8 km.

Yeats inferred a lower Mesozoic age for the Tung Hill section based on the lack of resemblance with other known occurrences of Paleozoic and Mesozoic strata in the region, and Reynolds et al. (1987) correlated the Tung Hill section with the Buckskin Formation of the Buckskin Mountains, to the north. The type section for the Buckskin Formation is located in the Planet-Mineral Hill area of the Buckskin Mountains, and consists primarily of quartzose sandstone, siltstone, and conglomerate, with a variable calcareous component. While carbonate intervals are typically lacking in sections from western Arizona which have been correlated with the Buckskin Formation (Reynolds et al., 1987), more distal facies of the calcareous-rich siltstones could be marine carbonates (Spencer, pers. comm.). Evaporite intervals are characteristic within the lower Triassic section of the eastern Mojave Desert (Walker, 1985, 1988) and in the Buckskin Formation of western Arizona (Reynolds et al., 1987), but they have not been recognized in the Valenzuela section.

Reynolds et al. (1987) identify four divisions of Mesozoic supracrustal rocks in west-central Arizona. In ascending stratigraphic order, these are: (1) quartzose to slightly feldspathic sandstones, siltstones and conglomerates that depositionally overlie the Permian Kaibab Limestone, (2) quartzite and quartzofeldspathic sandstone with locally interbedded volcaniclastic rocks, (3) voluminous silicic volcanic, hypabyssal, and volcaniclastic rocks, and (4) a thick section of volcaniclastic rocks assigned to the McCoy Mountains Formation. In the eastern Mojave Desert of southeastern California, the lower Mesozoic Moenkopi Formation consists of marine and non-marine terrigenous, carbonate and evaporite rocks (Walker, 1985, 1988). Facies within the Moenkopi Formation vary from alluvial redbeds on the Colorado Plateau to mainly marine carbonate rocks in the central Mojave Desert.

**SEDIMENTARY ROCKS**

Sedimentary rocks and sediments of the Moon Mountains range in age from Paleozoic to Recent, and are represented by minor amounts of carbonate, quartzite, conglomerate, sandstone, siltstone, and unconsolidated gravels. These rocks are
restricted to the hanging walls of the Moon Mountain and Copper Peak detachment faults, where they are variably faulted, tilted, and brecciated. Several of these rock types occur only in the Copper Peak area as small outcrops in the hanging wall of the Copper Peak detachment.

**COPPER PEAK AREA**

Exposed in the vicinity of Copper Peak is a collection of units which occur only in the hanging wall of the Copper Peak detachment. These units include quartzite, cherty limestone, sandstone, and mafic volcanic rocks (Plate 2-1). While these lithologies comprise an insignificant percentage of the rocks exposed in the Moon Mountains, they occupy an important structural position, and bear on the geologic evolution of the Moon Mountains area.

**Quartzite**

The top of Copper Peak is composed of highly brecciated, vitreous white quartzite. This quartzite breccia consists of reddish-brown weathering, angular, small pebble- to large cobble-sized quartzite clasts in a matrix of sub-angular to sub-rounded, crushed, fine-grained quartz. Preserved in some of the larger quartzite clasts are relict primary sedimentary features, including thin silty laminations and medium- to fine-grained, well-rounded quartz sand grains in quartz cement. Despite the high degree of fracturing and brecciation of this quartzite, the rock does not appear to be significantly recrystallized or ductilely deformed, unlike other quartzites exposed in the Moon Mountains.

Stratigraphic correlation of this laminated, medium- to fine-grained quartz arenite cannot be made with certainty. Several correlations are possible: the Cambrian Bolsa Quartzite, the Permian Coconino Sandstone, the Jurassic Aztec Sandstone, or quartzites associated with lower Mesozoic rocks in west-central Arizona.

**Cherty Carbonate Rocks**

A small irregular mound of brecciated, cherty limestone occurs at the northern base of Copper Peak. This rock outcrops in irregular blocks of greyish brown-weathering, laminated, cherty limestone which has been highly brecciated internally. Laminations and dark brown, irregular nodules of chert and/or silty material weather more resistantly than the medium- to fine-grained calcite matrix, giving the rock a rough,
mottled surface. Despite the high degree of fracturing and internal brecciation within the unit, the laminations and silty partings appear to be a primary sedimentary feature of the rock. Orientation of bedding is inconsistent, varying from one block to the next due to the extreme disruption of the outcrop.

The protolith of this limestone breccia is inferred to be one of the carbonate units that characterize the cratonic Paleozoic section of western Arizona. Cherty carbonates are unknown from Precambrian, Mesozoic, or Cenozoic strata in this region. Since the unit outcrops in structural isolation in the hanging wall of the Copper Peak detachment, a stratigraphic succession cannot be inferred. The rock occurs in close proximity to highly brecciated, laminated quartz arenite which caps the top of Copper Peak and may correspond to either the Cambrian Bolsa Quartzite or the Permian Coconino Sandstone of the Paleozoic cratonal section. Of the limestone units of Paleozoic age, the Permian Kaibab Limestone is known to contain chert-rich intervals (Richard, 1982). Based on this fact and the proximity to quartz arenite of possible Permian age, a correlation with the Permian Kaibab Limestone is preferred.

**Conglomerate**

Several small, poorly-exposed outcrops of coarse, pebbly sandstone and fine-grained conglomerate are found just north of Copper Peak in the hanging wall of the Copper Peak detachment. Structural thickness of this clastic section is difficult to assess due to incomplete exposure. A minimum thickness of ~15 m can be estimated from the available exposure. Contacts with surrounding units are also cryptic; however, the sediments appear to be intercalated with mafic volcanic rocks. These sedimentary rocks are dark brown-weathering, massive to thick-bedded, with medium- to small-sized, sub-angular to sub-rounded pebbles floating in a medium- to coarse-grained, sandy matrix composed primarily of quartz, feldspar, and lithic fragments. Pebble lithologies include basalt, quartzite, and carbonate. Formational affinity of individual clasts is difficult to determine based on small grain size.

The rocks have been strongly tilted based on the orientation of faintly-developed, fining upward sequences which indicate a westward facing in these rocks. The bedding is oriented ~N10W, dipping 80° SW to vertical. Based on lithology and clast composition and comparison with sediments of known Tertiary age, these terrigenous rocks are inferred to be of Tertiary age, and were apparently associated with subaerial basin deposition during development of the regional detachment system of western
Arizona and southeastern California. Spencer et al. (1988) indicate the presence of monolithologic sedimentary breccias derived from the Jurassic quartz porphyry in association with these fine-grained, terrigenous sediments. Tilting of these sediments, to vertical attitudes, is probably associated with rotation in the hanging wall of the Copper Peak detachment, as is the case for extension-related sediments in many other parts of the detachment system (cf Davis et al., 1980, in the Whipple Mountains).

**MOON MOUNTAIN AREA**

A sequence of conglomerates and sandstones which has been faulted and tilted in the hanging wall of the Moon Mountain detachment fault is exposed over an area of about two square kilometers to the east of Detachment Wash.

**Monolithologic Conglomerate (Tcs)**

Monolithologic conglomerate occupies the lowest exposed levels of this section, and rests in fault contact against crystalline gneisses of the Moon Mountain crystalline assemblage on the Moon Mountain detachment fault. This unit consists exclusively of poorly-sorted (pebble- to boulder-size), angular to sub-angular, clasts of greenish grey-weathering, quartz porphyry in a clast-supported conglomerate.

**BOUSE FORMATION (Tmb)**

Deposits of the upper Miocene to lower Pliocene Bouse Formation mantle bedrock exposures throughout the study area. The Bouse Formation was first described by Metzger (1968) on the basis of a 767-foot type section from a well in Parker Valley, and two reference sections, one of which is located along the western flank of Mesquite Mountain (SW1/4 sec. 26 and SE 1/4 sec. 27, T.8 N., R.20W., Gila and Salt River baseline and meridian).

Metzger (1968) identified three units within the Bouse Formation: (1) a basal limestone, (2) interbedded clay, silt and sand (which comprises most of the formation), and (3) a distinctive tufa deposit that mantles topography and is thought to have formed at or near the water surface throughout Bouse Formation deposition. Recent work by Buising (1987; 1988) shows the Bouse Formation to be interfingered with conglomerate and sandstone of the underlying Osborne Wash association. The Bouse Formation is overlain by and interfingers with conglomerates interpreted as ancestral Colorado River gravels (Buising, 1987).
ALLUVIUM (Qal)

Rocks mapped as alluvium consist predominantly of unconsolidated gravels and sands associated with the modern drainage system of the Colorado River and its tributaries. These deposits include alluvium, colluvium, talus, dune sand, and flood plain deposits of the Colorado River. No attempt has been made in the present study to distinguish these various Quaternary deposits on the geologic map.

IGNEOUS ROCKS

MOJAVE PAINT BASIN METAVOLCANIC SEQUENCE (mv)

A series of deformed and metamorphosed volcanic rocks is exposed in the northern end of the eastern arm of the Moon Mountains, in what is informally referred to as the Mojave Paint Basin (Fig. 2.2). These rocks (indicated by "mv" on the geologic map) outcrop as recessive slopes of green to grey weathering, medium- to fine-grained rock in the area of low relief to the south of the Copper Peak area. Contacts with surrounding units are generally not well exposed, and are either intrusive or fault-bounded where the contact relations can be observed. Due to the extreme internal deformation within this unit and the lack of stratigraphic contacts with other units, the stratigraphic order is unknown.

QUARTZ PORPHYRY (Jqp)

Limited outcrops of silicic volcanic or sub-volcanic quartz porphyry are restricted to the area around the Mojave Paint Basin, the area near Copper Peak, and the hanging wall of the Copper Peak detachment, all in the northeastern Moon Mountains. This lithology forms resistant, rounded hills of massive, blocky-weathering, quartz porphyry which appears orange to dark brown on a weathered surface and greyish green on a fresh surface. Near the Copper Peak detachment fault, extensive secondary alteration has produced red- and yellow-weathering of the unit. The rock consists of medium- to coarse-grained phenocrysts of quartz, plagioclase, lithic fragments, potassium feldspar, and relict hornblende and biotite, floating in a very fine-grained groundmass of quartz and feldspar. The presence of embayed quartz grains, lithic fragments, many angular or broken phenocrysts, and the microcrystalline groundmass, suggest a volcanic origin for this rock. Other primary features are lacking, as the quartz porphyry typically forms a structureless mass.
Exposures of the quartz porphyry are typically fault-bounded, such that stratigraphic relations with surrounding units are unclear. Below Copper Peak, the quartz porphyry rocks are intruded by the Copper Peak granite, which produces a baked and altered zone near the contact. South of the Copper Peak granite, the quartz porphyry appears to be in stratigraphic contact with deformed metavolcanic rocks of the Mojave Paint Basin sequence, but the contact is not well-exposed. The stratigraphic ordering of these two units is not discernible within the map area, but based on regional relations, the quartz porphyry is inferred to overlie the metavolcanic sequence.

The age of the quartz porphyry is inferred strictly from regional relations. Similar silicic volcanic rocks are known from a wide area in the Mojave-Sonora desert region (Pelka, 1973a; Hamilton, 1982; Reynolds et al., 1987; Tosdal et al., 1988). These rocks consistently occupy a stratigraphic position above lower Mesozoic sedimentary rocks correlative with the Triassic Moenkopi Formation. Reynolds et al. (1987) reported slightly discordant U-Pb zircon data for quartz porphyry rocks from the Buckskin Mountains and Black Rock Hills which they interpreted to signify an emplacement age of 162 to 160 Ma. Granitic plutons of known Late Jurassic age intrude these quartz porphyry rocks in several ranges (Tosdal et al., 1988). Based on these relations, a Middle Jurassic age is inferred for the quartz porphyry rocks exposed in the Moon Mountains.

MAFIC VOLCANIC ROCKS (Tb)

Very minor, low-lying exposures of dark brown- to black-weathering, mafic volcanic rocks occur in association with coarse-grained sandstones north of Copper Peak, in the northernmost part of the map area. Contacts of these volcanic rocks with the surrounding bedrock are very poorly exposed, but the Copper Peak detachment fault is inferred to project beneath the outcrops of basalt. Flow features were not observed in these rocks, but igneous textures suggest they were rapidly quenched. Contacts with associated sedimentary rocks are not well exposed in the area near Copper Peak, so the possibility that these are hypabyssal dike rocks cannot be ruled out. Further to the north, outside the map area, Spencer et al. (1988) shows more exposures of these mafic volcanic rocks in the continuation of the hanging wall of the Copper Peak detachment fault. The age of these mafic volcanic rocks is inferred to be Tertiary. Judging from timing constraints for Tertiary volcanism in western Arizona, these volcanic rocks are probably of late Oligocene to mid Miocene age.
INTRUSIVE ROCKS

Granitic intrusive rocks, ranging in composition from quartz syenite to garnet two-mica granite, comprise the majority of rocks exposed in the Moon Mountains area. Large volumes of megacrystic, porphyritic quartz syenite (Jqs) occur in the southern Moon Mountains, and are known from a number of surrounding ranges in the Mojave-Sonora region (Hamilton, 1982; Yeats, 1985; Tosdal, 1988). Five separate bodies of biotite-bearing granite are identified: 1) the Tyson Peak granite (tpg), 2) the Copper Peak granite (cpg), (3) a biotite-bearing leucogranite (lg), (4) a small stock of biotite granite (Tmbg), and (5) a small hornblende-biotite granite stock (Thbg). The Tyson Peak granite is exposed along most of the length of the western arm of the Moon Mountains, and is named for Tyson Peak. The Copper Peak granite outcrops in the northeastern part of the Moon Mountains, and is named for Copper Peak. The biotite granites are all similar in composition and may be genetically related, but can be differentiated on the basis of texture, mineralogy, color index, and/or contact relations. Together these granitic rocks constitute ~45-50% of the exposed bedrock in the Moon Mountains.

Megacrystic Quartz Syenite (Jqs)

A large body of megacrystic quartz syenite is exposed at the southern end of the Moon Mountains, over an area of several square kilometers. The rock outcrops as rounded, resistant, dark hills. The quartz syenite is characterized by variable amounts (3-50%) of small (<1 cm) to very large (>15 cm), grey to purple, potassium feldspar megacrysts in a medium- to fine-grained groundmass of quartz + potassium feldspar + biotite + plagioclase, with epidote, chlorite, and minor white mica as secondary alteration products (Fig. 2.7). Accessory phases typically include sphene, zircon, apatite, and opaque oxides.

In the Valenzuela area, the quartz syenite intrudes the Valen crystalline assemblage, and is carried in the hanging wall of the Valenzuela thrust fault above the Valenzuela metasedimentary section. Intruding the quartz syenite are two groups of granitic dikes: one is a biotite-bearing leucogranite (lg) and the other is a set of garnet+biotite-bearing pegmatites and aplites. In the southwestern part of the Moon Mountains, the quartz syenite is intruded by the Tyson Peak granite.

Uranium-lead zircon dating of the megacrystic quartz syenite yields a late Middle Jurassic to early Late Jurassic age (160 ± 15; Knapp and Walker, in prep.). These rocks bear a strong resemblance to porphyritic Precambrian granites known from the Mojave-
Sonora region (Anderson, 1983), and can be difficult to distinguish in the field. All of the megacrystic quartz syenite rocks which form a relatively homogeneous, continuous body at the southern end of the Moon Mountains are correlated with the unit which was dated from the hanging wall of the Valenzuela thrust fault in the Valenzuela area. Other bodies of similar, phenocryst-rich, megacrystic granite occur within both the Moon Mountain crystalline assemblage and Valen crystalline assemblage, and may be either Precambrian or Jurassic in age.

**Leucogranite (lg)**

Irregular pods and bands of deformed, gneissic leucogranite are present within rocks of the Valenzuela area in the southeastern Moon Mountains. These rocks weather a medium grey to brown, and occur in bodies up to tens of meters across, but more often are found as thin (<1 m), sheared dikes which are clearly intrusive into the surrounding units. The rock consists of medium- to fine-grained, biotite-bearing leucogranite, which contains primarily quartz, potassium feldspar, plagioclase, and biotite. The rock possesses a well-developed fabric with a strongly-developed foliation parallel to the fabric in the surrounding rocks. It is restricted solely to exposures in the Valenzuela area and in the southernmost Moon Mountains. In the Valenzuela area, this leucogranite intrudes the Jurassic quartz syenite, the Valenzuela metasedimentary section, and the Valen crystalline assemblage south of the Trail Pass fault.

Similar rocks are known from areas to the south of the Moon Mountains. Yeats (1985) mapped a bodies of gneissic leucogranite in the northern Dome Rock Mountains that are intrusive into both megacrystic granites and lower Mesozoic metasedimentary rocks. Tosdal (1988) has dated rocks thought to be of this same suite from the Dome Rock Mountains and areas further south in Arizona, and cites an early Late Jurassic (158 Ma) age of intrusion.

**Garnet-bearing Pegmatites**

A swarm of garnet-bearing pegmatite and aplite dikes is present in the Valenzuela area in the southeastern portion of the Moon Mountains. The dikes vary in width from 0.5-2 m and are continuous over 10's to 100's of meters. The highest concentration of these dikes occurs in the area of El Diablo peak, where they make up as much as 20-25% of the outcrop (Fig. 2.4b). The dikes are most prevalent within the quartz syenite, but occur also within the Valen crystalline assemblage (south of the Valenzuela cutoff), and
several garnet-bearing dikes are present in the base of the Valenzuela metasedimentary section. The dikes are not recognized elsewhere in the Moon Mountain area, and no granitic body is exposed structurally below the dikes as an obvious source for them.

The dikes consist compositionally of quartz (55-60%), potassium feldspar (15-20%), plagioclase (12-15), garnet (<1%), and muscovite (<1%), with minor amounts of biotite and Fe-Ti oxides. Zircon and apatite are present in trace amounts. The rock has a hypidiomorphic granular texture, and varies from fine- to coarse-grained between aplitic and pegmatitic varieties. Muscovite appears to be a primary phase, as it occurs as well-formed, cleanly terminated grains, and exists as inclusions in some feldspar grains. Garnet occurs as medium- to fine-grained, subhedral to euhedral grains, typically concentrated toward the centers of dikes.

These dikes clearly intrude a metamorphic foliation developed within the quartz syenite and Valen crystalline assemblage, however the dikes themselves are deformed. Due perhaps to the composition of these dikes, they do not have a well-developed fabric themselves, but are folded in complex patterns, and are cut by gently north-dipping shear planes (Fig. 2.8).

U-Pb zircon analysis of these dikes (Knapp and Walker, in prep) indicates they are Late Cretaceous in age, based on a lower intercept age of 71.1 ± 6.7 Ma (4 fractions). Hamilton (1982, 1984) described a similar swarm of muscovite-bearing pegmatites in the north-central and northwestern Big Maria Mountains to the west, which he inferred to be Late Cretaceous in age based on cross-cutting relations with Jurassic intrusive rocks and a K-Ar age of ~62 Ma (Martin et al., 1982).

**Tyson Peak Granite (tpg)**

The Tyson Peak granite (informal name) consists of a large, relatively homogeneous granitic body exposed over an area of several square kilometers in the southwestern part of the Moon Mountains (Plate 2-1, Fig. 2.2). This granite body intrudes gneisses of both the Moon Mountain crystalline assemblage (to the north) and the quartz syenite (to the south). Exposures of the Tyson Peak granite extend over eight kilometers from north to south, and a thickness of 150 m is represented. This must be taken as a minimum thickness as the base is nowhere exposed. Several satellite bodies of the granite occur within the quartz syenite. The granite is named for Tyson Peak, near the section corner for sections 1, 2, 11, and 12.
The unit consists of a medium- to coarse-grained porphyritic biotite granite, weathering to light greyish brown. Porphyritic potassium-feldspar crystals are 1-3 cm (with foliation bent around them), make up 20-25% of the rock, and sit in an equigranular, medium- to coarse-grained matrix of quartz (35%), feldspar (30%), and biotite (8-12%). Minor epidote is present as a secondary(?) phase. A moderate to well-developed foliation, defined by aligned biotite, elongate feldspar grains, and stretched quartz is present over much of the exposed extent of the granite. Abundant secondary white mica has grown within the plane of foliation where the rock is strongly foliated.

The contact of the porphyritic biotite granite with the surrounding crystalline country rock is highly sheared in places, but is clearly intrusive. Numerous aplitic dikes emanate from the granite body at the northern contact with gneisses of the Moon Mountain crystalline assemblage, and the abundance of these dikes decreases dramatically within ~100 m from the contact. In contrast, dikes are rare and a quartz-rich border phase is typically present along the southern contact of the granite, and blocks of the quartz syenite, up to 200-300 m across, occur within the granite near its margins. The granite contact is irregular on an outcrop scale, and clearly truncates an earlier foliation within the gneissic country rock (Fig. 2.9). Foliation is poorly developed within the margins of the granite, where the rock tends to be equigranular and crumbly with no preferred mineral orientation, and the mica has been extensively sericitized.

The age of the Tyson Peak granite is uncertain, but constrained to be post-Jurassic based on intrusive relations with the quartz syenite, and pre-Bouse Formation. The Tyson Peak granite bears a strong resemblance to foliated granite in the northern Dome Rock Mountains (just to the southeast, across Tyson Wash) named the Tyson Wash granite (Yeats, 1985). In that area, the Tyson Wash granite truncates the Tyson Wash thrust, here correlated with the Valenzuela thrust. These correlations would restrict the age of the Tyson Peak/Tyson Wash granite to be younger than ~71 Ma (post-Late Cretaceous). Outcrop examination of s-c fabrics within the Tyson Peak granite exhibit a top-to-the-northeast shear sense, consistent with kinematic indicators for the Moon Mountain detachment fault, and implying that the Tyson Peak granite pre-dates significant deformation in the footwall of the detachment.

**Copper Peak Granite**

The Copper Peak granite is exposed over an area of ~2 km² surrounding and to the south of Copper Peak, in the northeastern part of the Moon Mountains. The unit
outcrops as low ridges and irregular hills of orangish brown-weathering granite. Numerous dikes of intermediate to mafic composition intrude the granite, and form more resistant, west-northwest trending ridges. Contacts of the Copper Peak granite with surrounding units are either (1) fault-bounded, or (2) not well exposed. Along the northern margin of the Copper Peak granite, the unit is truncated by the Copper Peak detachment fault. The southern boundary of the Copper Peak granite consists of an intermediate- to high-angle fault, which juxtaposes the granite against metamorphosed Jurassic and lower Mesozoic(? ) volcanic and volcaniclastic rocks of the Mojave Paint Basin. Below the Copper Peak detachment, the Copper Peak granite is in direct contact with metamorphosed volcanic rocks of the Jurassic quartz porphyry (Jqp). The contact is not well exposed, but is inferred to be intrusive based on the baked, discolored nature of the quartz porphyry near the contact. Several blocks (5-10 m in diameter) of sheared, megacrystic quartz syenite occur as inclusions within the Copper Peak granite, indicating that significant deformation had affected the country rocks prior to intrusion of the Copper Peak granite.

The unit consists of a biotite-bearing, hypidiomorphic granite with the primary assemblage quartz + potassium feldspar + plagioclase + biotite. Secondary mineralization has resulted in chloritization of biotite and sericitization of feldspar. A weakly- to strongly-developed tectonic fabric is present over much of the exposed extent of the granite, and is characterized by flattened and stretched quartz grains and crushed potassium feldspar crystals. A consistent top-to-the-northeast shear sense is indicated by S-C fabrics (including bent micas and sygmoidal quartz ribbons) and asymmetric feldspar porphyroclasts beneath the Copper Peak detachment.

The age of the Copper Peak granite is constrained to be younger than Jurassic, based on intrusive relations with the Jurassic quartz porphyry, and is inferred to be Tertiary, based on compositional and textural similarity to other biotite-bearing granites in the Moon Mountains area. It may be roughly coeval with Tmbg, a biotite granite dated by U-Pb zircon to be 20.8 ± 3.2 (Knapp and Walker, in prep.).

**Biotite Granite (Tmbg)**

Outcrops of a small, unnamed stock of porphyritic biotite granite flank both the northern and southern margins of the Mojave Paint Basin area in the northeastern Moon Mountains. This granite forms steep, crumbly ridges and weathers to an orange-brown in knobby, rounded outcrops. The rock is typically a medium-grained biotite porphyry.
with phenocrysts of feldspar (40%), quartz (30%), and biotite (~5%) set in a fine-grained groundmass of quartz and feldspar. Some portions are not nearly so porphyritic, and form a medium-grained, hypidiomorphic granular texture.

Contacts with surrounding units are intrusive. In northern exposures, this biotite granite intrudes the Copper Peak granite, and can be differentiated from the Copper Peak granite by a higher biotite content and consequent darker color. This biotite granite is clearly intrusive into rock of the Mojave Paint Basin metavolcanic sequence, which have been strongly mylonitized. The granite truncates mylonitic fabrics in these country rocks that indicate a predominant top-to-the-northeast asymmetry. The granite does possess a locally developed foliation consisting of flattened quartz grains and aligned micas, but the rock is generally not foliated, and is interpreted to be late- to post-tectonic with respect to development of mylonites in the footwall of the Copper Peak detachment. Along the southern margin of this granitic body lies another biotite granite (Thbg). Intrusive relations between these two granites are equivocal. The contact is marked by a distinct mineralogical and color change to the darker, hornblende-bearing granite to the south (Fig. 2.10), but (1) no baked contact is evident, (2) no dikes emanate from one body into the other, and (3) no textural evidence for quenching of one body against the other was observed. Several small outliers of the hornblende-bearing granite (Thbg) occur within the biotite granite (Tmbg), but their contacts are not well exposed, and they may either by included blocks in or intrusive outliers to the main body of hornblende-bearing granite.

U-Pb zircon dating of the Tmbg unit indicates it is early Miocene in age, based on a lower intercept of 20.8 ± 3.2 (Knapp and Walker, in prep.). The spatial association and similarity in composition of other biotite granites in the Moon Mountains area suggests that they may also be of early Miocene age. These granites usually possess only one foliation, where they are deformed, and the fabric is characteristically the Tertiary mylonitic fabric.

**Hornblende-biotite Granite (Thbg)**

A small stock of mesocratic, hornblende-bearing, biotite granite is exposed over about a square kilometer in the eastern Moon Mountains. The rock outcrops as resistant ridges of medium grey granite which weathers to a brownish dark grey with desert varnish, and is easily distinguishable from the neighboring biotite granite and rocks of the Valen crystalline assemblage. Most of the unit consists of a medium- to coarse-grained, hypidiomorphic granular, unfoliated granite, with potassium feldspar (40-50%), quartz
(25-30%), plagioclase (10-15%), biotite (8-10%), and hornblende (4-5%). Some portions are porphyritic, with potassium feldspar phenocrysts up to 1 cm making up 25% of the rock. Foliation, where present, is only moderately developed, but appears to be tectonic based on stretched and flattened quartz grains. The margins of the granite body are distinctly unfoliated, and discordantly truncate all fabrics in the Valen crystalline assemblage. This unit appears to intrude the Tmbg granite, and is therefore inferred to be early to mid-Miocene in age.

**Basic to Intermediate Dike Rocks (Td)**

Basic to intermediate dike rocks are irregularly distributed within the Moon Mountains, but are most prominent in the Copper Peak area, in the Moon Mountain crystalline assemblage in the vicinity of Moon Mountain, and in the Miocene granites to the south of the Mojave Paint Basin. These dikes are typically northwest to west-northwest trending and steeply dipping to vertical. Compositions range from diabase to biotite-porphyry dacite, but no regular variation in composition with location was observed. All dikes post-date development of ductile fabrics in the country rocks, however some faulting clearly post-dates dike emplacement.

In the Copper Peak area, a series of west-northwest-trending dikes intrudes the Copper Peak granite in the footwall of the Copper Peak detachment fault. These dikes are in turn cut by a high-angle fault which offsets the detachment, and may therefore place an upper age limit on movement of the Copper Peak/Moon Mountain detachment system. Along the western side of Moon Mountain, a large dike of intermediate composition intrudes across a series of north-northeast trending faults which cut a splay of the Moon Mountain detachment, placing an upper age limit on movement on this structure. These dikes are inferred to be mid- to late Miocene in age, based on the presence of widespread volcanism of this age known in the region.

**DESCRIPTION OF STRUCTURES**

The structural geology of the Moon Mountains records elements of both Mesozoic thrust faulting and Tertiary detachment faulting. These deformational episodes have been identified regionally in surrounding ranges, within the Late Cretaceous Maria fold and thrust belt (Reynolds, et al., 1986) and the mid-Tertiary Whipple-Buckskin-Rawhide-Bullard detachment terrain (Davis, et al., 1980; Reynolds and Spencer, 1985; numerous
other references.). In the Moon Mountains, three major structures are identified: (1) the Valenzuela thrust system, (2) the Moon Mountain detachment fault, and (3) the Copper Peak detachment fault.

**VALENZUELA THRUST FAULT**

The Valenzuela thrust fault is exposed in the Valenzuela area of the southeastern Moon Mountains, where it places crystalline rocks of the Valen assemblage and sheared, Jurassic quartz syenite above the deformed and metamorphosed Valenzuela section (Plate 2-3, Fig. 2.2). The thrust system is complicated by later folding and faulting, such that the present expression of the Valenzuela thrust consists of irregular, discontinuous segments.

Three major factors complicate understanding of the Valenzuela thrust system. First, the uncertainty of stratigraphic ordering and correlation of the Valenzuela metasedimentary sequence obscures a clear picture of structural juxtaposition, particularly in the northernmost exposure of the Valenzuela thrust. As a result, the thrust contact has been mapped at the sheared contact between rocks identified as part of the Valenzuela metasedimentary sequence, and lithologies which are clearly part of the Valen crystalline assemblage or the quartz syenite. Secondly, the Valenzuela thrust appears to be characterized by a multi-stage kinematic history, with evidence for both south- and north-directed phases of movement. Finally, the dismembered nature of the thrust system due to later folding and faulting considerably complicates the present geometry of the thrust system.

The nature of the Valenzuela thrust fault differs across the northeast-striking, high-angle Graveside fault. On the southern side, the Valenzuela thrust carries sheared gneisses of the Valen crystalline assemblage and quartz syenite above the deformed and metamorphosed Valenzuela section. The thrust contact is marked by a thin (5-10 cm) zone of mylonitic gneiss, which typically is in contact with either the thinly-bedded quartzite or micaceous carbonate of the Valenzuela section. The contorted nature of the Valenzuela thrust is due in part to folding of the fault surface subsequent to movement. Broad folding about northeast-southwest trending fold axes is suggested by the outcrop pattern of the thrust surface.

The southernmost exposures of the Valenzuela thrust fault dip moderately to gently to the southeast, and juxtapose gneissic quartz syenite above calc-silicate and
quartzite units of the Valenzuela section. The southeastward dip of the thrust beneath the
hills of quartz syenite at the south end of the east arm of the Moon Mountains suggests
that the Valenzuela thrust continues in the subsurface to the south. Exposures in the
northern Dome Rock Mountains (Yeats, 1985) reveal the exact same structural
juxtaposition across the Tyson thrust zone. Here, along the northeastern edge of the
Dome Rock Mountains, the Tyson thrust places sheared megacrystic gneiss of the Tyson
augen gneiss above a deformed and metamorphosed sedimentary section which Yeats
(1985) referred to as the Tung Hill section. Where exposed, the Tyson thrust is a gently
north-dipping feature, with abundant evidence for north-directed shear (Yeats, 1985).

MOON MOUNTAIN DETACHMENT FAULT

The Moon Mountain detachment fault is exposed for about 1.5 km of its length,
along the eastern flank of the western arm of the Moon Mountains, in the vicinity of
Moon Mountain (Plate 2-1, Fig. 2.2). The fault is marked by a very distinctive lithologic
break, and alteration and discoloration of the gneissic basement rocks exposed in the
footwall just below the fault. The detachment strikes generally north-northwest to south-
southeast, with variable intermediate to shallow dips ranging from 20-40° to the east.
Excellent exposures of the Moon Mountain detachment are present at the head of
Detachment Wash (informal name), where the fault places a sequence of block-faulted
and tilted Tertiary conglomerates and sandstones above mylonitized and subsequently
brecciated gneisses of the Moon Mountain crystalline assemblage (Fig. 2.11). To the
north of Detachment Wash, the detachment is covered by deposits of the late Miocene
Bouse Formation, but a lower splay of the fault continues into the crystalline rocks, and
cuts below the top of Moon Mountain. High angle faults with apparent normal
displacement cut the crystalline rocks in the hanging wall of the splay, and appear to
either merge with or be truncated by the splay of the Moon Mountain detachment.

Several notable structural relations are preserved in the footwall of the Moon
Mountain detachment. The lower splay of the detachment which carries crystalline rocks
of the Moon Mountain crystalline assemblage is cut by a large (3 m-wide) dike, which
also appears to cross-cut high-angle faults in the hanging wall of the detachment splay.
This intermediate dike, as well as the detachment splay, is in turn cut by a series of north-
northeast-trending high-angle faults with an apparent normal sense of displacement,
judging from offsets of the crude lithologic layering in the Moon Mountain crystalline
assemblage rocks. Radiometric dating of these dikes could place important timing
constraints on the age of movement on this splay of the detachment, as well as movement on the main strand of the detachment.

The southeastward continuation of the Moon Mountain detachment is buried beneath Bouse Formation deposits, but is inferred to be present from ductile, northeast-directed fabrics in the Tyson Peak granite and the Jurassic quartz syenite in the southern Moon Mountains (Fig. 2.12). The trace of the detachment in the subsurface projects directly through the alluvial wash which separates the two arms of the Moon Mountains and into Tyson Wash. As discussed previously, rock types appear to be continuous across this separation in the southern Moon Mountains. In addition, rock types and structures (in particular the Valenzuela thrust system) appear to be continuous from the southern Moon Mountains into the northern Dome Rock Mountains. These relations suggest two possible alternatives for the continuation of the Moon Mountain detachment: (1) the detachment rapidly loses displacement toward the southeast, and essentially dies out in the southern Moon Mountains, or (2) the Moon Mountain detachment is truncated against a high-angle, subsurface fault, and is offset to the northeastern Moon Mountains, where it appears again as the Copper Peak detachment.

The magnitude of displacement on the Moon Mountain detachment system is difficult to estimate. No correlation of rock types can be made from the hanging wall to the footwall of the detachment. Ductile fabrics in the footwall gneisses are concordant with the detachment and are indicative of high shear strain. The juxtaposition of mylonitic gneisses and supracrustal sedimentary rocks across the detachment is suggestive of a large net throw on the fault in order to bring rocks from depths suitable for mylonitic deformation to near-surface conditions.

**COPPER PEAK DETACHMENT**

The Copper Peak detachment fault, exposed in the Copper Peak area at the northeastern edge of the Moon Mountains, carries an assemblage of sedimentary and volcanic rocks over a ductilely deformed footwall of granitic and Mesozoic volcanic rocks. The fault surface dips generally northeastward, and is marked by a 2-3 m zone of chloritized mylonitic gneiss. Ductile fabrics in the footwall are characterized by S-C mylonites within the granitic rocks, and decrease in intensity away from the fault.

Units preserved in the hanging wall of the Copper Peak detachment occur as fault-bounded slivers, and include Jurassic quartz porphyry, Tertiary sedimentary and mafic
volcanic rocks, and quartzite and carbonate of inferred Paleozoic age. Pre-Tertiary units are highly brecciated, and Tertiary strata exhibit steep westward dips.

The geometry of the Copper Peak detachment fault has been significantly modified by later faulting and folding. High-angle faults offset the detachment on either side of Copper Peak, and the exposure of the detachment below Copper Peak defines a long, narrow reentrant, probably as a result of folding of the surface subsequent to displacement.

The Copper Peak detachment continues down dip in the subsurface northeast of the Moon Mountains. Spencer et al. (1988) describe the geology of the Copperstone Gold Mine to the northeast of Copper Peak, and attribute the gold mineralization in brecciated Jurassic quartz porphyry to fluid circulation along the developing detachment system and associated hanging wall structures.

The age of movement on the Copper Peak detachment is only roughly constrained by the presence of Tertiary-age sediments and mafic volcanic rocks which are tilted in the hanging wall, and the unconformable overlap of the Bouse Formation across the fault. Volcanic rocks from tilt blocks within other regions of the detachment terrain of western Arizona and southeastern California yield Miocene ages (Davis, 1980; Frost, ?), and likely represent the age of volcanic rocks in the Copper Peak detachment system. Spencer and Reynolds (1988) cite an age of about 20 Ma for similar sedimentary rocks which are tilted in the hanging wall of the Buckskin detachment.

The trace of the Copper Peak detachment is buried both to the northwest and southeast by deposits of the Bouse Formation. Geophysical data (proprietary gravity data from Cyprus Minerals Co.; J. Spencer, pers. comm.) suggest the Copper Peak detachment fault is truncated by a northeast-trending, high-angle fault along the western side of the eastern arm of the Moon Mountains (Plate 2-1, Fig. 2.2). No expression of this structure can be seen in the Bouse sediments or overlying alluvial cover, but the presence of such a fault is consistent with termination of the Moon Mountain detachment in the southern Moon Mountains, where lithologic units and structures appear to be continuous across the projection of the Moon Mountain detachment through Tyson Wash.

Correlation of the Copper Peak detachment with the Moon Mountain detachment is made on the basis of (1) similarity of geometry and style of the two detachments, (2) rough timing constraints indicating these are both mid-Tertiary features, and (3)
resolution of the continuation of the Moon Mountain detachment fault towards the southeast.

**DISCUSSION**

The geologic evolution of the Moon Mountains involved multiple phases of deformation and metamorphism. Structures associated with both the Maria fold and thrust belt and the Whipple-Buckskin-Rawhide detachment terrain are exposed here. The present study provides important new information about (1) the continuation of the Maria fold and thrust belt from exposures known to the west (Big Maria and Riverside Mountains) to exposed thrusts to the east (Plomosa, Granite Wash, Harquahala Mountains), (2) the conditions of metamorphism associated with thrusting, based on assemblages and fabrics developed in lower Mesozoic rocks, and (3) the timing of thrusting, and (4) another occurrence of lower Mesozoic sedimentary rocks in west-central Arizona. With regard to Tertiary extension, data from the Moon Mountains indicate that accommodation of extension did not primarily take place along pre-existing thrust faults, and that rocks directly in the footwall of the western-most exposures of the detachment system originated at relatively deep crustal levels, implying that the actual surface break of the detachment is not preserved at this latitude.

**GEOMETRY OF THRUSTING**

The geometry of Mesozoic thrust faulting in the Moon Mountains, as exhibited by the Valenzuela thrust fault, is complicated by a multi-stage history of movement on the thrust fault in addition to post-thrusting modification of the thrust. Footwall structure is defined by an apparent repetition of the section in the Valenzuela metasedimentary sequence in a large, recumbent, south-opening fold which is cored by the micaceous marble unit. Shearing of contacts within the section has disrupted a continuous stratigraphy, such that units have been omitted in the upper limb of the fold. Since the exact original stratigraphy of the Valenzuela section is unclear, it cannot be determined with certainty whether the fold represents a large, south-vergent syncline, or an overturned, synformal anticline with northward vergence. Two factors favor the former interpretation: (1) descriptions of the lower Mesozoic section from surrounding areas in Arizona and southeastern California indicate that the base of the section is characterized by calcareous sandstones, siltstones, and gypsum deposits (similar to the present exposed...
base of the Valenzuela section), and (2) a large, south-facing, thrust-related syncline is preserved in Paleozoic rocks in the Boyer's Gap area just to the south of the Moon Mountains.

Reactivation of the Valenzuela thrust is demonstrated by fabric relations in both the hanging wall and footwall of the thrust. S-C relations within both the hanging wall gneisses and footwall sediments of the Valenzuela thrust exhibit a consistent top-to-the-northeast shear sense. The micaceous marble unit has been dismembered along the thrust contact, and boundaries of this unit truncate foliation in lower units of the Valenzuela sequence (Fig. 2.4a). In addition, foliation in hanging wall gneisses is strongly discordant with the thrust contact, implying that slip has taken place subsequent to the fabric formation.

**CORRELATION WITH TYSON THRUST**

Similarities between the Valenzuela thrust system of the Moon Mountains and the Tyson thrust system (Yeats, 1985) from the northern Dome Rock Mountains allow a reliable correlation of these structures, and imply that they are of regional significance. The Tyson thrust zone of the northern Dome Rock Mountains is a northeast-dipping shear zone which places megacrystic augen gneiss (Tyson augen gneiss) above a deformed and metamorphosed sequence of metasedimentary rocks (Tung Hill section). Both the lithologic description and structural relation of these units correspond to the Valenzuela metasedimentary section and Valenzuela thrust fault exposed in the southern Moon Mountains (Fig. 2.14).

**CONDITIONS OF METAMORPHISM**

Basement-involved thrusting on the Valenzuela thrust fault was associated with lower amphibolite facies metamorphism. Evidence for this grade of metamorphism comes both from amphibolites of the Valen crystalline assemblage and schists of the Valenzuela metasedimentary section. Amphibolites of the Valen crystalline assemblage in the vicinity of the Valenzuela thrust exhibit an aligned mineral foliation and lineation, defined by elongate hornblende and epidote grains, which generally parallels the thrust contact. Aluminous schists from the interbedded schist and quartzite unit of Valenzuela section contain the assemblage quartz + muscovite + sillimanite after kyanite. The presence of this assemblage in rocks of lower Mesozoic age clearly requires a period of amphibolite facies metamorphism subsequent to the age of deposition (Triassic?).
significance is the association of this assemblage with the Valenzuela thrust fault, demonstrating that this high-grade metamorphic event was associated with the emplacement of crystalline rocks of the upper plate.

TIMING OF THRUSTING

The age of thrusting on the Valenzuela thrust fault is relatively well constrained on the basis of U-Pb zircon geochronology. Jurassic quartz syenite, which is carried in the hanging wall of the thrust, is dated at 160 ± 15 Ma, and provides a lower limit on the age of thrusting. Garnet-bearing granitic pegmatite and aplite dikes, which were intruded during the latest, north-directed phase of movement on the Valenzuela thrust, yield a lower intercept age of 71.1 ± 6.7 Ma. The entire history of movement is therefore bracketed between late Middle Jurassic and Late Cretaceous, and the latest phase of movement was clearly Late Cretaceous in association with the Maria fold and thrust belt.

TERTIARY DETACHMENT FAULTING

The Moon Mountain and correlative Copper Peak detachment faults of the Moon Mountains are part of the regional mid-Tertiary detachment system of western Arizona and southeastern California. This major extensional terrain is evidenced along a 300 km tract within the lower Colorado River region (Howard and John, 1987). The Moon Mountains area has been proposed as part of the breakaway zone for this regional extensional system based on: (1) the northeast-dipping geometry and top-to-the-northeast kinematic history of the detachment system, (2) the absence of detachment fault exposures for some 150 km further to the southwest, along the direction of tectonic transport, and (3) evidence from seismic data which show a shallow-dipping reflector within the subsurface connecting the Buckskin detachment fault with the Moon Mountain detachment fault (Hauser, et al., 1987).

GEOMETRY OF DETACHMENT SYSTEM

Reconstruction of the Whipple-Buckskin-Rawhide detachment system has typically been hindered by the lack of continuous stratigraphy and/or distinctive piercing points across the detachment fault. Severe disruption of Paleozoic and Mesozoic stratigraphy and facies trends during Mesozoic thrusting precludes restoration of these units, and the geometry of structures associated with the Maria fold and thrust belt is not sufficiently clear to allow a confident reconstruction of these structures. The situation is
complicated by the fact that a significant portion of the thrust belt was erosionally denuded during the early Tertiary.

Rocks in the hanging wall of the Copper Peak detachment fault may place important constraints on reconstruction of the detachment system. Significantly, brecciated limestone and quartzite, correlated with units of the Paleozoic cratonic section, appear to have escaped the ductile deformation and high-grade metamorphism which most Paleozoic rocks of west-central Arizona display. These units could not have been buried and metamorphosed to any significant degree during any of several phases of Mesozoic folding and thrusting, implying they were originally outside the main locus of deformation during development of the Maria fold and thrust belt. Similar strata of demonstrable Paleozoic age were reported by Scarborough and Meader (1983) from the hanging wall of the Plomosa detachment fault in the northern Plomosa Mountains. Unmetamorphosed and undeformed Paleozoic strata in the footwall of the detachment system are known from the southern Plomosa Mountains (Miller and McKee, 1971). The correspondence of these unmetamorphosed carbonates and quartzites in the segmented detachment system may help in restoration of the pre-Tertiary configuration of the Maria fold and thrust belt.

Constraints on the timing of deformation in the footwall of the Copper Peak detachment system suggest a Late Oligocene to Early Miocene age for development of mylonitic fabrics. The Copper Peak granite of the northeastern Moon Mountains exhibits ductile, top-to-the-northeast directed fabrics below the Copper Peak detachment. This granite is intruded by a similar biotite granite (Tmbg) which is late- to post-tectonic based on (1) intrusion of this granite into mylonites of inferred Tertiary age, and (2) only local development of a weak mylonitic fabric within the granite. The Tmbg biotite granite yields a U-Pb lower intercept age of 20.8 ± 3.2, reflecting the age at which the rocks in the lower plate of the Copper Peak detachment were no longer at appropriate conditions for mylonitization.

CONCLUSIONS

The rocks and structures exposed in the Moon Mountains of the Colorado River Indian Reservation, west-central Arizona, record Mesozoic thrusting within the Maria fold and thrust belt, and superimposed Tertiary detachment faulting related to the regional Whipple-Buckskin-Rawhide detachment system. The major structures of the Moon
Mountains consist of the Valenzuela thrust fault, the Moon Mountain detachment fault, and the Copper Peak detachment fault. Thrusting in the Moon Mountains resulted in the emplacement of crystalline basement rocks over supracrustal sedimentary rocks at amphibolite facies conditions of metamorphism. Movement on the thrust was characterized by a multi-stage history, with apparent evidence for an earlier phase of south-directed movement, and a final phase of north-directed shear. Dating of this later phase of thrusting at ~71 Ma is the first direct documentation of the age of thrusting in the Maria fold and thrust belt. The Valenzuela thrust system is correlated with the Tyson thrust system of the northern Dome Rock Mountains, implying a regional extent for this structure.

The Moon Mountain detachment fault in the northern Moon Mountains places a section of faulted and tilted Tertiary sedimentary rocks above gneisses, schists rocks of the Moon Mountains crystalline assemblage. At least two fabrics are present in the footwall gneisses. Gneissic compositional layering is parallel with the detachment fault, but primarily represents a Mesozoic feature. Ductile shear fabrics are variably developed in gneisses and granites of the footwall, and indicate a consistent top-to-the-east shear sense associated with the detachment systems. Strata in the hanging wall of the detachment show tilting which is strongly oblique to the inferred direction of movement for the detachment fault. Regional relations dictate that the Moon Mountain detachment fault is the exposed western limit at this latitude for the regionally extensive Whipple-Buckskin-Rawhide detachment system of southeastern California and western Arizona.

The Copper Peak detachment fault, exposed in the Copper Peak area of the northeastern Moon Mountains, carries sedimentary and volcanic rocks of Paleozoic(?), Mesozoic, and Tertiary age above a ductilely deformed footwall consisting primarily of granitic intrusive rocks. Ductile footwall fabrics exhibit a consistent top-to-the-northeast sense of shear. The Copper Peak detachment is correlated with the Moon Mountain detachment fault, from which it is offset by an inferred, high-angle fault. The lack of penetrative ductile fabrics in Paleozoic/Mesozoic sedimentary rocks in the hanging wall of this fault is distinctive in the western Arizona region, and may constrain reconstruction of the detachment system.

The timing of development of ductile fabrics in the footwall of the Copper Peak detachment is constrained by the ductilely deformed Copper Peak granite (of probable Tertiary age), and a late to post-tectonic biotite granite (Tmbg) which yields an early Miocene (20.8 ± 3.2) U-Pb zircon age. Despite pre-existing zones of weakness
introduced by basement-involved thrust faults of the Maria fold and thrust belt, accommodation of extensional strain in the Tertiary detachment system was largely accomplished by the initiation of new structures.

The Moon Mountain and Copper Peak detachment faults are the western exposed limit of the Whipple-Buckskin-Rawhide detachment system at the latitude of the Moon Mountains. The presence of Tertiary ductile fabrics in the footwalls of these structures implies that the rocks originated at depths and temperatures sufficient to produce well-developed mylonitic fabrics, and that the actual breakaway (original surface break) for the detachment system is not preserved in this area. In addition, these east-dipping mylonitic fabrics dip antithetically to and not much higher in the crust than the seismically imaged mylonitic zone associated with the Whipple-Buckskin-Rawhide detachment system, suggesting that either (1) Tertiary mylonitization was characterized by anastomosing zones within the crust or that (2) different phases of Tertiary mylonitization are represented in the lower plate of the Whipple-Buckskin-Rawhide detachment system.

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FIGURE CAPTIONS

Plate 2-1: Geologic map of the Moon Mountains, Colorado River Indian Reservation, scale 1:24,000 (xerox reduced version).

Plate 2-2: Geologic cross sections of the Moon Mountains, scale 1:24,000, no vertical exaggeration.

Plate 2-3: Detailed geologic map of the Valenzuela area, southeastern Moon Mountains, scale ~1:12,000.

Figure 2.1: Location map of the Moon Mountains in the Mojave-Sonoran Desert area.

Figure 2.2: Geologic sketch map of the Moon Mountains, showing major structures, distribution of rock units, and geographic names used in text.

Figure 2.3: Augen gneisses typical of Valenzuela crystalline assemblage, showing well-developed fabric defined by flattened and aligned K-feldspar porphyroclasts. Predominant shear sense is not evident in rocks of this lithology. Lens cap for scale.

Figures 2.4a and b: Panoramic view of the Valenzuela area, southern Moon Mountains, showing (1) Valenzuela metasedimentary section (right side 4a), (2) Valenzuela Thrust fault (center), and (3) El Diablo peak (left side 4b). Thrust fault is marked by contact of dark resistant cap of Jqs with more recessive units of metasedimentary section, just above distinctive ledge of light-colored marble. Southeast-dipping Graveside fault trends up major drainage (center of 4b), and separates exposures of the Valenzuela thrust from El Diablo peak, which is extensively intruded by garnet-bearing pegmatites. Note (1) discordance of marble unit with underlying units of Valenzuela metasedimentary section (right of 4a), (2) discordance of west-dipping foliation in gneisses of hanging wall with trace of thrust, and (3) relative absence of pegmatite dikes to east (right) of Graveside fault as compared to El Diablo peak on the west. View spans NE to E. Northern Plomosa Mountains visible in distance. Exposed relief is approximately 150 m.
Figure 2.5: Basal calc-silicate unit of Valenzuela metasedimentary sequence, with lenses of pure, vitreous quartzite floating in a fine-grained matrix of quartz + potassium feldspar + biotite + epidote ± muscovite. Hinges of rootless isoclinal folds are preserved in the quartz bands, which are interpreted as deformed quartzite pebbles and cobbles. Lens cap for scale.

Figure 2.6: Fold hinges of rootless isoclines developed in thinly-bedded quartzite of Valenzuela metasedimentary section, below Valenzuela thrust fault, southern Moon Mountains. View is toward the ESE; hammer for scale.

Figure 2.7: Well-developed S-C fabric in Jurassic quartz syenite of hanging wall of Valenzuela thrust, indicating top-to-the-north (right) shear sense. S surfaces are sub-horizontal, sygmoideal in cross-section, and cut by c planes which dip gently to the right. Hammer for scale.

Figure 2.8: View of garnet-bearing, granitic pegmatite dikelets which intrude discordantly across metamorphic foliation in amphibolite schists of Valenzuela crystalline assemblage, but are cut by N-dipping shear planes which appear synchronous with the foliation development. Dikes are interpreted to be syn- to late-kinematic with development of this fabric, which indicates a top-to-the-N (left) sense of shear. Footwall of Valenzuela Thrust fault. Lens cap for scale.

Figure 2.9: Detail of intrusive contact of porphyritic biotite granite with foliated gneisses formed from megacrystic quartz syenite. Undulatory contact is discordant to foliation in gneisses of country rock, and granite has only poorly developed fabric here. Southern margin of main body of porphyritic granite, southern Moon Mountains. Lens cap for scale.

Figure 2.10: Contact of hornblende-biotite granite (upper left) and biotite granite (lower right) in central Moon Mountains, marked by line of dark to light color contrast running from left center to upper right. Relief is about 180 m.

Figure 2.11: Moon Mountain detachment as exposed in Detachment Wash, just south of Moon Mountain. Rocks in hanging wall are massively bedded, unsorted, angular, monolithic conglomerates derived from quartz porphyry. Footwall gneisses are highly sheared and retrograded rocks of the Moon Mountain crystalline assemblage. Detachment dips ~40° NE. Daypack (just below center) for scale.
Figure 2.12: Intense ductile deformation developed within Jurassic quartz syenite (Jqs), southern Moon Mountains. White streaks of feldspar were originally potassium feldspar megacrysts. Lens cap for scale.

Figure 2.13: Deformed sygmoideal lens of granite within footwall gneisses of Moon Mountain detachment, clearly indicating a top-to-the-northeast (left) asymmetry of shear. Granitic dikes are related to intrusion of porphyritic biotite granite, which outcrops just to west at mouth of Detachment Wash. Hammer for scale.

Figure 2.14: Geologic sketch map of the southern Moon Mountains and the northern end of the Dome Rock Mountains. Mapping from this report and Yeats (1985). Units shown include (1) porphyritic biotite granite (Tyson Peak granite and Tyson Wash granite), (2) megacrystic Jurassic quartz syenite, (3) lower Mesozoic sedimentary rocks (Valenzuela metasedimentary section, Tung Hill metasedimentary section), (4) gneissic leucogranite, (5) Precambrian crystalline rocks, and (6) cratonic Paleozoic section.
Figure 2.1
Figure 2.3
Figure 2.11