THE BOYER GAP: A RECORD OF JURASSIC INTRA-ARC
FOLD AND NAPPE TECTONICS IN THE NORTHERN DOME ROCK MOUNTAINS
OF SOUTHWESTERN ARIZONA

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geological Sciences

by
Robert Ellis Logan III
Spring 1986
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Approved by:

[Signatures]
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CHAPTER 1

INTRODUCTION

General Statement

The concept that much of western North America represents a "collage" of accretionary terranes has gained a great deal of support in recent years (Coney and others, 1980; Coney, 1981; Jones and others, 1982; Howell, 1985a,b; Fig. 1). It is becoming increasingly evident that oblique convergence and tectonic accretion are major factors in the development of the North American Cordillera and in the process of continental margin orogenesis, in general. As geoscientists begin to test this revolutionary new concept, the need to identify and analyze suspected accretionary boundaries becomes critical. This is often a very difficult task, for, as Coney (1981) points out, suture zones have characteristically undergone a complex history of deformational events. In the case of the North American Cordillera, such suture zones have been active from mid-Paleozoic time to the present.

In the Mojave-Sonoran region, a composite accretionary terrane has been postulated by a number of recent authors (Fig. 1,2; Coney and others, 1980; Howell and others, 1982, 1983; Vedder and others, 1983; Champion and others, 1983;). Harding (1982a,b), and Harding and Coney (1985) have suggested that the suture zone linking the
Figure 1. North American "suspect terranes". These terranes are thought to be accreted fragments of material allochthonous to North America. Shaded area is underlain by autochthonous cratonic North American basement. "Mo" is the Mojave terrane, "O" represents the Orocopia terrane, "Sg" is the San Gabriel terrane, and "CP" is the Colorado Plateau (From Coney, 1981).
Figure 2. Proposed composite of terranes accreted to North America in the Mojave-Sonoran desert region. Pelona-Orocopia Schist (Baldy terrane) is overridden by rocks obliquely obducted onto North America (From Vedder and others, 1983).
Mojave-Sonoran composite terrane to North America is best exposed in the Palen Pass portion of the Palen Mountains and in the Boyer Gap region of the northern Dome Rock Mountains (Fig. 3). Several studies of the Palen Pass area have been completed (LeVeque, 1981, 1982; Demaree, 1981), with other, more detailed studies in progress by the United States Geological Survey. The detailed geology of the Boyer Gap area has not been deciphered and is the focus of this study. Detailed field work done in the Boyer Gap provides the basis on which to assess the validity of the suggestion that Boyer Gap represents a major terrane boundary.

**Physiography**

The Dome Rock Mountains of west-central Arizona are a north-south trending range adjacent to the Colorado River and are approximately 60km in length. The range is moderately rugged and rises 700m above the pediment to a maximum height of 1011m at Cunningham Mountain. Several apparently fault-controlled, northwest-trending valleys breech the range and a roughly north-trending basin-and-range normal fault forms the western range boundary (Dahm, 1983). The west side of the mountains drains westward via numerous large channels into the Colorado River. The majority of the eastern side drains into Tyson Wash, which flows northward, parallel to the range. This major wash then sweeps west through a pass separating the northern Dome Rock Mountains from two elongate, "v"-shaped projections of the Moon Mountains and continues
Figure 3. Regional tectonic map of the McCoy Basin. Harding (1982), and Harding and Coney (1985) propose that the McCoy Basin has been collapsed between rocks of North America and the accreted Mojave-Sonora terrane. Barbed lines are considered major terrane boundaries that evolved synchronously during the late Mesozoic. Note that the northern boundary is exposed only in the Palen Pass region of the northern Palen Mountains and in the Boyer Gap (Redrawn from Harding, 1982).
on to the Colorado River.

The Dome Rock Mountains were named for the striking manner in which planar elements have been arched or domed. Foliation within Paleozoic and Mesozoic metasediments as well as Mesozoic intrusive units is inclined generally northward in the north as are penetratively-cleaved Jurassic metavolcanic rocks in the central portion of the range. This relationship gives way through a horizontal transition zone to a south-dipping orientation of bedding and cleavage within the clastic McCoy Mountains Formation in the south (Crowl, 1979; Marshak, 1979; Harding, 1982a,b). The south-dipping attitude does not persist into the Tertiary volcanic and sedimentary, Mesozoic(?) intrusive, and Precambrian units present at the southern tip of the range. (Dahm, 1983)

**Location and Access**

The range is located about 10km east of the Colorado River and is roughly bisected by Interstate 10 (Fig. 4). Blythe, California, is just west of the river on Interstate 10 and Quartzsite, Arizona, is 5km east of the range at the highway 95-Interstate 10 junction. Long-term mining throughout the Dome Rock Mountains has produced a myriad of jeep trails, which makes most of the range fairly accessible. The area of this study is centered on a low, east-west pass through the northern Dome Rock Mountains shown as Boyer Gap on the Middle Camp Mountain 7.5 minute quadrangle (Fig. 5; Plate I; in back pocket). Access to Boyer Gap is available via the unimproved
Figure 4. Index map showing the location of the Dome Rock Mountains, Arizona, and their relationship to major compressional (thrusts) and extensional (detachment) faults in the lower Colorado River region. Sawteeth are on the hanging wall of thrust faults and prongs are on the upper plate of detachment faults.
Figure 5. Index map highlighting the location of the study area in the northern Dome Rock Mountains, Arizona.
Moon Mountain Road, which is clearly marked in Quartzsite and leads roughly north-northwest from the main east-west road through town. Approximately 8km from Tyson Drive the first significant westerly offshoot leads to Boyer Gap. Other westerly offshoots further north provide access to the northernmost portion of the range while Moon Mountain Road itself utilizes Tyson Wash to reach the Moon Mountain projections. High-clearance, 2-wheel drive vehicles are necessary to reach Boyer Gap while the extensive sand travel in Tyson Wash requires a 4-wheel drive vehicle to reach the Moon Mountains.

_**Methodology**_

Field work commenced in October, 1983, and was completed in March of 1985. A total of 58 field days, most between October, 1984, and March, 1985, were necessary to complete the project. Mapping was done on a 1:12,000 scale map by enlarging the 7.5 minute Middle Camp Mountain and Moon Mountain SE topographic quadrangles by a factor of two. In order to gain a clear picture of the structural style within the study area, Paleozoic rocks and associated intrusives appearing in Plate II (in back pocket) were mapped in great detail at the 1:12,000 scale and then transferred to the 1:6,000 scale for presentation purposes (Plate I,II). The remaining areas were mapped in a much less-detailed reconnaissance fashion. Air photos were used as an aid to ground-level mapping, but were never employed as the sole source of data.

During the mapping process, macrostructural data such as
mineral lineations, minor fold-axes orientations and asymmetries, and shear textures were collected. A total of 55 petrographic thin sections were prepared and examined to aid in lithologic identification, classification and determination of metamorphic grade. Microstructural fabrics of oriented samples were also studied and compared with the larger structural elements. Low-altitude oblique air photos were shot and examined as a means of viewing large-scale features in the area.

An attempt has been made to maintain continuity in classification and terminology. To this end, the classification schemes of Streckeisen (1976) and Folk (1980) have been used for plutonic and metasedimentary rocks, respectively. Metamorphic textures are described as suggested by Spry (1969), while metamorphic grade was determined according to Winkler (1976).

Previous Work

Early geologic surveys of the Dome Rock Mountains began after the turn of the century and were prompted primarily by a growing interest in ore deposits of the region beginning in the latter 1800's (Keith, 1978). These initial surveys document mineral resources, map physiography, and briefly describe some of the lithologic units present in the region (Bancroft, 1911; Jones, 1916; Ross, 1922; Darton, 1925; Heineman, 1935). The next published work on the area was the Geologic Map of Yuma County compiled during the 1950's and published in 1960 (Wilson, 1960). This work was
incorporated basically intact into the Geologic Map of Arizona (Wilson, and others, 1969) and remains the only published regional geologic map for the area. The Geologic Map of the Quartzsite Quadrangle of Miller (1970) primarily covers the Plomosa Mountains to the east, but includes a small east-central portion of the Dome Rock Mountains.

Over the past decade, interest in the geology of the Colorado River region has intensified. Crowl (1979) mapped Jurassic metavolcanic rocks and Mesozoic (?) intrusives in the central portion of the Dome Rock Mountains. The Mesozoic clastic rocks present in the southern Dome Rock Mountains and their correlatives in adjacent ranges (McCoy Mountains Formation) have spawned numerous recent contributions from the University of Arizona (Harding, 1978, 1980, 1982a,b; Harding and Coney, 1985; Harding, and others, 1980, 1982, 1983; Marshak, 1979, 1980; Robison, 1979, 1980). United States Geological Survey workers (Tosdal, 1982, 1984a,b; Tosdal and others, 1982) have proposed an extension of the Mule Mountains thrust through the southern Dome Rock Mountains. Recent interest in mid-Tertiary deformation in the Colorado River region has also resulted in several studies in the Dome Rock Mountains by workers from San Diego State University (Baker, 1981; Dahm, 1983; Blaettler, 1983). In addition, a concurrent study of the Boyer Gap region that began approximately one year after the inception of this work was recently completed by Yeats (1985a, b).
CHAPTER 2

REGIONAL GEOLOGIC SETTING

Introduction

Recent paleomagnetic, structural, and sea-floor studies indicate that the Pacific Plate and its immediate precursors subducted northward with varying degrees of obliquity under the California portion of the North American continent for much of Mesozoic time (Jones and others, 1977; Coney and others, 1980; Coney, 1981; Saleeby, 1981; Champion and others, 1983; Howell and others, 1983; Vedder and others, 1983). Studies of presently active oblique junctures in the Indo-China region show that the products of inter-plate collisions of this type and duration are much more complex than those predicted by previous models based on perpendicular convergence (Fig. 6; e.g., Kaizuka, 1975; Hamilton, 1978; Karig and others, 1979; Silver and Smith, 1983). In addition, northward translations along transcurrent faults that seem to be characteristic features of obliquely convergent margins may have removed key pieces required to complete the Mesozoic story of the California-Arizona region (Saleeby, 1981). These complexities and possible limitations notwithstanding, the Boyer Gap is positioned such that information gleaned from this area has a direct bearing on several key problems of southwestern Cordilleran tectonics.
Figure 6. Comparison of obliquely convergent neotectonic setting in the Indo-China region with the terrane map of the North American Cordillera. Actualistic plate boundary relationships such as this appear to produce accreted terranes, or "suspect" terranes, that comprise the collage of western North America (From Silver and Smith, 1983).
Late Precambrian and Paleozoic Time

Precambrian units in the region consist of high-grade rocks that yield 1.7-1.8 Ga. U-Pb ages that are intruded by a 1.4-1.5 Ga. (U-Pb) anorogenic granitic complex (Silver and Anderson, 1974; Anderson and Silver, 1976; Anderson, 1983; Burchfiel and Davis, 1981). Diabase dikes and sills dated at 1.1 Ga. (U-Pb) are intrusive into the older Precambrian units and may record an aborted rifting event (Anderson, 1983). Precambrian rocks are present in ranges adjacent to the Boyer Gap including the Big Maria and Riverside Mountains to the west (Hamilton, 1964, 1971, 1982; Carr and Dickey, 1980; Lyle, 1982a,b), the Plomosa Mountains to the east (Miller and McKee, 1971; Scarborough and Meader, 1983), as well as the Trigo Mountains to the south (Garner and others, 1982). Precambrian rocks may be present in the Boyer Gap, but their identity is concealed by metamorphism or deformation. Upper Proterozoic miogeoclinal rocks are well preserved to the northeast in southeastern California and southern Nevada (Stewart and Poole, 1974; Stewart and Suczek, 1977) and in Sonora, Mexico (Stewart and others, 1984), but are not exposed in the vicinity of Boyer Gap. Although the exact location of the Paleozoic hingeline in southeastern California and southwestern Arizona is as yet unresolved, the greater Boyer Gap region appears to have occupied a stable platform position throughout much of Paleozoic time.
**Mesozoic Time**

The onset of Mesozoic time marks a fundamental change in the tectonic character of southwestern North America. The quiescent trailing-edge setting of the Paleozoic Era stands in stark contrast to the dynamic tectonic conditions that shaped and reshaped the southwestern Cordillera more or less continuously to the present day.

**Mesozoic Magmatic Arc**

A northwest-trending magmatic arc brought about by long-term subduction of oceanic plates beneath western North America extends through southern Arizona and southwestern California projecting in either direction for the entire length of the Cordilleran orogenic belt (Hamilton, 1969; Dickinson, 1970; Burchfiel and Davis, 1972, 1975). Early Triassic intermediate plutonic rocks present in the western Mojave (C. F. Miller, 1977a,b; E. Miller, 1977; Miller and Sutter, 1982) and now adjacent Transverse Ranges (Silver, 1971) place a minimum age limit on the inception of arc magmatism in the area. Burchfiel and Davis (1981) have shown that the eastern edge of arc magmatism fluctuated throughout the Mesozoic Era such that most of the Mojave region was affected. Coney and Reynolds (1977) suggest that the locus of arc magmatism swept systematically inboard and then outboard in response to changing subduction rates and angles during Mesozoic time. Regardless of the validity of this model, the critical key to understanding the regional importance of
Boyer Gap lies in its location within the main axis of arc magmatism during the Jurassic (Fig. 7) and subsequent arc-rear position during Cretaceous time (Fig. 8). Lower to Middle Jurassic volcanic and hypabyssal rocks are present in the central Dome Rock Mountains (Crowl, 1979; Marshak, 1979, 1980), Plomosa Mountains (Reynolds, 1980), McCoy and Palen Mountains (Pelka, 1973a,b), as well as apparently correlative metavolcanic rocks in the Big Maria Mountains (Hamilton, 1982; Krummenacher, in press). In addition, mid-Jurassic U-Pb ages of about 160 Ma. have been obtained from intrusive rocks in the west-central Big Maria Mountains (Hamilton, pers. comm. to D. Krummenacher, 1979) as well as from similar rocks in the Boyer Gap (G. Haxel, pers. comm., 1985).

Regional Mesozoic Compressional Structures

Regional Mesozoic folding and thrust faulting near Boyer Gap is poorly constrained chronologically and is further complicated by the complexities of Mesozoic plutonism. Mid-Tertiary low-angle structures related to crustal-scale detachment deformation further overprint the Mesozoic folds and faults. Correlation of compressional structures from range to range is therefore extremely difficult even assuming that they were once regionally continuous. Terms such as Sevier and Laramide have typically been used to refer to separate orogenic events in the Cordilleran mountain building process, when in fact deformation was diachronous (Armstrong, 1974; Burchfiel and Davis, 1981). As used in this study, Mesozoic deformation is termed part of the Cordilleran orogeny, a general
Figure 7. Intra-arc position of Boyer Gap during Jurassic time. Compressional structures in the Boyer Gap region (Big Maria terrane) indicate tectonic transport was to the southwest at this time (After Anderson and Silver, 1979; Burchfiel and Davis, 1981).
Figure 8. Arc-rear location of Boyer Gap during the Cretaceous Era. This position appears to have favored formation of NE-directed compressional structures that frequently overprint the previously developed SW-directed structures (After Kistler, 1974).
encompassing phrase emphasizing the continuous nature of collisional plate interactions along the western margin of the North American continent throughout Mesozoic time (Drewes, 1978).

Southwest-trending, east-vergent structures of the Cordilleran fold and thrust belt have been traced without significant change in structural style across the Las Vegas Valley and into the Clark Mountains of southeastern California (Burchfiel and Davis, 1971; Fig. 4). Structural relations in this area suggest middle Triassic to early Jurassic timing for development of the oldest structures. They appear to be part of an ongoing process of thrust and fold formation that terminated in the late Cretaceous (Sutter, 1968; Fleck, 1970; Burchfiel and Davis, 1971, 1981; Burchfiel and others, 1974). This belt of deformation was later shown to extend out of the miogeoclinal realm of the Clark Mountains, through the New York Mountains (Burchfiel and Davis, 1977), and into the craton in the Little Piute Mountains, the Old Woman Mountains, and ultimately the Kilbeck Hills (Howard and others, 1980; Fig. 4). A recently determined age for a syntectonic pluton in the Old Woman terrane (E. Frost, pers. comm. from K. Howard, 1985) indicates that thrusting and plutonism were Late Cretaceous in age. Slightly older plutons have been cut by the thrust, constraining deformation in the area to the Late Cretaceous (Howard and others, 1980). Thermal softening by arc magmatism was apparently responsible for the high ductility of the structures in the Little Piute-Old Woman-Kilbeck Hills terrane where Precambrian basement and Mesozoic granitic and metasedimentary
rocks are intimately involved in the southeast-vergent structures (Howard and others, 1980; Howard, 1981; Burchfiel and Davis, 1981).

Multiple deformations of late Mesozoic age have been clearly documented in the Riverside Mountains of southeastern California (Lyle, 1982a,b) and in the Harquahala Mountains of southwestern Arizona (Reynolds and others, 1980; Fig. 4). Lyle (1982a,b) suggests that the east-southeast vergent folds in the Riverside Mountains and the southeast-vergent folds in the Harquahalas may be related to similar structures in the Old Woman terrane (Howard and others, 1980), thus extending the Cordilleran fold and thrust belt into these areas. Northeast-vergent folds and thrusts that clearly postdate the southeast-vergent structures are also represented in the Riverside and Harquahala Mountains (Reynolds and others, 1980; Keith, 1982; Lyle, 1982a,b). The high ductility of the Paleozoic cratonal metasediments, involvement of Mesozoic granitic and metasedimentary rocks, and remobilization of Precambrian basement are all characteristic features of these ranges.

Thrust faulting in the central and northern Plomosa Mountains has been described by Miller (1970), Miller and McKee, (1971), Keith and others (1983), and Scarborough and Meader (1983; Fig. 4). The kinematics and timing of this deformation are poorly constrained in these areas. The presence of mid-Tertiary low-angle structures that have been confused with Mesozoic thrust faults further complicates the interpretation of these data. Unequivocal thrust faults in the central Plomosa Mountains dip eastward and separate an undeformed
fossiliferous Paleozoic upper plate from intensely deformed Paleozoic sections in the lower plate (Miller, 1970; Miller and McKee, 1971). These relationships led Miller and McKee to propose westward overthrusting of the undeformed units over the deformed sequence. Reconnaissance studies of the northern Plomosa Mountains by Scarborough and Meader (1983) and Keith and others (1983) identified several thrust plates of probable Mesozoic age that involve Precambrian crystalline rocks, attenuated Paleozoic cratonal metasediments, Mesozoic metaclastic units and a probable Late Cretaceous intrusive unit. These sets of workers also delineated a mid-Tertiary low-angle normal fault. Detailed examination of the area as part of a regional study of mid-Tertiary extensional kinematics by Hillemeyer (1984) suggests that at least one of the previously mapped major thrust faults may be of mid-Tertiary extensional origin as well. Further clarification of the direction of tectonic transport and the timing of the deformation is warranted, but preliminary data indicate that east-to northeast-directed thrusting is at least 65-75 m.y. old and may be overprinted by younger, south-directed thrusting (Keith and others, 1983; Scarborough and Meader, 1983).

The Big Maria-Little Maria Mountains and Palen Pass portion of the Big Maria nappe and thrust terrane of southeastern California is very similar to the Boyer Gap in lithology and structural style (Fig. 9). Large-scale folds and associated thrusts can be traced west-northwest from Boyer Gap, through the Big Maria (Hamilton,
Figure 9. Big Maria nappe and thrust terrane of southeastern California. Geologic relationships present in the southern portion of this terrane (Big Maria-Little Maria Mountains and Palen Pass area) extend eastward across the Colorado River into the Boyer Gap (From Krummenacher, in press).
1964, 1971, 1982; Ellis, 1981, 1982; Ellis and others, 1981), Little Maria (Emerson, 1981a,b, 1982), and Palen Mountains (Demaree, 1981; LeVeque, 1981, 1982). To date, deformation can only be loosely bracketed between mid-Jurassic and Late Cretaceous time. Tectonic transport in this terrane is a matter of considerable debate. Arguments supporting northeast overthrusting (Hamilton, 1971, 1982), and underthrusting (Krummenacher and others, 1981; Ellis, 1981, 1982) are present in the literature and it appears that elements of both may be present in this terrane (Ellis, 1981, 1982; Frost, pers. comm., 1983; Krummenacher, in press).

Kinematic indicators for the Vincent-Chocolate Mountains thrust system in the Chocolate and Peter Kane Mountains of southeastern California as described by Haxel and Dillon (1978), suggest northeastward transport of Precambrian and Mesozoic crystalline rocks over the enigmatic Orocopia Schist in late Mesozoic time (Fig. 4; Haxel and others, in press). Similar relationships in the Mule Mountains also involve northeast thrusting of Precambrian gneiss and Mesozoic plutonic rocks over the thick metaclastic section known as the McCoy Mountains Formation of southeastern California and southwestern Arizona (Pelka, 1973a,b; Harding, 1980, 1982a,b; Tosdal, 1982, 1984a,b; Haxel and others, in press; Fig. 3,4).

Post-Mesozoic Tectonics

Although the main focus of this study centers on Mesozoic compressional tectonics, an understanding of subsequent events that
might have modified older structures is essential. In general, post-Mesozoic events that are likely to overprint earlier structures in the area include mid-Tertiary detachment faulting, late Tertiary basin-and-range block faulting, and presently active San Andreas transform tectonics.

**Mid-Tertiary**

Mid-Tertiary time in the Mojave-Sonoran region is characterized by abundant volcanism and intra-arc extensional (detachment) processes. Magmatism swept inboard from the mid-Cretaceous Peninsular batholith, through the study area, to New Mexico and west Texas by Eocene time. A rapid retrograde sweep concluded with the voluminous eruptions in the Mojave-Sonoran region through the mid-Tertiary (Coney, 1978; Cross and Pilger, 1982). This sweep has been interpreted by Coney and Reynolds (1977) to have been a consequence of progressive flattening and subsequent steepening of the Benioff zone in response to changing rates of subduction (see also: Keith, 1982).

Mid-Tertiary detachment faulting had a profound effect on previous structures in the Mojave-Sonoran region (Fig. 10). The usage of Hillemeyer (1984) is adapted for the term detachment fault as follows:

the term "detachment fault" refers to the low-angle fault forming at the base of an imbricate system of high-angle normal faults ... it becomes important to further define the term by saying that the detachment fault is also a low-angle fault forming the uppermost
Figure 10. General map of the southwestern United States showing a portion of the known detachment terrane (From Wallace and English, 1982).
surface of a system of stacked, low-angle faults genetically related to crustal extension. In other words, a 'detachment fault' is a surface of separation between two structural styles of deformation and is actually the product of merging high-angle, upper-plate faults and low-angle, lower-plate faults (Fig. 11).

The effects of detachment fault-producing processes that have the greatest bearing on this study are two-fold. Firstly, large-scale (low amplitude-large wavelength) crustal folding is a well-documented consequence of detachment faulting (Heidrick and Wilkins, 1980; Woodward and Osborne, 1980; Cameron and Frost, 1981; Frost, 1981, 1983b). This folding is responsible for the present distribution of basins and ranges in the region and is the major influence on the current level of exposure. In addition, this folding tends to "arch" all previous planar elements such that present attitudes must be interpreted with caution. Secondly, detachment faults, by their low-angle nature, can easily be confused with thrust faults. To further complicate things, detachment faults are often localized by the physical anisotropies generated in rock bodies by previous thrust faults (Frost and Martin, 1983; Haxel and Grubenski, 1984). Therefore, as recognized by other workers, the importance of understanding and removing the effects of the mid-Tertiary overprint cannot be overemphasized in this region (Lyle, 1982a; Frost, 1983a; Frost and Martin, 1983; Hillemeyer, 1984). Examples of detachment faults in the vicinity of Boyer Gap are well documented in the literature. Shackelford (1975, 1976a,b, 1980), Davis and others (1977, 1979, 1980), Rehrig and Reynolds
Figure 11. Model for large-scale interaction of crustal lenses formed by anastomosing detachment faults (From Hillemeyer, 1984).
Dickey and others (1980), Frost and Otton (1981), and Lucchitta and Suneson (1977, 1980) have described extensive areas of detachment faulting to the north in the Rawhide, Whipple, Buckskin, Harquvar and Harquahala Mountains of western Arizona and eastern California (Fig. 4). Detachment-related tectonics are known to the south in the Trigo (Garner and others, 1982), Kofa (Dahm and Hankins, 1982) and Castle Dome Mountains (Logan and Hirsch, 1982) of southwestern Arizona as well as the Peter Kane-Picacho Peak-Chocolate Mountains area (Hillemeyer, 1984) and the Midway Mountains of southeastern California (Berg and others, 1982). Detachment faults are also present in the adjacent southern Riverside and northern Big Maria Mountains of southeastern California (Carr and Dickey, 1980; Hamilton, 1982; Lyle, 1982a, b) and to the immediate east in the northern Plomosa Mountains (Keith and others, 1983; Scarborough and Meader, 1983; Hillemeyer, 1984). Closer yet to the Boyer Gap, detachment deformation is documented in the southern Dome Rock Mountains by Dahm (1983) and to the immediate north in the Moon Mountains by Baker (1981) and Blaettler (1983).

**Late Tertiary to Recent**

The mid-Tertiary volcanic and extensional events ceased with the initiation of basin-and-range block faulting and basaltic volcanism in middle Miocene time (Coney, 1978; Eberly and Stanley, 1978; Shaffiullah and others, 1980; Angelier and others, 1985). In the Boyer Gap region, basin-and-range faulting plays a subordinate role to detachment faulting in producing the present
morphology of the area. Nonetheless, high-angle, range-bounding block faults are known to affect the region. Crowl (1979) mentioned the possibility that one such fault may form the western margin of the Dome Rock Mountains. This suggestion was supported by Dahm (1983) in his treatment of the southern Dome Rock Mountains where he recognized exposures of a north-northwest striking high-angle normal fault that postdates Miocene valley-fill sediments along the southwestern margin of the range.

By latest Tertiary time, the transform boundary of the North American and Pacific plates had jumped inboard to rift open the Gulf of California initiating the San Andreas transform fault system (Atwater, 1970; Atwater and Molnar, 1973). The effects of this wrench tectonic setting probably extend into the Mojave-Sonoran region (Dokka, 1983; Costello, 1985), although perhaps not to the extent that many previous workers have inferred (e.g., Miller and McKee, 1971; Crowl, 1979). Many previously-mapped "strike-slip" faults are probably oblique-slip normal faults exhibiting right separation and are a product of mid-Tertiary detachment faulting rather than recent transform tectonics (Murray and others, 1980).
CHAPTER 3
LITHOLOGIC UNITS

Introduction

The lithologic units present in Boyer Gap can be divided into three basic entities: (1) Paleozoic cratonic metasediments, (2) Mesozoic metaclastic rocks, and (3) Jurassic and perhaps Cretaceous plutonic rocks. Unequivocal Precambrian rocks do not appear to be present, although slivers of Precambrian may be present at the base of the Paleozoic section. The Paleozoic package has been deformed into a west-northwest trending syncline that is south-overturned and plunges gently to the west. (Fig. 12; Plate I,II). Meta-arkose, coarse pelitic schist, and fine-grained metaclastic rocks of probable Mesozoic age comprise an extensive area (approximately 2 square miles) south of the Gap. The detailed structure and stratigraphy of this thick package are poorly understood. Nowhere in the study area are the Paleozoic and Mesozoic metasedimentary units in direct contact. Instead, plutonic bodies intervene and effectively separate the two packages (Fig. 12; Plate I,II). These plutonic units are syn- to late-kinematic, show various degrees of mylonitic deformation, and intrude both the Paleozoic and Mesozoic rocks. Greenschist-grade minerals are common to all three units.
Figure 12. Generalized geologic map of the Boyer Gap region, northern Dome Rock Mountains, Arizona.
Paleozoic Metasedimentary Rocks

General Statement

Exposed in a large (amplitude = approximately 1 km), roughly east-west trending synclinal structure is a sequence of quartzite, schist, marble, and calc-silicate rocks (Fig. 13). Although greenschist-grade metamorphism and intense deformation have left these units devoid of fossils and most sedimentary structures, the formational boundaries and stratigraphic sequence are still intact. This distinctive sequence is characteristic of the lower Paleozoic cratonic section and allows for lithostratigraphic correlation of these units with other metamorphosed Paleozoic cratonic units in the area. The distribution, regional variation, and correlation of metamorphosed Paleozoic strata in the Mojave Desert region has been discussed by Stone and others (1983) and is summarized in Figure 14. In keeping with the recent works of other authors in the region (e.g., Hamilton, 1982; Lyle, 1982a,b), the stratigraphic nomenclature of the Grand Canyon has been used rather than the formation names in the northeastern Mojave Desert or southern Arizona. Metamorphosed lithologic equivalents of the Cambrian Tapeats Sandstone, Cambrian Bright Angel Shale, Cambrian and Devonian Muav Limestone, Mississippian Redwall Limestone, and the Pennsylvanian(?) and Permian Supai Group are present in the Boyer Gap.
Figure 13. Diagrammatic stratigraphic column of nonplutonic rocks exposed in the Boyer Gap region. Thicknesses shown are maximum tectonic thicknesses observed within the study area and probably do not represent the original depositional thickness.
Figure 14. Correlation chart for metamorphosed Paleozoic sedimentary rocks of the southeastern Mojave Desert region. Vertical-line pattern denotes hiatus; diagonal-line pattern denotes nonexposure (From Stone and others, 1983).
Due to the time-transgressive nature of these units, assigned ages are for the equivalent unit in the Grand Canyon and are not to be taken in the strict sense for this area. The Paleozoic section is bounded by a thrust-intrusive contact to the south and by an intrusive contact to the north (Fig. 12). Thicknesses are strictly tectonic and probably do not accurately reflect the original stratigraphic thickness.

**Cambrian Tapeats Sandstone (€t)**

This basal Paleozoic formation is composed predominantly of clean quartzite with minor amounts of arkose and quartz pebble conglomerate. Intercalations of pelitic schistose material are present with increasing abundance up section near the contact with the Bright Angel. This probably represents the effect of tectonic transposition superimposed on primary depositional features. These relations can best be viewed in section 34 (Plate I, II) where the Tapeats-Bright Angel-Muav succession is most complete. With few exceptions, megacrystic two-mica granite (Jp₁) forms an intrusive contact with the stratigraphically lowest portion of the Tapeats. Although a contact with Precambrian rocks was suspected, and has been reported in this area (Harding, 1982), only intrusive contacts are unequivocally present. Slivers of Precambrian rocks may be present, but must be deformed or metamorphosed to hide their identity. Detailed petrologic and geochronologic studies may delineate the presence of Precambrian rocks in this area in the future, but none are obviously present.
In outcrop, the unit is commonly brown to reddish-brown, but varieties exhibiting pale- to dark-gray (almost black) coloration are also present. Fresh surfaces are typically light gray to white and vitreous with gold and (or) red iron oxide stain. Darker examples are dark on fresh surfaces. The only semblance of original bedding preserved within this rock type are thin (about 1mm) laminations of dark minerals (microcrystalline epidote, mica, and opaques) that are predominantly plane parallel. Some suggestion of a low-angle intersection of these layers is preserved and may represent transposition of cross-bedded strata. Cross bedding is reportedly a common feature in unmetamorphosed (see McKee, 1969) as well as metamorphosed (i.e., Hamilton, 1982; Stone and others, 1983) exposures of the Tapeats Sandstone, but is not clearly recognized in this study area.

Although deformational fabrics are not typically well-displayed within this dominantly quartzitic unit, fracture cleavage and spectacular isoclinal folds (Fig. 15) are locally present (see chapter four). The more massive portions of this unit tend to form resistant ridges and cliffs while low-relief slopes typify areas exhibiting a penetrative cleavage. Tectonic thickness of this unit varies from zero to 190 meters.

**Cambrian Bright Angel Shale (Cba)**

Overlying the Tapeats is a section of pale- to medium-green pelitic schist. Fine-grained quartzite layers 2 to 10cm thick are commonly intercalated throughout the section and increase in
Figure 15. Isoclinal folds within the Tapeats.
abundance toward the Tapeats-Bright Angel contact. Extreme internal
deformation in the form of isoclinal folding and transposition of
layering is prominently displayed within the Bright Angel.

The most characteristic lithotype within the Bright Angel is a
coarse-grained, tourmaline-chlorite-epidote-bearing quartz-mica
schist. This unit is very fissile with abundant sericite, which
causes it to weather into chips that resemble silver dollars.
Examples of this sericitic schist are widespread in the center of
section 34 and to a lesser extent in the northern portion of section
28 (Plate I, II).

The largest outcrop of Bright Angel occurs in the northern half
of section 27 where it attains a maximum structural thickness of 210
meters. (Plate I, II). In this region the unit is highly deformed
(see chapter four) and exhibits a strong deformational fabric that
locally resembles worm-eaten wood. Epidote is abundant as is
sericite giving the schist a pale pistachio-colored sheen (Fig.
16). Isolated pale-blue sericitic variations are also present and
appear to be epidotic talc-schists.

**Hornfelsic(?) Bright Angel.** The region mapped as Bright Angel
in the southwest corner of section 27, southeast corner of section
28, and extending into the northernmost portion of section 34 is
markedly different from the more normal outcrops of Bright Angel.
In this area, the well-developed sericitic foliation and quartzite
interbeds are absent. Instead, the unit is fine-grained, massive,
and exhibits an even-textured dark green color (Fig. 17). Fracture
Figure 16. Typical outcrop pattern of Bright Angel in section 27. Abundant epidote and sericite impart the characteristic pale pistachio-green colored sheen that can be seen in the lower portion of the photo. Note the strongly-developed fissility. Plant in lower right corner is approximately 1 meter high.
Figure 17. View to the northeast of hornfelsic (?) Bright Angel. Note that this rock type is darker green, lacks the sericitic sheen, and is not as fissile as the more characteristic outcrop of Bright Angel viewed in figure 16. Northern Plomosa Mountains are in the background.
cleavage is moderately developed with fine-grained biotite lying in the fracture planes. Hornblende prisms up to 5mm in length are locally visible on foliation planes, but are oriented at oblique, random angles to this foliation. Folded, remobilized quartz layers a few centimeters in thickness are sparsely distributed through the unit. The unit as a whole is fairly resistant in contrast to its low-weathering, sericitic counterpart.

A moderately well-developed foliation defined by optically oriented biotite and granular epidote can be seen in thin section. Sericitic material, a major constituent of the normal Bright Angel outcrops, is almost completely absent. Recrystallized quartz and microcline are present as the dominant minerals and exhibit a granoblastic texture. These petrographic textures and the proximal location of a late-tectonic leucocratic pluton suggest that these rocks have undergone thermal metamorphic transformations subsequent to the regional, foliation-producing event(s).

Cambrian Muav Limestone and Cambrian to Devonian Dolomitic Marble (6m)

Interlaminated, coarse-grained, blue-gray, yellow-gray, and pinkish calcitic and dolomitic marbles locally overlie the Bright Angel in the Boyer Gap. These rocks correspond to units assigned to the Cambrian Muav Limestone in the Big Maria (Hamilton, 1982) and Riverside Mountains (Lyle, 1982a,b). These layers are frequently found isoclinally flow folded illustrating the high degree of internal deformation that these rocks have undergone (Fig. 18).
Figure 18. Vague isoclinal flow folds in the Muav. Gray and pink-colored layers characterize this unit. White marble on the skyline is Redwall. Cliff face is approximately 12 meters high.
The unit has a characteristic granular weathering style and exhibits the same color on fresh surfaces as it shows externally. The Muav is most prominently displayed on the upright limb and in the axial portion of the syncline in the center of section 34.

Massive, fine- to coarse-grained dolomitic marble that is typically a uniform yellow-brown color in outcrop and pure white where broken and fresh is described as being in gradational contact with the underlying Muav in adjacent ranges (Hamilton, 1982; Lyle, 1982a,b; Emerson, 1981, 1982). This unit is present in the Boyer Gap and is of much greater areal extent than the Muav (Fig. 19). The fact that this unit can also be found in contact with the Bright Angel is probably due to tectonic elimination rather than original depositional variations. The unit is considered correlative with the Cambrian to Devonian unnamed dolomite of the western Grand Canyon by other workers in the area (i.e., Hamilton, 1982), but in this study has been combined with the Muav Limestone for mapping purposes. This unit forms very resistant cliffs and is present in the axial portion of the syncline in the northeast corner of section 33, and the east-central and southeast portions of section 28.

A sequence of black-varnished quartzite interbedded with light-brown dolomitic marble is present in the Riverside Mountains and has been correlated with the Temple Butte Limestone (Lyle, 1982a,b). This unit has not been described in the Big Maria or Little Maria Mountains (Hamilton, 1982; Emerson, 1981, 1982; Ellis, 1981, 1982), but does appear to be present (E. Frost, pers. comm., 1985).
Figure 19. Yellow-brown dolomitic marble with minor amounts of pure white (note broken piece at far left) Redwall infolded. This unit is probably correlative with the unnamed dolomite of the western Grand Canyon, but has been mapped with the Muav in this study.
Isolated pockets of rocks fitting this description are preserved in the northeast quadrant of section 33 and in the south-central portion of section 28, but extreme tectonism in this area renders their stratigraphic position undecipherable. For this reason, these rocks have also been included with the preceding units for mapping purposes. The maximum structural thickness for the Muav as mapped in this study is 71 meters.

Mississippian Redwall Limestone (Mr)

Massive, coarse-grained, pure white marble is present above the metadolomite and is correlative with the Mississippian Redwall Limestone (Stone and others, 1983). The snow white appearance of this unit both in outcrop and on fresh surfaces makes this a very distinctive rock type. Wollastonite is locally present in minor amounts. Internal structure is not well portrayed, but is apparent on a local scale in the form of transposition and isoclinal folding of vague layers illustrating deformation by ductile flow. The variation in thickness of this unit in adjacent ranges and in the Boyer Gap records its susceptibility to tectonic attenuation (Emerson, 1981, 1982; Hamilton, 1982; Lyle, 1982a,b). The unit is present primarily in the axial portion of the syncline where it forms the synclinal core and reaches a maximum thickness of 60 meters (north-central section 34). As this unit is traced to the west it is commonly preserved as dismembered, attenuated slivers, which do not exceed 5m in thickness and are infolded between the dolomitic marble and the overlying Supai Group.
Pennsylvanian(?) and Permian Supai Group (PPs)

Exposed in the core of the major syncline in its westernmost reach is a sequence of interbedded impure quartzite, calcitic and dolomitic marble, and calc-silicate rock. Structural thickness of this unit varies from 150 to 270 meters. These rocks weather to a very distinctive dark brown color and characteristically form imposing, near-vertical cliffs. A sedimentary breccia composed of angular blocks of the Supai thoroughly cemented by calcite commonly covers slopes beneath this unit. Isoclinal folding and boudinage are especially well-preserved due to the contrast in ductility and resistance to weathering of the constituent lithologic layers. These factors make this one of the most easily identified Paleozoic units in the area and is considered to be the metamorphosed equivalent of the Supai Group of the western Grand Canyon (Hamilton, 1982; Stone and others, 1983).

Mesozoic Metaclastic Rocks

Introduction

Greenschist-grade metaclastic rocks of probable Mesozoic age are present south of Boyer Gap. In the area structurally below the thrust zone, two units were differentiated, a meta-arkose and a body of pelitic quartz-mica and biotite schist. Undifferentiated fine-grained metaclastic rocks are present south of these units. Mafic schist, which appears to have originally been a diabase, crops
out in this region, but is discussed in a later section. Meta-rhyodacite porphyry is also present, but in bodies that were too small to map in this study.

**Meta-Arkose (Mza)**

The first metaclastic unit encountered south of the thrust zone is a strongly deformed arkose. It occurs as slivers trapped within intrusive bodies in the south-central portion of section 34, but becomes a coherent, structurally thickened package 40m thick a short distance to the south (Fig. 20, Plate I). The unit forms a steep, resistant body that has a medium-brown exterior varnish and is typically pale green on fresh surfaces. Whitish examples are also locally present. In outcrop, the unit appears fine- to medium-grained and a significant feldspar contribution is discernable. Grain size variations suggestive of graded bedding are the only sedimentary structures recognized within this unit. It is not clear if this represents original depositional properties or is the result of metamorphic processes. For this reason these structures were not considered sufficient indicators of stratigraphic top.

In thin section, the arkose shows varying amounts of recrystallization, with original grain boundaries apparently obliterated. A wide range in grain sizes is present in samples showing the least amount of recrystallization. Quartz forms 35 to 50% of this rock by volume and is typically found as polygonized aggregates or as stretched-out ribbons of recrystallized material. Feldspar is abundant in all samples and combines with quartz
Figure 20. Northeast-facing view of differentiated Mesozoic units south of the Boyer Gap thrust. Granitic rocks in this area are two-mica megacrystic granites. The manner in which these two units are infolded is visible in the upper right hand corner where a large block of meta-arkose is isolated within the schist.
to form 90 to 95% of the rock. Accessory minerals include (in decreasing order of abundance) biotite, sericite, epidote, sphene, tourmaline, limonite, and calcite. Plagioclase feldspar appears to be predominantly albite and varies from 25 to 40% of the total volume of the rock. Overall, the unit obviously had a high feldspar content and poor sorting.

**Pelitic Schist (Mzsh)**

Structurally beneath the meta-arkose is a slope-forming unit composed predominantly of medium-green, coarse-grained quartz-mica schist (Fig. 20). Impure quartzite layers approximately 5cm in thickness are present in some parts of the section. In this region, the unit bears a strong resemblance to the Bright Angel. It typically is not as sericitic, however, and can be distinguished from the Bright Angel through the presence of apparently interstratified coarse biotite schist. This schist is composed of over 75% biotite and contains relict grains of plagioclase, microcline, and quartz up to 2mm in diameter. Plagioclase is sausseritized and quartz is completely recrystallized to polycrystalline aggregates. It seems likely that these rocks were arkosic sediments with an argillic matrix, which has been transformed into biotite. The quartz-mica schist also contains feldspathic material and was apparently also derived from an arkosic protolith.

Similar schists are also present in the extreme southeast corner of section 33 and in the southwest portion of section 2
(Plate I). It is not clear if these outcrops represent a once-continuous body or if they were deposited at different stratigraphic horizons.

**Undifferentiated Mesozoic Metaclastic Rocks (Mz)**

Undifferentiated Mesozoic metaclastic rocks present south of the meta-arkose, are composed largely of very fine-grained material that has a strongly layered appearance and is interstratified with sparse layers of phyllitic material (Fig. 21). Layering within the fine-grained body is defined by sharp color contrasts without macroscopically-visible textural or mineralogical changes. Pale gray-green and white layers 2 to 15cm thick alternate within the predominant light reddish-brown color. These colors do not persist on freshly broken surfaces. Instead, a homogeneous pale grayish-green color is characteristic. Small, stretched-out blebs of quartz 1 to 2mm thick and no greater than 5mm in length are the only other textural qualities that can be seen in this rock. The strongly layered nature of this unit is also noticeable on a larger scale where distant views give the impression of very thickly bedded strata.

In thin section, the unit is almost completely recrystallized, and consists of very fine-grained quartzofeldspathic material averaging approximately .1mm in diameter. Only a few relict feldspar grains escaped recrystallization. The quartz blebs visible in hand sample are polygonized, lozenge-shaped, and lie within well-developed foliation planes. Minor amounts of microcrystalline
Figure 21. Undifferentiated fine-grained metaclastic rocks in the southern portion of the study area. Note the laminated appearance of the light-colored rocks and interstratification with the green phyllitic material.
sericite, epidote, tourmaline, and chlorite are present and also lie within the foliation planes.

The fine grain size, predominance of quartzofeldspathic material, and the recrystallized character of these rocks make assigning a protolith difficult. Compositionally, the unit may have originally been a granite, rhyolite, or arkose. All three of these rock types are present in the vicinity of Boyer Gap. Since textural criteria have been largely destroyed by recrystallization, field relationships are probably the best guide to the correct identification of these rocks. These relationships suggest that the unit is probably metaclastic, but the possibility that all or part of the unit is metavolcanic cannot be overruled.

Age and Correlation

Very little geochronologic control is available for this metaclastic package of rocks. An upper limit of 160 Ma. is provided by a two-mica megacrystic granite (Jp₁) that intrudes the section and has been isotopically dated by U-Pb methods (see following section for details). The section is bounded by intrusive bodies and no fossils have been discovered. There does not appear to be any basis for correlation with Paleozoic formations in the region, nor are there Precambrian rocks to which the metaclastic units bear a resemblance (E. Frost, pers. comm., 1985). The section does appear to be lithologically similar to regional Mesozoic clastic sequences that include the McCoy Mountains Formation (Harding, 1982a), the Palen Formation (Pelka, 1973a,b; LeVeque, 1981, 1982),
and the Mesozoic section of the Big Maria, Little Maria, Arica, and Riverside Mountains (Hamilton, 1982; Miller, 1981; Krummenacher, in press). On the basis of this lithologic similarity, a Mesozoic age for the metaclastic rocks in the Boyer Gap has been assigned.

Jurassic Granitic Rocks

A suite of mid-Jurassic granitic rocks that are syn- to late-kinematic in origin (see chapter four) forms the bulk of the study area (Fig. 12; Plate I). These plutons are representative of the intrusive portion of the Jurassic magmatic arc, a portion of which extends through southeastern California and southwestern Arizona (Fig. 7). Most of the units are true granites although quartz-poor varieties border on quartz monzonites. All units display metamorphic mineral assemblages indicative of greenschist-grade metamorphism and exhibit a wide range of mylonitic textures in which recrystallization processes were dominant. The result is a highly deformed, well-foliated texture (including augen and banded gneiss in the more extreme examples) for most exposures of the Jurassic granitic rocks. It is possible to trace the units into a less-deformed area such that the protoliths can usually be determined. For this reason, igneous nomenclature was deemed more informative and was used rather than metamorphic textural names in mapping these units. Several Jurassic subunits have been differentiated on the basis of mineralogical and textural criteria established in the field. It is not possible to easily evaluate the
coeval or cogenetic character of these units at this time.

**Two-Mica Megacrystic Granite. (Jp1)**

By far the most conspicuous and abundant intrusive unit in the Boyer Gap is a two-mica megacrystic granite. It is present primarily as a well-foliated rock possessing potassium feldspar (microcline) megacrysts, which locally exceed 10 cm in length (Fig. 22). These megacrysts are grayish-white with a faint suggestion of pink. A dark greenish-gray (almost black) matrix composed of fine-grained (recrystallized and neomineralized) biotite, epidote, muscovite, sphene and tourmaline, along with stretched-out quartz conforms to the margins of the megacrysts. The presence of potassium feldspar megacrysts (porphyroclasts), coupled with enough dark matrix material to clearly distinguish the megacrysts and (or) define a measurable foliation is the field criteria used for mapping this unit. Well-foliated examples with sparse, rounded megacrysts of potassium feldspar may represent deformed, relatively megacryst-depleted portions of the two-mica megacrystic granite, or perhaps deformed varieties of the unfoliated Middle Camp quartz monzonite of Crowl (1979). These units have been differentiated to the south where the Middle Camp pluton is usually undeformed, but it was not possible to make this distinction in the highly deformed areas. For this reason, both varieties have been mapped as Jp1 in the central portion of the study area where they are typically a dark greenish-brown color when viewed from a distance. This color becomes progressively lighter as the ratio of megacrysts to matrix
Figure 22. Detail of large K-feldspar megacrysts (porphyroclasts) in the two-mica megacrystic granite.
increases. Weathering style is closely linked to the degree in which the unit at any given locale has been deformed. The least-deformed examples have a very rubbly-weathering appearance while increasing deformation results in grain size reduction and recrystallization that makes for a much more resistant rock.

**Medium-grained Granite (Jp₂)**

A medium-grained, equigranular two-mica granite that is intrusive into Jp₁ is present and does not appear to be a border phase of Jp₁. The unit can be divided into two varieties for descriptive purposes, both of which are strongly foliated and deformed. The first variety is dark-brown weathering, but is a medium-gray color on fresh surfaces (Fig. 23). The gray coloration is due to an abundance of fine-grained biotite and epidote. Other accessory minerals include (in decreasing abundance) sphene, chlorite, muscovite, and apatite. This variant is typically resistant, but has a granular appearance when extremely weathered. In contrast to this gray colored, biotite-rich, medium-grained granite, the other variety is rich in macroscopically visible fine-grained muscovite and is a characteristic orange-brown color due to iron-oxide staining (Fig. 24). Accessory minerals include (in decreasing abundance) biotite, hematite (as stain), calcite, tourmaline, sphene, and chlorite. One variety appears to grade into the other suggesting that they may be minor compositional variants of the same intrusive pulse.

In addition to the outcrops of Jp₂ adjacent to the Paleozoic
Figure 23. Gray-colored, medium-grained, biotite-rich granite (Jp2).
Figure 24. Orange-colored medium-grained muscovite granite occupies the upper portion of the photo. The gray-green unit below is the hornfelsic(?) Bright Angel.
units, a significantly larger area forming the extreme northern tip of the range has also been included as Jp$_2$. It is distinctly more leucocratic than the dark-colored Jpu with which it is in contact and appears to be a single pluton, therefore it is easily mapped. It is not clear what relationship this pluton may bear to the more southerly, less-voluminous outcrops of Jp$_2$, but it does possess the characteristics set out for defining rocks to be mapped as Jp$_2$. This medium-grained, sphene-muscovite-epidote-bearing biotite granite is relatively undeformed in its interior (although incipient recrystallization is apparent in thin section), but possesses a moderately developed mylonitic foliation near its margins.

**Leucocratic Granite (Jp$_3$)**

The final Jurassic granitic unit crops out most extensively as a tabular, sill-like body in the central portion of the study area (Fig. 25; Plate I, II). The defining parameter for mapping this unit is that matrix minerals must be lacking to the extent that it is difficult to determine crystal size and/or foliation. Several pulses of intrusion appear to be represented within this unit as grain size covers the entire spectrum from aphanitic to megacrystic. The composition is consistently granitic although plagioclase content varies considerably within this field. Accessory minerals do not exceed 5% of the total volume of the rock and are typically confined to sparse, isolated clots of muscovite, biotite (typically partially altered to chlorite), epidote, calcite, opaques, and rare, amorphous sphene. The unit has a light reddish-
Figure 25. Western margin of the light-colored leucocratic granite viewed to the northwest. This unit has intruded the Bright Angel (dark green unit at left) semiconcordantly and may have produced the hornfelsic(?) texture that the Bright Angel locally exhibits. The light colored peak (also granite) is approximately 500 meters away.
brown exterior varnish, but weathers into white-colored granitic debris that commonly litters the underlying slopes. Petrographic examination of the megacrystic varieties shows extreme amounts of recrystallization and mylonitization. Contrary to this, coarse-grained samples show varying amounts of recrystallization, but do not exhibit a significant amount of internal shear. Some coarse-grained samples have purely igneous textures both in outcrop and in thin section and are probably correlative with the Diablo quartz monzonite of Crowl (1979). Rocks of this type intrude the Middle Camp quartz monzonite in the central portion of the range. This undeformed unit is difficult to identify at a distance where it is intrusive into the older leucocratic granites in the study area. For this reason, it has been included as part of Jp3 north of the thrust zone, and has been left undifferentiated from the Middle Camp pluton to the south.

**Middle Camp Quartz Monzonite (Jmc)**

Crowl (1979) studied the central portion of the Dome Rock Mountains where he mapped and described a large body of light- to dark-brown quartz monzonite in which "the most distinctive feature is the presence of large (0.5-1cm) K-feldspar phenocrysts . . . set in a medium-grained matrix of quartz, K-feldspar, plagioclase, and biotite". The unit is reported to be only locally foliated and intrudes a metavolcanic terrane that has yielded Lower to Middle Jurassic U-Pb isotopic ages (L.T. Silver, cited in Crowl, 1979; p. 29; G. Haxel, pers. comm., 1986).
The Middle Camp pluton is only locally deformed south of the thrust and forms the eastern and southern terminus of the undifferentiated Mesozoic unit. Sausseritized plagioclase and chloritized biotite combine to impart a greenish color to this unit (Fig. 26, 27). Crowl (1979) reports a quartz monzonite composition for this pluton, while outcrops sampled in this study consistently plot in the granite field. Small, undeformed masses of Crowl's (1979) Diablo quartz monzonite are intrusive into the Middle Camp pluton south of the thrust, but were not mapped in this study.

Age Constraints

Field relationships clearly indicate that the oldest intrusive unit in the study area is the two-mica megacrystic granite (Jp1). It is commonly in contact with the metasedimentary units and was intruded into these rocks as they were being deformed. The medium-grained granite (Jp2) appears to have been intruded semi-concordantly subsequent to emplacement of Jp1. The bulk of Jp3 was intruded as the last of the Jurassic intrusive units. It is not clear at present what relative age should be assigned to the northern Jp2 pluton, although it definitely intruded post-Jp1.

The Jurassic age assigned to this suite of granitic rocks is derived largely from a U-Pb isotopic determination of 160 ± 5 Ma. that was obtained by L.T. Silver and reported to G. Haxel (pers. comm. from G. Haxel, 1985). The exact location and specific unit sampled is not known, but is assumed to have been the two-mica megacrystic granite (Jp1). The basis for this assumption lies in
Figure 26. Hand sample of relatively undeformed Middle Camp pluton.
Figure 27. Photomicrograph of Middle Camp pluton sample pictured in previous figure. Uncrossed polars above, crossed polars below. Textures are primarily igneous. Sausseritized plagioclase can be viewed in the extreme left-center of the photo. Microcline, quartz, and biotite are the other dominant minerals. Base of photo is 2.5 cm. across.
the similarity that this unit bears to the 1.4–1.5 Ga. anorogenic rapakivi granite that is present extensively in the Mojave-Sonoran region (Anderson, 1983). The sample was obtained at a time when L. Silver was actively studying the distribution of Precambrian rocks in the area (i.e., Silver and Anderson, 1974) and the two-mica megacrystic granite would seem a likely candidate for sampling. The fact that all units considered to be Jurassic in age are syn- to late-kinematic in nature and possess a mineral lineation that is consistent with Jurassic regional lineations further supports a Jurassic age designation for these units.

Other Intrusive Rocks

Mesozoic(?) Metabasic Rocks (Mzd)

Numerous outcrops of very dark green, coarse-grained, highly foliated chlorite-epidote-bearing amphibole schist are present south of the thrust zone (Plate I). This rock type crops out as elongate tabular bodies concordant to the prevailing foliation. Hornblende porphyroblasts 2mm in length are visible in outcrop. The unit has a very dark-brown exterior varnish and weathers into small, disc-shaped chips (Fig. 28). Petrographically, blue-green, highly pleochroic hornblende is typically found forming at the expense of pyroxene, which is partially preserved in the cores (Fig. 29). Chlorite commonly forms pressure shadows adjacent to the hornblende crystals. Epidote is present in granular form. The metamorphic mineral assemblage implies that this is a basic rock metamorphosed
Figure 28. Northwest-facing view of amphibole schist south of the Boyer Gap thrust. Note the strongly developed cleavage and dark green color. Hammer at right center for scale.
Figure 29. Photomicrograph of amphibole schist pictured on preceding page. Uncrossed polars above, crossed polars below. Large crystals are hornblende that commonly rim pyroxene (center-left). Groundmass is amphibole, granular epidote, albite, chlorite and apatite. The mineralogy and outcrop pattern of this unit suggests it is a metadiabase. Base of photo equals 2.5 cm.
to greenschist grade. The elongate outcrop pattern suggests that these are diabase dikes or sills, which intruded prior to or during, the regional Jurassic deformational event and thus are Mesozoic in age.

Metabasic rocks are also present north of the thrust zone, but are of limited extent. The best example occurs in the northern portion of section 27, where a very dark-colored, resistant, sill-like body concordantly intrudes the Bright Angel (Fig. 30; Plate II). The unit possesses a strong deformational fabric that gives the rock a rounded, low-relief, lumpy exterior surface. In thin section, the rock is mostly composed of microcrystalline epidote with minor amounts of chlorite, albite, and muscovite. The epidotic mineralogy, unique texture, and sill-like form suggest that this rock is a highly deformed metadiabase.

**Diablo Quartz Monzonite**

Medium- to coarse-grained micrographic quartz monzonite has been described and informally named the Diablo quartz monzonite by Crowl (1979). This unit is reported to be undeformed, relatively unaltered, and intrudes both the Middle Camp pluton and the metavolcanic terrane in the central Dome Rock Mountains. The lone thin section of this unit was of granite composition and exhibited microperthitic and graphitic textures. Minor accessory minerals include muscovite, biotite, chlorite and hematite. Crowl (1979; p. 37) assigned a tentative Tertiary age to this unit, but Harding (1982) considered these rocks to be Cretaceous. No known isotopic
Figure 30. Northwest-facing view of metabasic unit that has intruded the Bright Angel in section 27. Note that this tabular body is concordant to foliation in the host schist. Sill is 3 meters thick at photo center.
dates have been reported for this unit, but it does appear lithologically similar to regional two-mica granites that yield Cretaceous ages.

**Mid-Tertiary(?) Hornblende-Rich Andesite Dikes**

Porphyritic, hypabyssal dikes of medium gray-green color are present throughout the study area. Abundant dark green, needle-like hornblende crystals less than 2mm in length and subordinate orange-weathering pyroxene blebs stand out against the aphanitic groundmass. These dikes are typically near-vertical and cut all previous structures. The most common strike is N40-60W, but examples are present that deviate from this orientation to follow the prevailing older fabric (WNW). Dikes of this composition and orientation are widespread throughout the Mojave-Sonoran region and presumably reflect mid-Tertiary intra-arc extensional processes (for example, see Rehrig and Heidrick, 1976; Logan and Hirsch, 1982).

**Late-Tertiary(?) Basaltic Dikes**

Isolated occurrences of undeformed basaltic dike material are present in the study area. Several have been mapped within the northernmost granitic pluton (Jp2; sections 16 and 21; Plate I) and generally display northwest to north-northwest strikes. At this locale, the basalts are dark green, aphanitic and vesicular. Unmapped examples were also recognized intruding the Paleozoic marbles where they typically exhibit metasomatic alteration to fibrous dark-green amphibole along their margins. Post-tectonic
basalts are present in many of the adjacent ranges including the Plomosa Mountains where K-Ar whole rock ages of approximately 17 Ma. have been obtained (Black Mesa; Shaffiqulla and others, 1980).

**Calc-Silicate Rocks (cs)**

Rocks of calc-silicate mineralogy have been mapped as such largely due to the difficulty in recognizing the protolith in the field. As illustrated in Plate II, rocks of this composition are abundant in association with the Paleozoic marbles. The typical pistachio-green color attests to the abundance of epidote that these rocks possess. They are commonly very fine-grained, although isolated pockets of euhedral epidote crystals reaching lcm in length are present. Field relationships suggest that these rocks are the result of metasomatic alteration of marble, typically at the Bright Angel-Muav and Redwall-Supai contacts. Additional pockets of calc-silicate rocks appear to be localized in the anticlinal hinges of internal folds within the marbles, presumably from the migration of hydrothermal fluids driven off one or all of the many intrusive bodies.

The large masses of calc-silicate rock present in the northeast corner of section 33 and the southeast corner of section 28 (Plate II) may have a different origin than the rocks discussed above. The mass in section 33 is very dark brownish-black and mineralogically unidentifiable in outcrop. The origin of this body is unknown, but probably is related to the calc-silicate mass in section 28, which
appears to be of intrusive origin (Fig. 37). This rock body is medium-grained, equigranular, and bright pistachio- and dark-green in color. Epidote and actinolite, along with subordinate amounts of albite, predominate in thin section (Fig. 31). Planar fabrics are absent, perhaps due to a post-tectonic intrusive history or an inherent resistance to shear.
Figure 31. Photomicrograph of calc-silicate mass present in section 28. Uncrossed polars above, crossed polars below. Actinolite, epidote, and albite are the predominant minerals. Low birefringent mineral at photo center is apatite. The mineralogy and undeformed character of this rock suggest that it is a basic intrusive that has undergone a metasomatic exchange with its marble host. See figure 37 for large-scale view of this unit. Scale is 2.5 cm. across bottom of photo.
CHAPTER 4
DEFORMATION AND METAMORPHISM

General Statement

Deformational structures present in the Boyer Gap region reflect two major types of tectonism; deep-seated Mesozoic compression and near-surface Tertiary extension. Mesozoic compressional structures are spectacularly displayed and only mildly disrupted by the subsequent extensional events. Syntectonic, greenschist-grade metamorphism attended formation of the compressional structures that are considered to be Jurassic in age. Intrusion of late-kinematic granitoid bodies resulted in minor disruption of the preexisting structures giving the initial impression of extreme structural complexity, when in fact the major structures are relatively coherent and straightforward. The most obvious major structure is a large amplitude (about 1km), WNW-trending, S- to SW-overturned syncline. The syncline occupies an upper-plate position relative to an inferred thrust fault, here informally termed the Boyer Gap thrust, which places Paleozoic cratonal metasediments structurally above Mesozoic(?) metaclastic rocks. Strongly foliated, mylonitic granitic rocks synkinematically intruded the thrust zone, separating the upper- and lower-plate packages, and destroying the actual fault surface.
Metamorphism

Greenschist grade, regional metamorphism characterizes the Boyer Gap area. It occurred in association with Mesozoic tectonism and granite emplacement. Minor contact metamorphic effects are also present and are overprinted on the regional greenschist-grade metamorphism. Pelitic schists were selected from the lower and upper plates for petrographic examination as the most sensitive indicators of metamorphic grade. General mineral assemblages for Mesozoic pelitic schists (biotite + muscovite + quartz + epidote + chlorite + albite + sphene) and the Bright Angel (biotite + muscovite + epidote + chlorite + quartz + tourmaline + albite + sphene + apatite) are typical of greenschist-grade metamorphism.

Contact metamorphic effects are minimal adjacent to Jurassic granitic rocks. With the exception of remobilization of quartz in the Tapeats, contact relations involving the two-mica megacrystic granite (Jp₁) and its metasedimentary wall rocks show little or no signs of thermal disequilibrium. The medium-grained granite (Jp₂) and (or) the leucocratic granite (Jp₃), however, produced hornfelsic textures and formed blue-green hornblende porphyroblasts in the Bright Angel. An example of this is present in the extreme SW corner of section 27 and the SE corner of section 28 (Plate II). Scheelite-bearing scarn deposits are present locally in the marbles and are typically proximal to sulfide-bearing aplite sills. It is not clear if the sills are responsible for the mineralization in the
marbles, or if they merely signal the presence of a larger, non-exposed intrusive body at depth. Calc-silicate mineralization apparently associated with marble-invading basic intrusive bodies(?) are also locally present.

**Tectonic Fabrics**

A strongly developed, pervasive, axial-planar foliation is preserved within most rocks in the study area. Undeformed mid-Tertiary(?) hornblende-rich andesite dikes, mid- to late-Tertiary(?) basaltic dikes, amorphous basic intrusive rocks of unknown age, and many of the calc-silicate rocks do not possess an axial-planar foliation. Portions of some of the Jurassic intrusive bodies are also relatively unfoliated. For example, the medium-grained granite (Jp2) at the extreme northern end of the range exhibits strongly foliated margins, but appears undeformed in its core. This is not uncommon in synkinematic intrusives (ie., Miller and others, 1981) and is to be expected for this pluton, which appears to be somewhat late-kinematic and removed from the major thrust zone where shearing and foliation-development are the most penetrative.

Foliation within the granitic rocks is defined by a preferred orientation of micas, finely recrystallized quartzofeldspathic materials, and, especially in the megacrystic varieties, the alignment of K-feldspar porphyroclasts (Fig. 22). Foliation is easily recognized in all but the leucocratic granite (Jp3), where
foliation is clearly evident in thin section, but often difficult to recognize at the outcrop. Most metaclastic rocks exhibit a preferred orientation of mica flakes, although fracture cleavage is common in the Tapeats. Transposition of layering defines the foliation in marbles and the Supai Group, and may have played an important role in the development of foliation in the undifferentiated Mesozoic unit (Mz). Discrete, laminar color changes and tiny stretched quartz blebs define the foliation in this otherwise featureless unit (Fig. 21).

Foliation within the study area strikes predominantly WNW-ESE and dips moderately to the NNE. Foliation within adjacent units is typically parallel and lithologic contacts are usually coplanar with foliation in the surrounding rocks. The general strike of foliations associated with Paleozoic rocks has been summarized in figure 12, where they systematically change to parallel the axis of the major syncline. Foliation within the northernmost granitic pluton (Jp₂) is sympathetic to the WNW-ESE orientation at its southern margin, but becomes increasingly NNW-SSE striking and ENE-dipping toward the north. Foliation within the relatively massive, undifferentiated Mesozoic unit (Mz) is not easily measured, but appears from reconnaissance mapping to strike roughly northeast and dip shallowly to the northwest—across other major trends in the area. More detailed study is required before the implications of this, as well as the undeformed Jmc-deformed Mz contact relations can be reasonably addressed. All present attitudes must be
considered within the context of mid-Tertiary detachment faulting, through which all previous structures have been slightly reoriented.

Mineral stretching lineations, although not pronounced, are measurable within the Jurassic granites. Stretched, partially recrystallized K-feldspar porphyroclasts are the dominant source of lineation data in these rocks. Lineations are best displayed within the two-mica megacrystic granite (Jp₁). An exception is provided by the northernmost medium-grained granite pluton (Jp₂), in which quartz ribbons and aggregates of biotite exhibit a preferred alignment (Fig. 32). Mineral stretching lineations collected throughout the study area have an average trend of N20E, and range from N10-50E (Fig. 33). Since lineations tend to align subparallel to the direction of tectonic transport in areas of simple shear, a NNE-SSW slip line is suggested by the mineral stretching data (Escher and Watterson, 1974).

Rootless fold hinges within the Supai Group in section 33 as well as Bright Angel in the northern portion of section 27 (Plate II), are characteristically aligned down the foliation dip in the area. In places of high shear strain, as is the case in this portion of the range, rootless fold hinges may act as lineations and rotate into parallelism with the direction of tectonic transport (Ramsay, 1967; Escher and Watterson, 1974). These structures commonly appear as elongate rods of quartz within the Bright Angel. The average N18E trend of these features (Fig. 34) supports a NNE-SSW direction of tectonic transport for these rocks.
Figure 32. Moderately well-developed mineral stretching fabrics in the northernmost medium-grained granite pluton (Jp2). The N23E trend of lineations in this picture is very near the mean trend for all lineations in the study area.
Figure 33. Equal-area stereographic projection (lower hemisphere) of the trend and plunge of mineral stretching lineations obtained from granitic rocks in the upper plate. Different symbols designate sample locations: dots = section 27; squares = sections 28, 33, and 34; triangles = northernmost Jp2 pluton. Mean trend and inferred transport direction is N20E.
Figure 34. Equal-area stereographic projection (lower hemisphere) of the trend and plunge of rootless fold hinges from the Supai in section 28 (triangles), and Bright Angel in section 27 (dots). In areas of high shear strain, these features behave as lineations and rotate into the direction of tectonic transport. The mean trend of N18E agrees well with lineation data presented in figure 33.
Although the megacrystic character of the two-mica megacrystic granite (Jp₁) would be expected to yield asymmetric augen structures that would aid in vergence interpretation (Simpson and Schmid, 1983), such was not the case. Nor do these rocks have well-developed S-C fabrics. The best S-C fabrics are present in the northernmost medium-grained granite pluton (Jp₂). In this area the S-C angle decreases as the amount of strain increases, but the sense of shear remains obscure (Berthe' and others, 1979). It is possible that, assuming the two-mica megacrystic granite (Jp₁) was intruded synkinematically as a crystal mush, the megacrysts were aligned in a "soft" matrix such that the rotational history was not recorded.

**Folding**

**Upper Plate**

The major structural feature in the study area is a large syncline that occupies an upper-plate position and involves Cambrian through Permian strata (Fig. 12; Plate II, III). The syncline is most complete and straightforward in the east where both limbs are preserved and Redwall is exposed in the core (Fig. 35; Plate II, III). Foliation dips moderately to the north and parallels the E-W strike of the synclinal axis on its flanks, but steepens abruptly to near-vertical in the axial region. Minor folds superposed on the major structure commonly produce an interdigitated appearance. The interdigitated aspect of the major fold is best displayed in the
Figure 35. Eastern portion of the major syncline viewed toward the east. Muav Limestone and minor undesignated amounts of Redwall are present in the axial region in this area. The interdigitated aspect of the structure appears as a repetition of Muav surrounded by older Bright Angel in the upper-left portion of the photo. Jurassic granitic rocks (Jg) are two-mica megacrystic granite. Width of view is approximately 500 m.
eastern portion of the structure where hinges of minor synclines appear as elongate slivers surrounded by older strata (Fig. 35).

Rocks of the Supai Group appear in the core of the syncline in the extreme west where the axial plane strikes NW and dips shallowly to the NE. Most of the upright limb has been removed through granite emplacement. The overturned limb is complete, but greatly attenuated (Fig. 36; Plate III). The large, structurally-complex area of Bright Angel present in the northern portion of section 27 (Plate II) may represent strata squeezed into this location from the hinge area of the syncline by the synkinematic intrusive bodies.

In contrast to the relative structural coherence in the eastern and western extremes of the syncline, the midsection is quite complex. Field relations in this area strongly suggest that the structure has been disrupted by late kinematic intrusion of the leucocratic pluton (Jp₃) present in the southern portion of section 27, and perhaps to a lesser extent the medium-grained granite (Jp₂). Foliations in metasedimentary rocks in this area are chaotic and bear no systematic orientation that could be determined. In addition, the syncline is nearly recumbent in this vicinity, suggesting the structure was slightly rotated to accommodate the rising leucocratic pluton (Fig. 37). This may also account for the bend in the axis of the structure that clearly does not reflect refolding in response to some later compressional event.

Although formational boundaries are typically plane-parallel, intense intraformational folding attests to the enormous amount of
Figure 36. Western portion of the major syncline viewed to the east. Dark rocks of the Supai comprise the core in this area. Attenuated lower Paleozoic strata (Tapeats through Redwall) are present above the Supai in the overturned limb. Late kinematic (?) granitic rocks are present beneath the Supai. Note the concordant relationship between overlying Jurassic granites (Jg) and the overturned syncline. Motorcycle at bottom–left for scale.
Figure 37. Midsection of the synclinal structure viewed to the northwest. In this near cross-sectional perspective the structure opens to the left (SW) with Supai in the core and a thickened section of Muav in the hinge area. Attenuated nature of the overturned limb is apparent in the upper-left portion of the photo. The leucocratic pluton (Jp3) is present off camera to the right (east) and appears to have disrupted and slightly rotated the structure into a near-recumbant orientation in this area. The calc-silicate unit appears to be a metasomatized basic intrusive.
deformation that these rocks have undergone. Open, tight, and isoclinal folds can best be viewed in formations such as the Bright Angel or Supai in which competent siliceous layers are interstratified with less-competent carbonate or shale (Fig. 38). Ductile flow was the dominant fold-forming mechanism, but kink folds are present in Redwall Limestone in the eastern synclinal axis (Fig. 39). It appears that in the axial region where deformation was the most intense, flow folding was no longer sufficient to accommodate shortening and the rocks were forced to deform in a more brittle fashion. This may reflect shallowing of the rocks during progressive deformation or perhaps deformation occurred at depths transitional between flow- and kink-fold producing crustal levels. Alternatively, subsequent coaxial deformation occurring at reduced depths may have overprinted the previous flow-folded structures.

Attitudes of numerous folds were collected in the process of field mapping. The interlayered nature of the Bright Angel was most conducive to accurate measurement and thus is the dominant source of fold data. Equal-area stereographic plots of these data suggest that upper-plate metasedimentary rocks may be divided into three structural domains, each having a unique strain history (Fig. 40). The simplicity of the synclinal structure in domain #1 is reflected in the orientation of minor folds in this area (Fig. 41) Fold axes roughly parallel the strike of their respective axial surfaces which are subparallel to the trend of the major synclinal axis. Domain #2 is comprised primarily of the disrupted midsection of the major
Figure 38. Flow-folding is spectacularly displayed within the Supai where the ductility and weathering contrasts between siliceous and impure carbonate layers are considerable.
Figure 39. Detail of kink folding within Redwall marbles. Folding of this nature is limited to the axial portion of the syncline in its eastern reach. Note lens cap at right-center for scale.
Figure 40. Index map for structural domains. Equal-area stereographic plots of fold data suggest that these areas have somewhat unique strain histories. Domain #1 consists largely of the straightforward eastern portion of the syncline. Domain #2 is the disrupted synclinal midsection. Domain #3 is occupied predominantly by a thick section of Bright Angel that records the greatest strain in the study area.
Figure 41. Equal-area stereographic projection (lower hemisphere) of trend and plunge of fold axes and poles to axial surfaces from structural domain #1. The relative simplicity of the structure is reflected in the orientation of minor folds in this area. Fold axes roughly parallel the strike of their respective axial surfaces, which are subparallel to the near E-W trend of the major synclinal axis. Symbols designate sample unit. Solid dots = Bright Angel; open squares = Tapeats; solid squares = Jp1; open triangles = Jp2; open circles = Jp3; solid triangle = aplite dike in Jp1; stars = Muav and Redwall.
syncline. The relatively random orientation of folds in this area is probably attributable to the disruptive effects of the late-kinematic intrusives ($Jp_2$ and $Jp_3$; Fig. 42).

The greatest amount of strain appears to be recorded in domain #3. In this region, axial surfaces are subparallel to the major syncline, but fold axes have been rotated into a NNE-SSW orientation (Figs. 43, 44). Fold axes are thought to nucleate perpendicular to the direction of tectonic transport, but rotate into parallelism as strain increases (Ramsey, 1967; Escher and Watterson, 1974). This contention is supported by the presence of sheath folds (Fig. 45), which are indicative of large shear strain environments (Minnigh, 1979).

**LOWER PLATE**

Due to the less-detailed mapping style and unknown stratigraphy of the lower-plate units, no major structure could be identified. A strongly developed foliation (transpositional layering?) appears to be the only major structural feature within the large undifferentiated Mesozoic region (Mz). Folding is, however, clearly displayed in the meta-arkose (Mza) and pelitic schist (Mzsh) immediately south of the thrust zone (Plate I). The contact at the base of the meta-arkose exhibits an interdigitated folding style reminiscent of the intraformational folds in structural domain #1. These, as well as folds within the meta-arkose, tend to be open to tight, but are rarely isoclinal (Fig. 46). This probably reflects the relative competency of the meta-arkose unit. In contrast, folds
Figure 42. Equal-area stereographic projection (lower hemisphere) of trend and plunge of fold axes and poles to axial surfaces of minor folds for structural domain #2. This domain is comprised primarily of the disrupted midsection of the major syncline. The relatively random orientation of minor folds in this area is probably attributable to the disruptive effects of the late-kinematic intrusives (Jp₂ and Jp₃). See figure 41 for key to symbols.
Figure 43. Equal-area stereographic projection (lower hemisphere) of trend and plunge of fold axes and poles to axial surfaces of minor folds for structural domain #3. The greatest amount of strain in the study area appears to be recorded in this domain. Axial surfaces strike subparallel to the major syncline (WNW), but fold axes have been rotated into a NNE-SSW trending orientation. See figure 41 for key to symbols.
Figure 44. Northeast-facing view of folded siliceous layers within the Bright Angel in structural domain #3. Fold axes are inferred to have been rotated into a NNE-SSW trending orientation in this area. Leitz field notebook at bottom-right for scale.

Figure 45. Sheath fold in siliceous layer from Bright Angel in structural domain #3. Folds of this nature are considered indicative of large shear strain environments (Minnigh, 1979).
Figure 46. Fold style exhibited in the Mesozoic meta-arkose unit.
within the pelitic schist are characteristically isoclinal (Fig. 47). Although it is not obvious in figure 48, small-scale folds are very similar in orientation to folds in structural domain #1; fold axes parallel the strike of the axial plane, which are in turn subparallel to the axial-planar foliation. Rod-shaped structures .5 to 2m in diameter and 5 to 10m in length are developed within the meta-arkose as well as plutonic rocks near the northern Mza/Jpu contact (Plate I). The long axis of these rods is aligned exclusively NNW-SSE suggesting that they may be a sort of "rolling" lineation or rootless fold hinge that formed perpendicular to the tectonic transport direction. The style and orientation of folds within the meta-arkose (Mza) and pelitic schist (Mzsh) leaves no doubt that these rocks have undergone a folding history very similar to metasedimentary rocks of the upper plate. This statement cannot however, be applied to the undifferentiated Mesozoic unit. These rocks are separated from the meta-arkose and pelitic schist by intrusive rocks, do not display folding, and appear to possess a foliation largely unique to that of all study area rocks to the north (Plate I).

**Thrust Faulting**

The major thrust fault in the study area, here informally termed the Boyer Gap thrust, places upper-plate Paleozoic metasedimentary rocks structurally above lower-plate Mesozoic metaclastic rocks (Fig. 12; Plate I,II). No discrete fault plane in
Figure 47. Characteristic isoclinal folding within the Mesozoic pelitic schist (Mzsh).
Figure 48. Equal-area stereographic projection (lower hemisphere) of trend and plunge of fold axes and poles to axial surfaces of minor folds for lower-plate rocks. All measurements obtained from meta-arkose (Mza) and pelitic schistose (Mzsh) units.
which upper-plate strata are physically in contact with lower-plate strata exists. Instead, a thick (about 500m) zone of mylonitic Jurassic intrusive rocks separates the upper- and lower-plate packages—presumably intruded synkinematically into the developing thrust. Elongate metasediment inclusions 1 to 2m thick and several meters long are encountered with increasing frequency near the respective metasediment-intrusive contacts. The thrust fault location has been drawn on the geologic maps (Plate I, II) between the most southerly sliver of Tapeats, and the most northerly outcrop of meta-arkose.

Two-mica megacrystic granite (Jp₁) is by far the most abundant rock type within the thrust zone. Thin (about 3m) sill-like, mylonitic bodies of medium-grained (Jp₂) and leucocratic granite (Jp₃) are intruded just north of the inferred thrust location (Plate II), and are also present in the area designated "Jpu" immediately south of the thrust. A strong, axial-planar foliation is developed within all thrust zone rocks, but shearing becomes distinctly more intense within discrete mylonitic zones that cannot be traced in any direction for more than a few tens of meters. By approaching a shear zone normal to the prevailing foliation, the progressive development of the increasingly mylonitic fabric can be observed (Fig. 49). In the least-deformed examples of two-mica megacrystic granite (Jp₁), foliation is pronounced and porphyroclasts are relatively intact, but interstitial material is completely recrystallized. As strain
Figure 49a-g. Sequence of photographs illustrating the progressive development of increasingly mylonitic fabrics within the two-mica megacryistic granite (Jp₁) in the thrust zone. Strong, axial-planar foliation is common to all thrust zone rocks. Shearing is distinctly more intense within discrete zones that cannot be traced in any direction more than a few tens of meters. Field of view for photomicrographs in this sequence is 2.5cm.
Figure 49a. Relatively undeformed end member of two-mica megacrystic granite within the thrust zone. Note that K-feldspar megacrysts appear relatively intact.

Figure 49b. Photomicrograph (crossed polars) of K-feldspar megacrysts sampled from area shown in figure 49a. Incipient planes of recrystallization misleadingly appear to be fractures in outcrop. Note that groundmass minerals are completely recrystallized.
Figure 49c. Photomicrograph illustrating intermediate stage of thrust zone deformation (uncrossed polars). K-feldspar megacrysts are appreciably more rounded (photo center), quartz ribbons and neomineralized micas conform to the porphyroclast margins.

Figure 49d. Crossed polars of photomicrograph above. Note that although the porphyroclast appears to be relatively undeformed under uncrossed polars, it is actually a polycrystalline aggregate of recrystallized material.
Figure 49e. Highly deformed two-mica megacrystic granite end member. Note that the megacrysts have been stretched-out in the plane of foliation and the unit has taken on a gneissic appearance. It is possible to trace this unit a short distance into relatively undeformed examples similar to figure 49a.
Figure 49f. Photomicrograph (uncrossed polars) of highly deformed unit appearing in figure 49e. K-feldspar porphyroclasts are visibly deformed and elongated. Interstitial regions exhibit a great deal of neomineralized granular epidote and quartz ribbons are extremely elongated.

Figure 49g. Crossed polars of above photo. Epidote is visible as highly birefringent granular material. Quartz ribbons display undulose extinction and only one K-feldspar porphyroclast in the field of view has escaped complete recrystallization (extreme upper-left portion of photo).
increases, incipient planes of recrystallized material begin to develop within the microcline porphyroclasts as the first step in the breakdown of these resistant crystals. The process continues until, in the most extreme examples, grain-size reduction through recrystallization results in a completely recrystallized, vaguely banded mylonitic gneiss. These highly sheared zones actually comprise a very small percentage of the total volume of rock within the major thrust zone. Displacement accommodated by the Boyer Gap thrust is unknown, but is thought to be on the order of several kilometers versus several tens of kilometers or more.

Field relationships in several areas suggest the presence of minor thrust faults that are difficult to document with certainty and thus do not appear on the geologic maps (Plate I,II). These faults occur at formation boundaries or within formations so that the section does not become out-of-sequence. Repetition of strata is common, but appears, in almost every case, to be the result of folding.

Within structural domain #2 (Fig. 40), it is possible that the thick section of Muav present in the NE corner of section 33 (Plate II) has been structurally thickened by an intraformational thrust fault. Vague folds with 10 to 20m amplitudes are present within the Muav at this location and give the unit a highly complex, contorted appearance. This, and the intraformational aspect of the suspected fault makes it difficult to verify with confidence. If present, the fault would strike roughly WNW to NW and dip moderately to the NE.
An additional example is provided at the east-central edge of section 28 and the west-central edge of section 27, just north of the main body of Jp$_2$ in this area (Plate II). At this location, the NNW-striking, WSW-dipping foliation within the Bright Angel strikes into foliation developed within the overlying Muav (Fig. 50). In addition, calc-silicate mineralization has developed near this contact that is the site of a now-abandoned mine. The apparent drag of foliation suggests that Bright Angel was underthrust to the WSW relative to the overlying Muav. These features do not appear to be indicative of regional stresses oriented about some WSW-ENE slip line, but instead represent "pushing" of the relatively ductile metasediments to accommodate the leucocratic (Jp$_3$) and (or) medium-grained (Jp$_2$) plutons.

Although most formational contacts within structural domain #3 can be explained as a result of intense folding, several contacts clearly record a loss of section (Plate II). Most notable are the pieces of Redwall that are "floating" in Bright Angel in the western portion of the domain. These contacts can, by definition, be considered thrust faults, but since they were apparently squeezed into position by the Jurassic intrusives, thrust faults were not employed.
Figure 50. Northwest-facing photo and sketch of Bright Angel foliation striking into foliation in overlying Muav. Minor amounts of pure white marble within the Muav may be pieces of Redwall. Features present at this location probably represent "pushing" of the relatively ductile metasediments to accommodate rising late-kinematic plutons [Jp3 and (or) Jp2].
Tectonic Transport

Although a general impression of tectonic transport emerges from the orientation of small-scale folds, rootless folds, and "rolling" lineations, the most accurate assessment of the actual slip line is provided by the mineral stretching lineations (Fig. 33). Since these data were collected at widespread locations throughout the upper plate, the NNE-SSW relative transport direction they suggest is thought to be most representative of the regional stress environment that formed the compressional structures in Boyer Gap.

Rotational fabrics such as asymmetric augen structures were not useful for determining the actual direction of tectonic transport in the study area. Asymmetric fold data for use in a Hansen analysis (Hansen, 1971) were also deemed unreliable. This type of structural analysis is most applicable when determining vergence along a specific plane of simple shear, such as a thrust fault. It can also be applied, with less confidence, to parasitic folds on a larger fold structure—providing the upright or overturned nature of the larger fold from which the small-scale fold orientation is being collected can be verified (Bell, 1981). Since the interdigitated nature of folding within the Boyer Gap reduces the confidence in which the actual position of parasitic folds within their respective larger-scale fold can be identified, the Hansen analysis was deemed ineffective for determining vergence in this region.
In light of the foregoing comments, the major synclinal structure must be utilized to determine the actual sense of motion for the compressional structures. Since the syncline is clearly overturned toward the south along its entire length, it is difficult to imagine a reasonable tectonic scenario that could produce the present configuration other than a top-to-the-south compressional event. This contention is supported by the presence of upright lower Paleozoic metasediments 3.5km to the north in the southern Moon Mountains (Figs. 51, 52). If, as seems likely, these strata represent the upright anticlinal limb of a syncline-anticline fold pair, the extent of the south-overturned structure is magnified.

Although the bend in the synclinal structure (Fig. 12; Plate I, II) may give the illusion that the structure has been refolded about some WSW-ENE-oriented event, there are no other structural features such as refolded foliations, etc., to support this observation. Indeed, the only clear example of refolding was provided by a thin section of Bright Angel from structural domain #3. Since immediately adjacent samples displayed only one foliation, it is likely that the observed refolding was a localized expression of the high strain history of domain #3 and therefore does not represent a separate tectonic event.

The presence of southward-verging structures, coupled with the NNE-SSW slip line indicated by the mineral stretching lineations and other small-scale structural features, leaves little doubt that overthrusting to the south-southeast formed the major compressional structures present within Boyer Gap.
Figure 51. Large arrow illustrates the approximate location of Paleozoic metasedimentary strata in the southern Moon Mountains.
Figure 52. East-facing view of lower Paleozoic metasediments in the southern Moon Mountains. The upright orientation of these units suggests that the overturned syncline present in Boyer Gap may be part of a syncline-anticline fold pair that extends into the Moon Mountains. Arrow points to Eric Frost on skyline for scale.
Age of Compressional Event(s)

The rocks at Boyer Gap appear to record primarily a single compressional episode of Jurassic age. A lower limit on the inception of thrusting is indirectly provided by metavolcanic rocks in the central portion of the range. These rocks yield Lower to Middle Jurassic U-Pb isotopic ages (Crowl, 1979; G. Haxel, pers. comm., 1986), are intruded by relatively undeformed Middle Camp quartz monzonite (Crowl, 1979), and possess a foliation that may be sympathetic to the structures present in Boyer Gap. It is, admittedly, unclear at this time if there is a direct connection between the structural fabric in the metavolcanic rocks and those of Boyer Gap, but this has been suggested by other authors (i.e., Harding, 1982; Harding and others, 1983; Harding and Coney, 1985), and seems likely. That deformation was ongoing by mid-Jurassic time is clearly demonstrated by the presence of synkinematic granites that yield 160 Ma. U-Pb ages (dated by L. T. Silver; pers. comm. from G. Haxel, 1985).

No absolute upper age limit can be placed on this compressional event, but clues are provided by the mineral stretching lineations. The weakly-developed character and N20E trend of lineations in Boyer Gap are similar to regional Jurassic lineations (E.G. Frost, pers. comm., 1984), but more importantly are very different from the late Mesozoic-early Cenozoic regional lineations prominently displayed within the so-called metamorphic core complexes of western North
America (e.g., Crittenden and others, 1980). Regional lineations from this time are typically strongly developed, mylonitic, and are consistently oriented in a N45-55E direction. Paleomagnetic studies in mountain ranges to the immediate south and southeast of the Dome Rock Mountains indicate that the region has not been significantly rotated about a vertical axis since mid-Tertiary time (Butterworth, 1984; Costello, 1985; Veseth, 1985). Thus, the lineation data suggest that the major compressional structures formed primarily during the Jurassic. The post-Jurassic, NE-directed compressional event that is documented in adjacent ranges (i.e., Hamilton, 1982; Ellis, 1982; Lyle, 1982a,b; Haxel and others, in press) appears not to have significantly affected the study area. Thus barring multiple, coaxial Jurassic events, compressional structures in the Boyer Gap record a single, SSE-verging Jurassic compressional event.

**Mid-Tertiary Extensional Structures**

Brittle fabrics attributable to mid-Tertiary detachment-type extensional tectonics are present in the Boyer Gap, but have only slightly altered the previously developed compressional structures. The most obvious of these fabrics are numerous brittle fractures that strike predominantly N40-60W and exhibit a very minor amount of offset (Figs. 53, 54). Additional fracture sets cluster in the NO-20W, and N75-90W directions. Field relations suggest that the nearly E-W trending sets are following the trend of previous structures and probably do not reflect N-S extension. Similar
Figure 53. Northwest-facing photo of brittle fault inferred to have formed in response to mid-Tertiary extensional doming of the range. Fractures of this nature are numerous and exert a major control on drainage patterns in the range, but do not appear to have an appreciable amount of offset.
Figure 54. Equal-area stereographic projection (lower hemisphere) of poles to brittle fault planes in the Boyer Gap region. Most brittle faults strike N40-60W, but may deviate from this orientation to follow previously formed structures.
circumstances are presented by undeformed, near-vertical (mid-Tertiary?) dikes that were locally observed bending from a N40-60W strike (the most common orientation) to trend nearly E-W (Fig. 55). NW- to N-striking fractures and dikes are common throughout the detachment terrane and reflect a regional extensional environment that appears to have been initially oriented NE-SW, but may have become increasingly E-W directed through time (Rehrig and Heidrick, 1976; Logan and Hirsch, 1982; Angelier and others, 1985). Striations, mulliun, and other near-surface relative motion indicators are rarely developed on high-angle surfaces (most likely due to the minimal amount of offset), but are common on low-angle foliation surfaces in the plutonic and quartzitic units. The attitude of these features has an average trend of N50E, ranges from N32-70E, and records distributed shear in response to mid-Tertiary NE-SW directed extension (Fig. 56).

In addition to the relatively small-scale features mentioned above, mid-Tertiary detachment tectonics have been clearly shown to "warp" the crust into fairly regular sets of regional antiforms and synforms that control the present distribution of mountain ranges and thus the level of crustal exposure in much of the Mojave-Sonoran region (Cameron and Frost, 1981). The Dome Rock Mountains derive their name from the striking manner in which this "warping" process has domed all previously-developed planar elements in the range. The nearest exposures of the actual detachment surface lie in the northern Moon Mountains and directly east in the Plomosa Pass region.
Figure 55. Equal-area stereographic projection (lower hemisphere) of poles to near-vertical (mid- to late-Tertiary?) dikes. NW- to N-striking fractures and dikes are common throughout the detachment terrane and reflect a regional extensional environment that appears to have been oriented NE-SW in the mid-Tertiary, but may have become increasingly E-W directed through time (Rehrig and Heidrick, 1976; Logan and Hirsch, 1982; Angelier and others, 1985). Dots = mid-Tertiary(?) hornblende-rich andesite dikes; squares = basaltic dikes; triangles = quartz-copper veins.
Figure 56. Equal-area stereographic projections (lower hemisphere) of the trend and plunge of striae and mullion structures indicative of near-surface relative motion. These data presumably record distributed shear in response to mid-Tertiary NE-SW directed extension. Symbols designate sample locations: dots = section 27; squares = section 33.
of the northern Plomosa Mountains (Fig. 4; Blaettler, 1983; Keith and others, 1983; Scarborough and Meader, 1983), suggesting that the now-exhumed fault surface projects over the top of the range, parallel to the domed foliation (Dahm, 1983). Thus, the structural expression of mid-Tertiary extension in the Boyer Gap is limited to: A) a slight NW inclination of previously subhorizontal compressional fabrics, and B) those brittle fabrics that developed in response to the doming process.
CHAPTER 5

REGIONAL IMPLICATIONS

Big Maria Terrane

Rocks in the Big Maria and Little Maria Mountains, Palen Pass region, and the Boyer Gap portion of the northern Dome Rock Mountains have undergone a very similar deformational history and comprise a unique geologic entity herein informally termed the Big Maria terrane (Fig. 57). Spectacularly folded Paleozoic cratonal metasediments and syntectonic Jurassic granitic rocks are common to all ranges within the terrane and form a coherent WNW-trending regional structure approximately 75km in length (Hamilton, 1982; Emerson, 1981a,b, 1982; Ellis, 1981, 1982; Demaree, 1981). Axial traces of large-scale folds (amplitude = approximately 1km) trend east-west to northwest-southeast and are overturned to the south to southwest (Krummenacher and others, 1981). A Precambrian granitic and gneissic complex is intimately involved in folding in the Big and Little Marias, but does not appear elsewhere in the terrane. Thrust faults are associated with fold formation and appear to be a final stage in flattening of the large-scale folds.

Two hypotheses are present in the literature concerning the structural history of this terrane—neither of which take the Boyer Gap into consideration. Hamilton (1982) suggests that the large-scale folds initially formed as randomly-oriented synclinal
Figure 57. Index map illustrating the location of rocks collectively referred to in this study as the Big Maria terrane. Similar geologic relationships in the Palen Pass area, Little Maria and Big Maria Mountains, and the Boyer Gap warrant considering this region a unique geologic terrane (See also figure 9).
keels deformed between rising Jurassic plutons. He then visualizes these structures being regionally deformed, refolded, and transposed by NE-directed overthrusting in the Cretaceous Era. Conversely, Krummenacher and students (1981) propose that the large-scale folds are overturned toward the south and therefore indicate overthrusting in that direction. In addition, they contend that small-scale folds formed during progressive flattening and do not represent multiple folding events. They consider deformation, associated plutonism, and metamorphism to have occurred between Middle Jurassic and 90 Ma.

Discussion

It appears from geologic relations in the Boyer Gap that elements of both scenarios are correct. The consistent WNW-strike and regional extent of this major structure strongly suggests that it formed in response to regional tectonic stresses and was not a set of formerly random metasedimentary screens that were subsequently oriented. The syntectonic character of the Jurassic plutons proves that a regional Jurassic deformational environment existed at the time of emplacement and thus the WNW-strike and southward overturning of the major fold structures cannot be ignored—they clearly must have formed from southward overthrusting active during mid-Jurassic time. While the fold data collected by Ellis (1981, 1982), Emerson (1981, 1982), and Demaree (1981) are impressive, they do not preclude multiple coaxial or near-coaxial deformational episodes that could have had opposite senses of
vergence (i.e., Tobisch and Fiske, 1982). The preponderance of NE-verging structures in adjacent ranges (Baltz, 1982a,b; Lyle, 1982a,b; Pelka, 1973a,b; Harding, 1982; Tosdal, 1982, 1984a,b; Haxel and others, in press) increases the likelihood that this was the case.

Application of data gleaned from the Boyer Gap suggests that the Big Maria terrane experienced south- to southwest-directed overthrusting and granite emplacement in mid-Jurassic time that produced the large-scale folds and associated thrusts. These structures were probably overprinted to some degree by NE-directed, late Mesozoic overthrusting and ultimately brought to the surface and reoriented via mid-Tertiary extensional processes.

Mid-Jurassic Intra-arc Transpression?

"Classic" convergent-margin models based on near-perpendicular plate impingement do not provide an adequate paleotectonic setting in which the Big Maria terrane may be placed. In these models, compressional structures form at the leading edge of the overriding plate and in the foreland region, while the magmatic arc develops in an environment relatively free of regional compressive stresses. In direct contradiction to this, geologic relationships in the Big Maria terrane clearly record synchronous compression and granite emplacement within the Jurassic magmatic arc of southwestern North America (Fig. 58).

In recent years, global neotectonic studies have shown that
Figure 58. Location of the Jurassic magmatic arc in southwestern North America highlighting the intra-arc position of the Big Maria terrane (dot pattern) and McCoy Basin (in black). Arc location after Anderson and Silver (1979), and Burchfiel and Davis (1981).
perpendicular plate convergence and associated morphotectonic features are presently an exception rather than the rule. Instead, oblique subduction is much more common with features such as en echelon ridges, intra-arc transcurrent faults, and transtensional basins developing as the crust is forced to resolve compressive and transcurrent stresses (i.e., Kaizuka, 1975; Hamilton, 1978; Karig and others, 1979; Howell and others, 1980; Silver and Smith, 1983). These findings, coupled with recent paleomagnetic, sea floor, and structural studies, strongly suggest that the margin of western North American was the site of oblique convergence for much of Mesozoic time. Most workers have concluded that this convergence was right-oblique since the Early Triassic (Jones and others, 1977; Coney and others, 1980; Burchfiel and Davis, 1981; Schweickert, 1981; Saleeby, 1981; Vedder and others, 1983), but several recent authors have suggested that there may have been a period of left-oblique convergence during Jurassic time (Engebretson, 1982; Oldow and others, 1984; Page and Engebretson, 1984; Harper and others, 1985). Most of these interpretations are, however, based on relative plate motion studies by Engebretson (1982) that, for pre-85 Ma. and especially pre-145 Ma. are poorly constrained and tenuous at best (see Page and Engebretson, 1984; p. 134). If some form of oblique convergence is assumed, the most reasonable origin for the Jurassic structures in the Big Maria terrane would be a transpressional environment within the Jurassic magmatic arc of southwestern North America. Intra-arc transcurrent faults are
common features in presently-active oblique margins and would be expected to induce somewhat localized environments of transpression. Analogous transpressional structures associated with the San Andreas transform system have been documented in the Transverse Ranges by Dibblee (1977). En echelon ridges, which are common features of presently active obliquely converging regions (Kaizuka, 1975), may represent the surface expression of intra-arc transpressional tectonics ongoing at depth.

McCoy Basin

Lying directly south of the Big Maria terrane are rocks assigned to the McCoy Basin by Harding and co-workers (Harding, 1982a; Harding and Coney; 1985). The basin is represented by the 7.3km-thick metasedimentary McCoy Mountains Formation and underlying Jurassic metavolcanic rocks. Thin, laterally equivalent clastic rocks are also present in depositional contact with cratonic strata near the basin’s northern margin (Apache Wash Formation of Harding, 1982). Basin rocks are present in at least six mountain ranges in southwestern Arizona and southeastern California and form a WNW-trending region 140km long and 25km wide (Fig. 3).

The basal strata of the McCoy Mountains Formation are interbedded with metavolcanic rocks that yield Early to Middle Jurassic U-Pb (central Dome Rock Mountains; L. T. Silver, cited in Crowl, 1979) and 175 Ma. K-Ar plagioclase ages (Palen Mountains; D. Krummenacher, cited in Pelka, 1973b). Latest Cretaceous K-Ar
minimum ages of crosscutting plutons and dikes provide a minimum age for these strata (Pelka, 1973a,b; Reynolds, 1980; Tosdal, 1984b). Fossil angiosperm wood has been used to assign a Late Cretaceous or Paleocene upper age to this formation (Pelka, 1973b; Hayes, 1970; Miller, 1970; Robison, 1980; Harding, 1982), but, as pointed out by Harding and Coney (1985), considerable disagreement concerning the age range of angiosperm wood limits the usefulness of these fossils. Extensive paleomagnetic data collected by Harding and others (1980, 1983) suggest that the McCoy Mountains Formation was deposited prior to late Middle to middle Late Jurassic time.

Rocks of the McCoy Basin form a large, south-dipping homocline with the uppermost strata deformed into an overturned, north-verging syncline (Fig. 59; Harding, 1982; Harding and Coney, 1985). A south-verging major thrust fault forms the northern basin margin, which is present in the Boyer Gap (Boyer Gap thrust, this study) and Palen Pass areas (Fig. 3; Demaree, 1981; LeVeque, 1981, 1982). The north-verging Mule Mountains thrust (Harding, 1982; Tosdal, 1982, 1984a,b) is inferred as the southern margin of the basin (Fig. 3, 59; Harding, 1982; Harding and Coney; 1985).

Harding and co-workers (Harding, 1982; Harding and others, 1980, 1982, 1983, 1985) suggest that the McCoy Basin formed as a rhombochasm along a transform fault active in Early to Middle Jurassic time (Fig. 60). The basin-bounding strike-slip faults are considered to have been reactivated in Late Jurassic time by a compressional event that simultaneously overthrust the basin from
Figure 59. Schematic structure sections of Harding and Coney (1985) through the Dome Rock, McCoy, and Palen Mountains, McCoy Basin. The south-verging, northern Basin-bounding thrust is exposed only in the Palen Pass and Boyer Gap regions. The north-verging Mule Mountains thrust forms the inferred southern margin of the Basin. Refer to figure 3 for legend (From Harding and Coney, 1985).
Figure 60. Block diagram illustrating the model proposed by Harding (1982), and Harding and Coney (1985), for the origin of the McCoy Basin. Left-lateral offset on the Mojave-Sonora megashear would open up a narrow, fault-bounded basin similar to the Salton Sea trough (From Frost, 1983a).
the northeast and the southwest. They visualize the left-lateral Mojave-Sonora megashear of Silver and Anderson (1974) as the transform fault and propose that the Mule Mountains thrust marks the location of a major tectonostratigraphic terrane boundary separating pre-Late Jurassic North America from the exotic, allochthonous Mojave Composite Terrane to the south (Fig. 3, 60). In this model, the McCoy Mountains Formation and its Jurassic volcanic basement would represent a basin collapsed between North America and the accreted Mojave Composite Terrane during a Late Jurassic docking event.

Discussion

In postulating the southern margin of the McCoy Basin as a tectonostratigraphic terrane boundary, Harding (1982), and Harding and Coney (1985) emphasize that pre-Late Jurassic rocks unequivocally linked to North America are not known to be present south of the proposed boundary. In fact, Paleozoic cratonal metasediments with North American affinities are present to the south in the El Capitan region of northernmost Sonora, Mexico (Leveille, 1984; Leveille and Frost, 1984), and in the northern Gila Mountains of southwesternmost Arizona (Wilson, 1933, 1960; Fig. 61). In addition, Haxel and others (1985) suggest that the lower portion of the McCoy Mountains Formation may correlate with the Jurassic(?) Winterhaven Formation, which is exposed in several mountain ranges immediately south of the McCoy Basin. Although
Figure 61. Location of Paleozoic cratonic metasediments (in black) with respect to rocks of the McCoy Basin (dot pattern). The presence of North American-affinity rocks southwest of the McCoy Basin in the Gila Mountains, Arizona, and El Capitan, Sonora, Mexico, suggests that the Mojave-Sonora megashear may not be linked genetically to the McCoy Basin. Post-megashear displacement on mid-Tertiary low-angle normal faults would require a minimum of 100-150km of southwest transport to account for their present location south of the proposed trace of the megashear.
current data are inconclusive, positive correlation would be significant because the Winterhaven Formation appears to be indigenous to southwestern North America (Haxel and others, 1985).

The presence of pre-Late Jurassic strata with North American cratonic affinities south of the McCoy Basin suggests that the Basin may not be linked genetically to the Mojave-Sonora megashear. The Paleozoic strata in the Gila Mountains and at El Capitan are deformed into NE-verging Mesozoic structures (Leveille, 1984; E. G. Frost, pers. comm., 1985), which seems to rule out post-megashear southwest translation via sub-horizontal compressional faults. Mid-Tertiary low-angle normal faults could be used to explain the present position of these rocks, but the 100-150km minimum required distance of transport seems to be prohibitive. For this reason, in addition to studies that suggest minimal offset (1-10km) on the Mule Mountains thrust (Tosdal, 1984a,b), caution should be exercised in considering the southern McCoy Basin-bounding thrust a major late Mesozoic tectonostratigraphic terrane boundary.

An additional problem is presented by the collapsed basin concept for the origin of the opposite-verging, basin-bounding thrusts. As exemplified by Harding's (1982) cross-section through the Dome Rock Mountains (Fig. 62), a space problem would exist if two separate upper plates were overthrust synchronously toward each other. The problem is amplified considering the present orientations of the thrust faults are largely a product of mid-Tertiary doming—a point apparently overlooked in Harding's
Figure 62. Reversed version of Harding and Coney's (1985) north-south cross-section through the Dome Rock Mountains (see figure 59). Note that a space problem would result if two separate upper plates were synchronously thrust toward each other. Compare this interpretation with figure 63. Refer to figure 3 for legend.
work—and thus planar elements most likely formed at a near-horizontal attitude. It is, therefore, much easier to visualize two separate events forming the observed geologic relationships (Fig. 63). This interpretation is supported by the apparently disparate ages of the north- and south-bounding thrusts. Tosdal (1982, 1984a,b), considers the Mule Mountains thrust to be a late Mesozoic to early Cenozoic feature, largely on the basis of K-Ar whole rock analysis of mylonitic shear zone rocks. He also reports the presence of superposed mid-Tertiary extensional faults, so the possibility of thermal resetting of the K-Ar system by detachment processes cannot be overruled (Martin and others, 1980, 1981, 1982; Frost and others, 1982). Much earlier, mid-Jurassic thrusting has been documented for the north-bounding thrust (Boyer Gap thrust, this study). This suggests that the McCoy Basin was originally overthrust from the north-northeast in mid-Jurassic time and subsequently overthrust from the southwest sometime in the late Mesozoic.

Mesozoic Tectonic Evolution: Big Maria and McCoy Basin Terranes

The foregoing comments suggest that, as proposed by Harding (1982), and Harding and Coney (1985), McCoy Basin rocks could have been deposited in a transtensional basin and the proposed Basin-boundary transcurrent faults may have subsequently been reactivated and (or) obscured by regional compressive stresses. This overprinting may account for the apparent lack of coarse
Figure 63. Reinterpretation of Harding and Coney's Dome Rock Mountain cross-section appearing in figure 62. This interpretation assumes that two separate thrusting events produced the McCoy Basin-bounding faults. Arching of planar elements is probably a product of mid-Tertiary detachment processes. This figure also implies that the boundaries of the McCoy Basin are not major tectonostratigraphic sutures, but are expressions of North American intra-plate deformation. Refer to figure 3 for legend.
proximal detritus and strike-slip kinematic indicators that should be generated along the margins of an evolving transtensional basin. Compressive tectonics were clearly active in this area by the Middle Jurassic, suggesting that basin formation must have concluded by this time. It does not appear that the Mojave-Sonora megashear (Silver and Anderson, 1974; 1983; Anderson and Silver, 1979; 1981;) was the responsible transcurrent feature. Based on the presence of Paleozoic cratonal metasediments in the El Capitan region, Leveille (1984), and Leveille and Frost (1984) suggest that the megashear, if it exists, must pass to the south of El Capitan (Fig. 64).

Thus, it seems much more likely that the McCoy Basin represents an intra-arc transtensional basin that formed in response to the oblique subduction of Pacific Plate precursors beneath the western margin of the North American Plate in late Early to early Middle Jurassic time. Very shortly thereafter, transpressional tectonics prevailed and the McCoy Basin was overthrust—reactivating the northern basin-bounding transtensional fault—from the north by rocks of the Big Maria terrane. The transtensional-transpressional tectonic setting suggested here is attractive for several reasons. Not only does it supply an explanation for synchronous compression and magmatic intrusion, it also provides a setting in which opposite stresses (extension and compression) can act at the same location within a very short span of geologic time without requiring a change in the overall tectonic setting. This would also provide a mechanism for the apparent rapid burial and metamorphism of McCoy
Figure 64. Tectonic and paleogeographic models of the southwestern United States and northern Mexico proposed by Stewart and others (1984). The presence of Paleozoic cratonic metasediments in the El Capitan region of northern Sonora, Mexico, suggests that model "B" may be the most reasonable alternative (From Stewart and others, 1984).
Basin units. Subsequently, perhaps in response to an outboard shift of the magmatic arc in the late Mesozoic (Fig. 65), the region became the locus of NE-directed back-arc overthrusting that reactivated the southern McCoy Basin-bounding fault and overprinted the previously developed Jurassic structures to varying degrees.

If the foregoing scenario for the tectonic evolution of the Big Maria and McCoy Basin terranes is viable, it is plausible to consider the Pelona-Orocopia Schist and the Vincent-Chocolate Mountains Thrust System within a similar context (Haxel and Dillon, 1978; Ehlig, 1981). Exposures of this enigmatic geologic terrane are located a mere 35km to the southwest of the McCoy Basin, have a similar WNW trend, and are preserved in adjacent regional mid-Tertiary antiforms (Fig. 66, 67; Frost, 1983a). Recent studies suggest that the Pelona-Orocopia protolith is pre-Late Jurassic in age and may have, at least in part, accumulated synchronously with the McCoy Mountains Formation (Mukasa and others, 1984; Haxel and others, in press). This presents the interesting possibility that the Pelona-Orocopia Schist may have been deposited in a transtensional basin(s) that formed near the outboard margin of the Jurassic magmatic arc as a consequence of north-oblique convergence. In addition, the structural history of mid-Jurassic southwest-directed compression overprinted by late Mesozoic northeast-directed back-arc thrusting recorded in the Big Maria and McCoy Basin terranes may apply to the Pelona-Orocopia Schist as well (Fig. 68).
Figure 65. Present position of the late Mesozoic magmatic arc relative to rocks of the Big Maria terrane (dot pattern) and McCoy Basin (in black). An outboard shift in arc magmatism relative to the Jurassic magmatic arc placed these terranes into a back-arc position that favored formation of NE-directed compressional structures at this time. Arc location after Kistler (1974).
Figure 66. Location of Pelona-Oroocopia Schist exposures in southeastern California and southwestern Arizona reconstructed for pre-San Andreas time. See figure 67 for location relative to the McCoy Basin (Modified from Dillon, 1976).
Figure 67. Sketch map illustrating the distribution of the Pelona-Orocopia Schist with respect to the McCoy Basin in southeastern California and southwestern Arizona. These rocks are exposed in the cores of adjacent regional mid-Tertiary antiforms (From Frost, 1983a).
Figure 68. Schematic diagrams illustrating the mid-Jurassic and late Mesozoic convergent margin settings hypothesized for formation of the geologic relationships present in the greater Boyer Gap region. Mid-Jurassic: Highly north-oblique subduction formed fore-arc features that reflected transverse component of convergence. McCoy and Pelona-Orocopia Basins may have formed as transtensional features at or prior to this time. Intra-arc southward-directed thrusting (transpression?) occurred within the Big Maria terrane and may also have formed an ancestral Chocolate Mountains thrust. Late Mesozoic: An outboard shift in arc magmatism and a change to near-normal relative plate motion induced back-arc NE-directed compressional stresses in the greater Boyer Gap region. Features such as the Mule Mountains and Chocolate Mountains thrusts formed in response to these stresses, overprinting and perhaps reactivating inactive transtensional and (or) transpressional structures.
MID-JURASSIC

SSW

Trench
Outer-Arc Ridge
En Echelon Ridges
Transcurrent Faults
CHOCOLATE MTNS.-THrust
BOYER GAP

CONTINENT

OBLIQUE SUBDUCTION

N.A.

LATE MESOZOIC — EARLY CENOZOIC

ACTIVE ARC

SSW

Outer-Arc Ridge
Fore-Arc Basin

REACTIVATED SEGMENT OF
CHOCOLATE MTN. THRUST
BOYER GAP

REDUCED OBLIQUITY
OF SUBDUCTION

EXTINGUISHED
JURASSIC ARC

N.A.

NNE
CHAPTER 6

SUMMARY

Paleozoic cratonic metasediments, Mesozoic metaclastic rocks, and syn- to late-kinematic granitic rocks of Jurassic age are present in the Boyer Gap region of the northern Dome Rock Mountains. The Grand Canyon-correlative Paleozoic rocks (Cambrian Tapeats through Permian Supai) are exposed north of Boyer Gap in a major (amplitude about 1km), SW-overturned syncline that trends roughly WNW-ESE. Precambrian rocks are not obviously present, but may be preserved as dismembered slivers at the base of the Paleozoic units. Mesozoic meta-arkose, coarse pelitic schist, and fine-grained (arkosic?) metaclastic rocks are present to the south of Boyer Gap. An inferred, NNE-dipping major thrust fault, informally termed the Boyer Gap thrust, places Paleozoic units structurally above Mesozoic metaclastic rocks. Syn- to late-kinematic mylonitic plutonic rocks, including two-mica megacrystic granite, medium-grained granite, and leucocratic granite, have intruded the evolving thrust zone so that the actual thrust surface is not preserved. Plutonic rocks appear to be Jurassic in age based on a $160 \pm 5$ Ma. U-Pb isotopic determination (L. Silver, pers. comm. to G. Haxel) and the presence of mineral stretching fabrics consistent with regional Jurassic lineations (NNE-SSW).
The rocks at Boyer Gap record SW-directed overthrusting and synkinematic granite intrusion within the Jurassic magmatic arc of the southwestern Cordillera. Deformation occurred at moderate crustal levels forming syntectonic greenschist-grade minerals, probably during a single, although perhaps prolonged, Jurassic event. Intrusion of late-kinematic(?) granitoids resulted in minor disruption of pre-formed features. Subsequent tectonic disturbances including late Mesozoic to early Tertiary NE-directed compression and mid-Tertiary extension have had little observable affect on the major Jurassic structures.

The Boyer Gap is part of a regional geologic terrane, informally termed the Big Maria terrane, that possesses a similar Jurassic-Cretaceous signature. This terrane lies structurally above (north) rocks of the McCoy Basin. The Boyer Gap thrust, together with the Palen Pass thrust, are the exposed segments of the tectonic boundary that juxtaposes these two terranes. Movement on this thrust appears to predate formation of NE-verging structures, including the Mule Mountains thrust, that form the southern tectonic margin of the McCoy Basin. This indicates that tectonic models in which the arrival of an exotic, allochthonous terrane synchronously produced both basin-bounding, opposite-verging thrusts are untenable.

As suggested by Harding and Coney, (1985), the McCoy Basin may have originated as a Jurassic intra-arc transtensional basin resulting from oblique plate interactions. The presence of North American-affinity rocks southwest of the Basin, however, suggests
that the Mojave-Sonora megashear may not be linked genetically to
the McCoy Basin. After basin formation, mid- to late-Jurassic
intra-arc transpressional tectonics thrust the Big Maria terrane
over rocks of the McCoy Basin. Following an outboard shift of arc
magmatism in the late Mesozoic, the region experienced back-arc,
NE-directed overthrusting, forming the structures present at the
southern margin of the McCoy Basin.
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Complex structural relations principally related to fold and nappe development within the Jurassic magmatic arc of the southwestern North American Cordillera are present in the Boyer Gap region of the northern Dome Rock Mountains. A basal thrust, here informally termed the Boyer Gap thrust, places Grand Canyon-correlative Paleozoic metasedimentary rocks structurally above metaclastic rocks of presumed early to middle Mesozoic age. A syn- to late-kinematic suite of mid-Jurassic plutonic rocks are intruded as sill-like concordant bodies into the thrust as well as lower- and upper-plate structures where their involvement appears of have facilitated large amplitude (about 1km) fold formation. The fold nappe above the Boyer Gap thrust as exposed in the northern Dome Rock and southern Moon Mountains contains a WNW-trending, S- to SW-overturned syncline-anticline fold pair that implies south to southwest tectonic transport. This is consistent with mineral stretching fabrics that suggest transport occurred along a NNE-SSW slip line. Post-Jurassic deformational elements can be identified in the Boyer Gap region, but do not significantly disrupt the major Jurassic structure. This affords the unique opportunity to view Jurassic deformation in a manner that is rarely possible in the Mojave-Sonoran region.

Jurassic structures present in Boyer Gap project westward through the Big Maria-Little Maria Mountains and Palen Pass area,
forming a regionally coherent geologic entity herein informally referred to as the Big Maria terrane. Regional geologic considerations suggest a tectonic scenario whereby oblique northward subduction of Pacific Plate precursors beneath western North America formed an intra-arc transtensional basin (McCoy Basin) in early Middle Jurassic. Intra-arc transpressional tectonics subsequently thrust the Big Maria terrane southward over the McCoy Basin. An outboard shift of arc magmatism in the late Mesozoic placed the region in an arc-rear position favoring formation of NE-verging structures such as the Mule Mountains thrust.
Plate III
Geologic Cross - Sections

By
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Fall 1985

The Boyer Gap: A Record of Jurassic Intra-Arc Fold and Nappe Tectonics in the Northern Dome Rock Mountains of Southwestern Arizona.

Note:
- See Plate I for key to symbols and scale.
- See Plate II for section location.

No vertical exaggeration.