STRUCTURAL GEOLOGY OF THE CENTRAL COYOTE MOUNTAINS

IMPERIAL COUNTY, CALIFORNIA

A Thesis

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A Thesis

by

Cavan S. Ewing

Fall 2014

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The Coyote Mountains are a small mountain range in a tectonically complex region of southern California. Previously undisturbed units of the Salton Trough have been uplifted, faulted, and deformed from displacement on the oblique Elsinore Fault of the southern California San Andreas fault system. Uplift and erosion have exposed the metamorphic basement complex and older Tertiary stratigraphic sequence for geologic interpretation.

Sedimentary and volcanic units were originally deposited on a highly irregular basement topography prior to faulting and deformation. Three east-west trending infilled paleocanyons are exposed within the mountain range and preserve the oldest Tertiary stratigraphy from erosion. Younger sedimentary units were preserved by fault escarpments in the basement complex. Transpressional stresses from the Elsinore Fault resulted in strain partitioning and the creation of a synthetic and antithetic fault array

observed in the system. Two large oblique synthetic faults strike to the northwest-southeast and create elongate structures in the typically unfaulted basement complex. Several smaller antithetic faults strike to the northeast-southwest and typically possess sinistral and normal displacement opposite the major Elsinore Fault. Antithetical faults in the basin to the north of the range have hinged motion from torsional stresses in the system.

Most of the measurable bedding orientations in the stratigraphic sequence have been translocated with the basement complex to their current orientations. Older sedimentary and volcanic units have been tilted with the large sections of uplifted basement complex during transpressional mountain formation. Younger, less indurated sedimentary units show ductile deformation to the south of the range. Folding in the younger sedimentary stratigraphy may be indicative of system-wide folding early in the geologic history of the Coyote Mountains.

The youngest stratigraphic units are high elevation older alluvium deposited after the onset of uplift and the erosion of the original basin stratigraphy. Found on the range crests and mountain flanks, the older Quaternary conglomerates are derived from the ancestral Coyote Mountains and are deposited as an angular unconformity with the faulted older stratigraphy. The unconsolidated units were uplifted to their current elevations from continued displacement on the Elsinore Fault.

CHAPTER I

INTRODUCTION

Background

The Coyote Mountains of southernmost California are a small, low-elevation range of crystalline basement rocks overlain by Tertiary volcanic and sedimentary deposits. The stratigraphy in the region records the tectonic evolution of the ancestral Gulf of California basin. The basement core of the mountain range consists of metamorphosed Paleozoic passive margin miogeoclinal sediments with Jurassic granodiorite intrusions (Hill, 1984). In the Late Miocene-Pliocene, displacement along the west Salton detachment fault created an asymmetrical basin known as the Salton Trough (Axen and Fletcher, 1998). Stratigraphic units of the Split Mountain Group represent fluvial, volcanic, and alluvial systems deposited in the region prior to and coeval with detachment faulting. Continued motion along the west Salton detachment fault increased basin subsidence, eventually leading to oceanic transgression. The region was buried by fossiliferous marine sandstones and mudstones of the Imperial Group that were deposited in the narrow seaway. Despite continual subsidence from continental rifting, progradation of the Colorado River delta filled the basin and led to the regression of the Gulf of California (Winker and Kidwell, 1996).

Reorganization of fault motion in the last 1-2 million years halted detachment faulting and ended regional subsidence (Dorsey, 2011). Relative displacement between the Pacific Plate and North American Plate was accommodated by the formation of three major dextral faults of the southern California San Andreas fault system: the San Andreas Fault, the San Jacinto Fault, and the Elsinore Fault. A transpressional bend in the southern Elsinore Fault uplifted the basin sequence and created the present-day Coyote Mountains (Marshall et al., 2006). Erosion of the range has exposed the local stratigraphy and structure for geologic study and interpretation.

Location

The study area is located within the Coyote Mountain Wilderness and is under the direction of the Bureau of Land Management. Approximately 80 miles east of San Diego, California and 20 miles west of El Centro, California, the mountains are found at the border of San Diego and Imperial Counties (Figure 1). Adjacent to the Anza-Borrego Desert State Park, the Coyote Mountain Wilderness is accessible through Imperial Highway S2 and local roads from the town of Ocotillo, California. The approximately 10-square-mile study area is a north-south transect of the central mountain range (Figure 2). In this study, the higher elevation mountainous region is named the “mountain block” and is composed primarily of metamorphic basement rock with Tertiary sedimentary and volcanic units. The area is accessible by foot from Cahuilla Canyon, West Canyon, and Fossil Canyon on the southern edge of the range. Mapped sedimentary sequences located on the southern side of the Coyote Mountains are herein named the “west range front” and “east range front” and are separated by a private gravel quarry. A small portion of the adjacent Fish Creek-Vallecito basin is found on the northern side of the mountain range (Dorsey, 2011). The basin segment is referred to as the “north basin” in this report. The

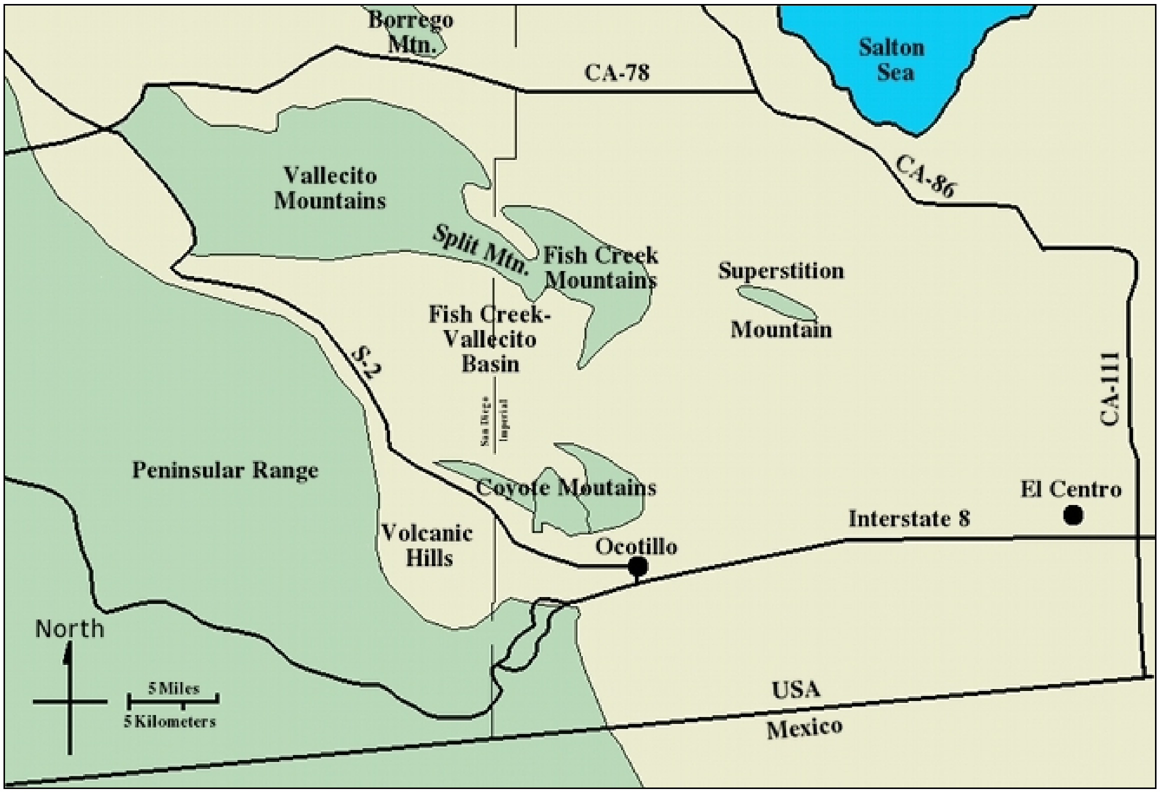

Figure 1. Location map of the central Coyote Mountains, Imperial County, CA.

north basin is accessible from the Wind Caves trailhead located west of the mapping region.

Problem

The Coyote Mountains are found within a structurally complex region of southern California. The area has undergone a history of tectonic transitions and fault reorganizations. While previous studies have primarily focused on stratigraphy and regional tectonics, detailed mapping of the Coyote Mountains will aid in understanding the mechanisms for mountain uplift and formation. The fishhook-shaped range is flanked to the south by a restraining bend in the still-active Elsinore Fault (Marshall et al., 2006). While transpressional forces are the current understanding for mountain uplift, the

Figure 2. Location names within the central Coyote Mountains mapping region.

complexity in deformation within the Coyote Mountains can be studied through the current structure of the study region. Determining whether deformation occurred during regional detachment in the Pliocene or more recently during transpressional uplift will be crucial in creating a geologic timeline for the mountain range. Subsequently, characteristics of the original basin prior to deformation can be determined through the structure and distribution of current stratigraphic units within the Coyote Mountains.

Purpose

The mapping project was conducted to partially fulfill the requirements for a Master's of Science degree at California State University, Chico. The Coyote Mountains were selected for its geologic setting and limited amount of detailed structural mapping of the area. Older maps lack modern understanding of the tectonic and geologic history of the Salton Trough, especially the role of the west Salton detachment fault. A detailed geologic map reveals the structure of the range and will help in determining relative timing for deposition and faulting (Plate 1). Stratigraphic measurements and fault orientations are used to create geologic cross sections of the range (Plate 2). Paleostress estimates from measured fault lineations are used to estimate the conditions during transpressional uplift within the mountain system.

The entire mountain range is also an ongoing project for Chico State students and faculty. Several studies are currently being conducted to understand local stratigraphy and structure as well as map the entire Coyote Mountains at a scale of 1:6,000. A complete map of the range will help confirm or deny predictions for mountain processes predicted in this study.

Limitations

Certain characteristics of the mountain range hinder the goal of discerning the complete geologic history of the area. The pre-Tertiary basement geology is a convoluted mix of Paleozoic metasedimentary rocks intruded by Jurassic plutons rich in metamorphic inclusions (Hill, 1984). With vast exposures in the study area, the crystalline core of the Coyote Mountains provided the substrate for Tertiary sedimentation. However, only major faults in the region visibly disrupt the basement complex. Smaller-scale faults do not show displacement in the basement material and can only be interpreted from the limited exposures in the Tertiary sedimentary sequence. Furthermore, similar faults that were once located within the eroded sedimentary units have been lost. This has limited the amount of measurable fault traces in the area and may affect the overall interpretation for mountain development.

Quaternary alluvial units cover a significant portion of the Coyote Mountains' structure. This is true primarily along the crest of the range and mountain fronts. While the units are important in understanding the region's geologic history, the alluvial cover prevents measurement and mapping of the underlying faults and stratigraphy. Bedding attitudes and fault orientations obscured by the young conglomerates must be inferred from the surrounding geology. The depositional contacts between Quaternary alluvial units and older Tertiary deposits of the Salton Trough will be useful in determining the specific geologic history for the study region.

Finally, due to the size of the Coyote Mountains, only the central portion of the range was mapped for the structural study. Geologic observations from the north-south transect reveal variations dependent on proximity to the Elsinore Fault. However, geologic units deposited in the asymmetrical Salton Trough typically vary laterally from west to east depending on the distance from the aforementioned detachment fault. Because the north-south transect is near parallel to the ancient trace of the west Salton detachment fault, unit characteristics change little within the mapping region. Similar sedimentary horizons in adjacent basins and mountains described in other studies may vary from units found in the central Coyote Mountains due to their location during basin development.

CHAPTER II

LITERATURE REVIEW

The earliest studies of the Salton Trough began with the discovery of marine fossil beds in the region. Paleontologists described local stratigraphy and created a basic nomenclature for the geologic units (Mendenhall, 1910; Kew, 1914; Hanna, 1926; Woodring, 1932). Mapping was not performed in great detail until accurate topographic maps were created in the late 1940s and early 1950s.

Dibblee (1954) created the first geologic map of the Salton Trough at the scale of 1:380,000 and standardized the basic stratigraphy. Christensen (1957) mapped the eastern and central Coyote Mountains at a scale at 1:24,000 and drafted geologic cross sections of the range. Atwater's (1970) modeling of plate relationships and California tectonics redefined the understanding of the Gulf of California and Salton Trough. Based upon oceanic magnetic anomalies, Gulf of California spreading occurred as a manifestation of relative plate motions parallel to the San Andreas fault system between 6-4 Ma (Atwater, 1970). Woodard (1974), Kerr (1982), Winker (1987), and Winker and Kidwell (1996) further refined the nomenclature for the oceanic basin stratigraphy that is used in this study. More recent work in the Salton Trough has focused on the geologic history and synthesis of tectonics with regional stratigraphy (Dorsey, 2011).

This review will first introduce the major tectonic events that shaped the structural geology of the region. Secondly, the stratigraphic sequence observable in the western Salton Trough will be presented. Emphasis is placed on unit descriptions obtained from the central Coyote Mountains by Christensen (1957). However, some sedimentary characteristics are from thicker exposures in the adjacent Fish Creek-Vallecito Basin to the north of the Coyote Mountains. A brief history of each unit's nomenclature is presented to highlight the continually changing stratigraphic organization in the western Salton trough. The depositional environments for each unit in the region will also be included. Finally, previous structural information and interpretations of the Coyote Mountains will be introduced.

Regional Tectonics

The current structure of the Coyote Mountains was shaped by two major tectonic features in the region: the west Salton detachment fault and the Elsinore Fault. Displacement along these two faults led to the stratigraphic sequence and eventual uplift and deformation observed in the Coyote Mountains. A brief geologic history for each fault will be introduced. More information on the depositional environments for individual units will be presented in the stratigraphy section later in the Literature Review.

West Salton Detachment Fault

Prior to tectonic activation in southern California, a fluvial system flowing over the metamorphic basement complex dominated the regional environment (Dorsey, 2005). Relative motion between the Pacific Plate and North American Plate led to continental rifting and the eventual creation of the Gulf of California seaway (Atwater, 1970). Rifting was accommodated by an approximately 250 kilometer detachment system that extended south along what is now Baja California. The northernmost section of the rift system was named the “west Salton detachment fault” by Axen and Fletcher (1998). Oblique movement along the low-angle top-to-east fault from the late Miocene to the Pleistocene created the asymmetrical Salton Trough (Axen and Fletcher, 1998). Marine incursion of the Gulf of California occurred at 6.3 Ma due to tectonic subsidence from continued fault displacement. Transtensional movement and tectonic subsidence remained active despite the recession of the Gulf of California during the Pliocene from an influx of Colorado River deltaic sediments. Displacement along the west Salton detachment fault halted with the initiation of the Elsinore Fault. Measurable basin subsidence in the Salton Trough ended by 0.95 Ma (Dorsey et al., 2011).

Stratigraphic units found in the Coyote Mountains were deposited on the hanging wall of the detachment system. While extension of the hanging wall block is typically observed in orthogonal detachment systems, oblique rifting may have prevented disruption in the hanging wall block prior to inception of the Elsinore and San Jacinto Faults (Dorsey, 2005). If this is true, deformation observed in the sedimentary units post-dated continental rifting.

<u>Elsinore Fault</u>

Transtensional oblique faulting of the west Salton detachment fault ended at ~1 Ma with the initiation of the Elsinore Fault (Johnson et al., 1983). The timing and mechanisms for the tectonic transition are poorly understood as dextral displacement may have overlapped with the end of detachment faulting. The Elsinore Fault is one of the three major faults in the southern California San Andreas fault system along with the San Andreas Fault and the San Jacinto Fault. The relative initiation ages between the three major strike-slip faults are unclear. Elsinore Fault scarps found in young alluvial fan deposits at the basin margins are dated as Middle to Late Quaternary (Dorsey et al., 2011).

As part of the San Andreas fault system, dextral motion is well documented along the Elsinore Fault. A recent study has determined displacement to be within 1.6 +/- 0.4 mm/year over the past 40,000 years based upon offset in alluvial fans along the southern edge of the Coyote Mountains (Fletcher, 2011). Overall, dextral displacement was estimated at approximately 7 km based upon rotation measured in the Fish Creek-Vallecito basin (Johnson et al., 1983). This estimate is problematic as rotational magnitudes have varied between studies of the region. The displacement rate along the Elsinore Fault may have also varied over time.

Vertical displacement was not consistent along the strike of the Elsinore Fault. To the northwest of the study region, the Elsinore Fault exhibited zero uplift since 1.1 Ma along the edge of the Fish Creek-Vallecito basin (Dorsey et al., 2011). To the southeast, a change in strike direction created a transpressional bend and uplifted the Coyote Mountains (Marshall et al., 2006). Channelized erosion within the range during uplift exposed the geologic stratigraphy observed in the range (Christensen, 1957).

Activation of the dextral Elsinore Fault introduced shear-strain to the western Salton Trough (Dorsey et al., 2011). Clockwise rotation from wrench tectonism was first measured at approximately 35° based upon paleocurrent interpretations in the stratigraphy (Johnson et at. 1983). Originally believed to have been completely post-depositional, new paleomagnetic studies suggest about 24° of rotation during Palm Spring Group emplacement between 4.0 and 2.5 Ma (Housen et al., 2005).

Torsion from the strike-slip system initiated a new stress regime in the region. Christensen (1957) described north-south compression and east-west tension from the Elsinore Fault as the major factors in Salton Trough deformation based upon his field mapping. North-south compression created east-west trending folds in the Tertiary sedimentary units (Sylvester and Smith, 1976). Later studies describe antithetical faults striking to the northeast-southwest in the adjacent Fish Creek-Vallecito basin related to the dextral Elsinore Fault (Winker, 1987). The idealized strain ellipse for pure dextral displacement predicts synthetic and antithetical fault orientations observed near the Elsinore Fault as well as compression and tension axes within the system (Figure 3). The effects of torsional stress in the Coyote Mountains will be described in greater detail in the Structure section below.

Stratigraphy

The stratigraphic nomenclature of the Salton Trough is complex and convoluted. Differing labels and subunit additions have led to a lack of standardization between studies (Figure 4). Difficulties arise from lateral facies changes within individual sedimentary strata throughout the Salton Trough. Thickness measurements for units are also problematic as they differ greatly within the region. The total thickness of the stratigraphic section is estimated at ~5.5 kilometers after decompaction, which is derived from studies of the Fish Creek-Vallecito basin (Dorsey, 2011). This estimate, however, excludes the older units of the Red Rock and Alverson Formations that do not outcrop in the adjacent basin.

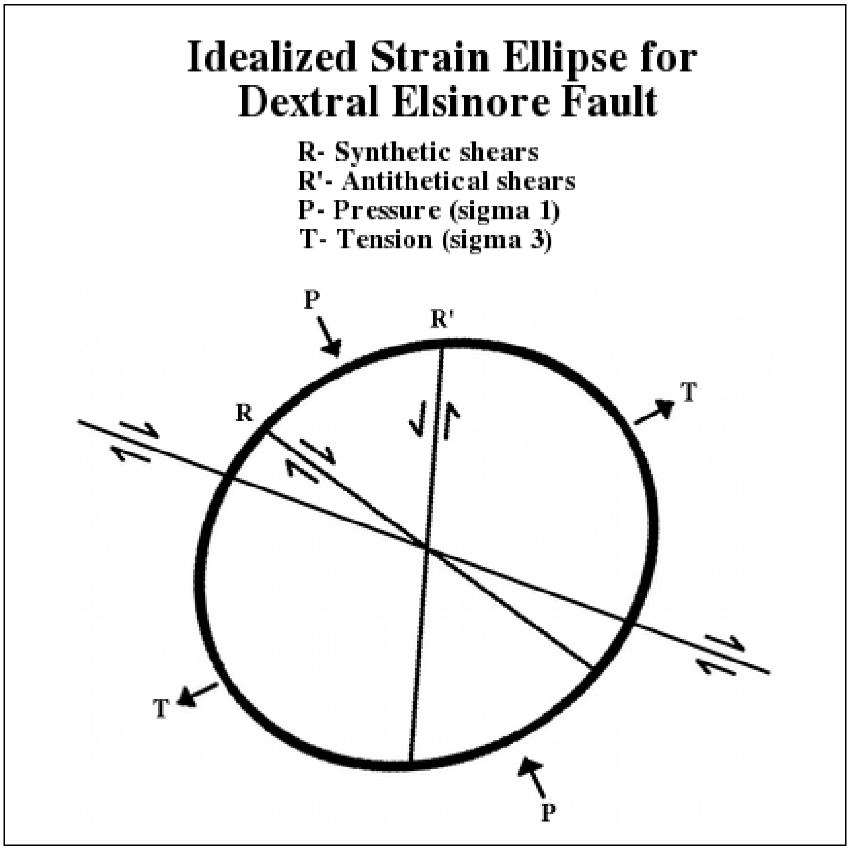

Figure 3. Idealized strain ellipse for the dextral Elsinore Fault.

The stratigraphic organization in this study is based on Winker and Kidwell's (1996) work on the western Salton Trough. Traditional formations from older studies were promoted to groups to allow more diversity in the stratigraphy. Because of the size of the Salton Trough, certain formations and members of Winker and Kidwell's stratigraphic sequence are not deposited in the Coyote Mountains mapping region and therefore are not included in this study. The specific nomenclature used in the mapping project will be presented in the Results section.

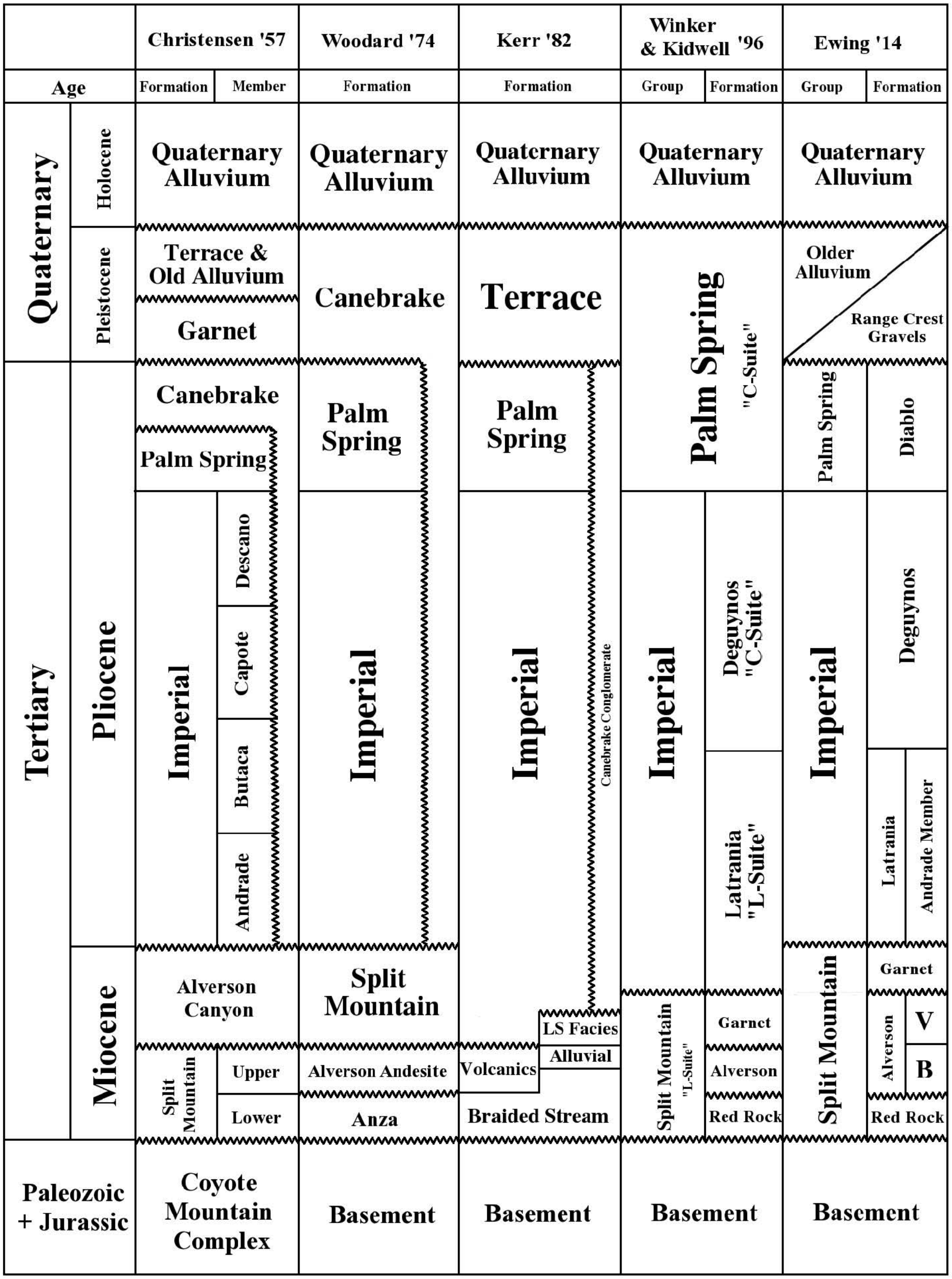

Figure 4. Comparative stratigraphic sections for the Coyote Mountains and adjacent Fish Creek-Vallecito Basin.

Basement

The basement is composed of metamorphic and igneous rocks that provided the substrate for Tertiary sedimentation and volcanism. Christensen (1957) named the group of interlayered schist, marble, and pegmatite as the Coyote Mountain Complex. Schist varieties within the unit include most commonly mica schists with occasional outcrops of quartzo-feldspathic schists. Locally, talc schist containing chlorite is found with a bright green color. Interbedded marble units are more erosion resistant and are found in thicknesses between 5-200 feet. Pegmatite dikes are found within the mountain system and the granitoid masses contain abundant black tourmaline crystals (Christensen, 1957).

Without accurate radiometric dating, differentiation of the basement was not possible until further research was performed. Todd (2004) correlated the basement geology with radiometrically-aged rocks of the Peninsular Ranges. The basement complex was separated into two units: the Paleozoic metasedimentary rocks (P_zm) and the migmatitic schist and gneiss of Stephenson Peak (Jsp).

The Paleozoic rocks (P_zm) are metamorphosed miogeoclinal sedimentary units from an ancient passive margin (Hill, 1984). An estimated 570-meter thick section of layered metasedimentary marble, schist, and quartzite is found in the eastern portion of the Coyote Mountains (Todd, 2004). Marble subunits have been found to contain conodont fossils aged to the Lower Ordovician (Dockum, 1982).

Jurassic basement rock (Jsp) is more common in the central Coyote Mountains. Classified as migmatitic schist and gneiss, the tectonically foliated Jurassic-aged granitoid unit cooled from a partial melt of metasedimentary rocks (Todd, 2004).

Outcrops of quartzite, marble, and amphibolite are also observed within the Jurassic unit (Todd, 2004).

Split Mountain Group

Red Rock Formation. The oldest unit deposited on the basement is the Red Rock Formation. Originally named the Anza Formation by Woodard (1974), the Red Rock formation is the basal unit of the Split Mountain Group. The Split Mountain Group was named by Tarbet and Holman (1944) and only included the conglomerates of the current Red Rock Formation. Christensen (1957) separated the conglomerates into an upper and lower member. Named after the large exposures in Red Rock Canyon in the southwestern Fish Creek Mountains by Kerr (1984), the unit varies dramatically by locality and is found to be 540 meters thick at its maximum(Todd, 2004). The Red Rock Formation is typically preserved in areas capped by the younger and partially contemporaneous Alverson basalt. This interbedded relationship with the Alverson Formation places the youngest deposits of the unit at 17 Ma (Morgan et al., 2012)

In the Coyote Mountains, Christensen (1957) described the lower member of the Red Rock Formation as a coarse-grained to very-coarse grained, granule to cobble conglomerate. The obscurely bedded to massive unit is deposited as a buttress unconformity on the crystalline basement. The white to cream-colored conglomerate is composed of a gritty arkosic arenite matrix with metamorphic and plutonic clasts.

The more resistant upper member is found above a gradational contact with the basal member (Christensen, 1957). According to Christensen, the thickness ranges from less than one foot to 15 feet and is distinguished by a reddish color and a higher percentage of plutonic rock clasts. The top of the member is described as a volcanic flow surface and is slightly metamorphosed from the deposition of the overlying Alverson Basalt member (Christensen, 1957).

The Red Rock Formation is composed of fluvial and eolian sediments of a braided stream environment deposited on eroded basement paleotopography (Winker and Kidwell, 1996). Kerr (1984) interpreted the basal member of the Split Mountain Group as evidence for tectonic initiation in the Gulf of California region. However, the Red Rock Formation may predate extension as suggested by measured paleoflow directions, which are parallel to the eventual fault trace of the detachment system (Winker and Kidwell, 1996).

Winker (1987) classified the Red Rock as the beginning of “L”-suite or “local” set of sedimentary units. The “L”-suite is composed of coarse-grained arkosic sandstones and conglomerates derived from local basement sources. Christensen (1957) hypothesized the provenance of the unit to be from the Southern California batholith to the west based upon the large percentage of igneous clasts within the conglomerate.

Alverson Formation. Deposited on the Red Rock Formation are the basalts, andesites, tuffs, and volcaniclastics of the Alverson Formation. Originally named by Diblee (1954) as the Alverson andesite, the formation consists of 120 meters of volcanic material (Todd, 2004). Recent U-Pb dating in the Coyote Mountains has discovered the Alverson Formation to be 17 Ma in age (Morgan et al., 2012).

Christensen (1957) described the lava flows in the Coyote Mountains as massive dark brown andesite with locally vesicular or scoriaceous texture that weather to a buff gray to purple color. Secondary minerals such as calcite, chlorite, and iron oxide are found locally in vesicles throughout the unit (Christensen, 1957). Winker and Kidwell

(1996) classified the basalts in the Coyote Mountains as an alkaline to tholeiitic basalt. While the chemical composition varies within the western Salton Trough, only basalt outcrops are found in the mapping region.

The volcaniclastic member of the Alverson Formation is interbedded with basalt flows throughout the Salton Trough (Todd, 2004). In the Coyote Mountains, Christensen (1957) described the volcaniclastic submember as a cream-colored tuffaceous conglomeratic wacke. The andesitic tuff matrix supports pebble to cobble subangular to angular clasts of basement and volcanic material. Individual deposits range from 4 to 6 meters but can be found upwards of 15 meters in the Salton Trough region (Todd, 2004).

Garnet Formation. The “Garnet Formation” is the original name given by Christensen (1957) to the poorly sorted angular boulder conglomerates commonly located along the crest of the Coyote Mountain range. Throughout future studies, however, the name was abandoned. The “Garnet” label reappeared in the study by Winker and Kidwell (1996) as the youngest member of the Split Mountain Group. The unit is mapped as the conformable conglomeratic unit below the Imperial Group. They correlated this alluvial unit with Christensen’s original conglomeratic unit at the crest of the Coyote Mountains and included both in the new Garnet Formation. Winker and Kidwell (1996) described the unit as a set of reddish-brown alluvial fan deposits, which grades laterally with the Imperial Group. Winker and Kidwell’s interpretation is problematic, and more information will be presented in the Andradé Member below. Christensen originally included Winker and Kidwell’s “Garnet conglomerates” at the base of the Imperial

Group. Therefore, Christensen's original descriptions for the unit will be included with the marine sandstones.

Deposition of the Garnet Formation occurred during the late Miocene to early Pliocene with the initiation of the west Salton detachment fault. Alluvial fan systems from the footwall of the detachment system deposited the conglomeratic unit to the early basin prior to marine incursion in the region (Winker and Kidwell, 1996). The proposed trace of the west Salton detachment fault is shown in Figure 5.

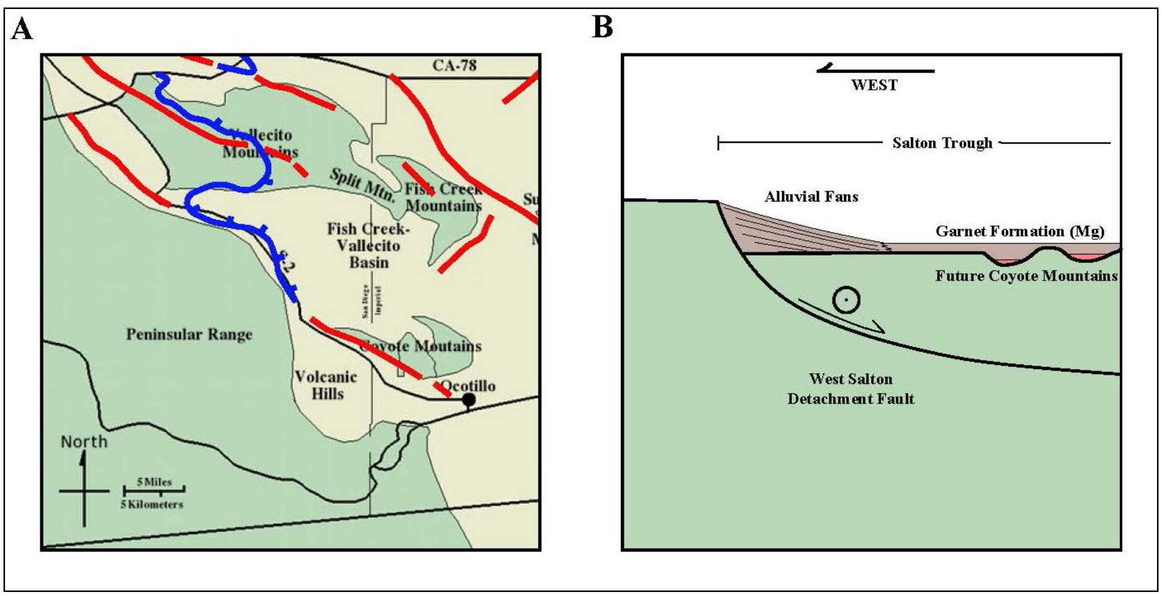

Figure 5. A. Current map view of west Salton detachment fault (Blue) and other major faults (Red); B. Schematic cross section of west Salton detachment fault during detachment.

Imperial Group

Latrania Formation: Andradé Member. The Andradé Member is the oldest unit of the Imperial Group found in the central Coyote Mountains. It is also the only member of Winker and Kidwell's (1996) Latrania Formation deposited in the mapping region. The Andradé Member was originally named by Christensen (1957) and included Winker and Kidwell's (1996) Garnet conglomerates described above. Composed of conglomerates and sandstones, Christensen separated the Andradé Member into three subunits: the volcanic conglomerate, the lower conglomerate, and the upper conglomerate. The volcanic conglomerate is not found in the study area and will be omitted from the stratigraphy.

Christensen (1957) described the lower conglomerate submember of the Andradé Member as a light reddish buff to dark red-brown massive unit with occasional faint bedding. The section contains poorly sorted pebble to cobble-sized volcanic, plutonic, and metamorphic clasts in a medium to fine-grained arkosic arenite matrix. The unit varies greatly in thickness and can be up to 125 feet thick. The lower conglomerates create a buttress unconformity when deposited on the basement complex, Red Rock Formation, or Alverson Formation.

Conformably deposited above the lower conglomerate is the upper conglomerate submember of the Andradé Member. Described by Christensen (1957) as a light buff fossiliferous conglomerate, the unit contains volcanic, metamorphic, and plutonic pebble to cobble-sized clasts. The matrix consists of arkosic arenite sand that varies slightly in composition throughout the range. The matrix content increases in percentage in the upper portion of the unit and is visible as thick buff to yellowish-buff sandstone beds. Fossilized corals, bivalves, gastropods, and mollusks are found in the sandy portion of the submember (Christensen, 1957).

Winker (1987) designated the conformable upper marine sandstone beds as the Latrania Member of the Imperial Formation. Winker and Kidwell (1996) promoted the Latrania Member to a formation and renamed the Coyote Mountain-specific fossiliferous sandstone beds as the Andradé Member.

The Andradé Member is the oldest marine unit deposited in the study region. Continued tectonic subsidence and crustal thinning from continued detachment faulting allowed for marine incursion at 6.3 Ma (Dorsey et al., 2011). Deposition of stratigraphically similar units throughout the length of the Gulf of California suggests a rapid marine introduction to the region as opposed to a slow, gradual flooding of the Salton Trough. Rapid oceanic transgression may have occurred from localization of plate motion in the Gulf of California around this time (Oskin and Stock, 2003). A global increase in ocean bathymetry may have also contributed to the rate of flooding within the narrow Salton Trough (Haq et al., 1987). The Andradé Member contains fossils consistent with shallow marine environments. Marine sandstones deposited directly on marble display pelecypod borings into the basement material (Watkins, 1990).

Deguyños Formation. The Deguyños Formation of the Imperial Group is a combination of Christensen's original Butaca, Capote, and Descano Members of the upper Imperial Group (1957). Described as yellowish gray feldspathic siltstones and claystones, the Butaca Member is conformably deposited above the Andradé sandstones and weather to yellow and greenish-yellow. The Capote Member is similar to the Butaca unit but contains coarser feldspathic siltsone and arenite beds. Each arenite section is capped by a reworked coquina or organic reef bed that can be up to six feet thick and create large dip slopes on the northern side of the range (Christensen, 1957). The Descano Member is conformable with the Capote Member and marks the transition zone between the marine deltaic sequence with the non-marine fluvial units of the Palm Spring

Group. The member is composed of thin, friable buff sandstone beds that are less resistant and less fossiliferous than earlier members of the Imperial Group.

Woodard (1967) consolidated the upper portion of Christensen's Imperial Formation into the all-inclusive Deguyños Member. With the promotion of the Imperial Group by Winker and Kidwell (1996), the Deguyños label described the entire marine section above the Andradé sandstones.

The Deguyños mudstones represent the distal prodelta of the Colorado River, which entered the region in the Pliocene (Winker, 1987). Winker classified the deltaic and fluvial sediments of the upper Imperial and Palm Spring Groups as the "C"-suite or "Colorado"-suite of sedimentary units. The "C"-suite is characterized by well-sorted fine-grained quartzose sediments eroded from the Colorado Plateau. Turbidity currents filled the narrow Imperial seaway with rhythmic siltstones and mudstones (Winker and Kidwell 1996). Continued sedimentation from the prograding delta system shallowed the marine basin despite an increase in tectonic subsidence (Dorsey et al., 2011). Sediment sizes in the Deguyños Formation coarsen upwards as the prodelta transitioned to the delta front. Fossil beds stratigraphically higher in the section are consistent with intertidal and brackish environments (Woodard, 1974).

<u>Palm Spring Group</u>

<u>Diablo Formation</u>. Woodring (1932) named the nonmarine units above the Imperial Formation as the Palm Spring Formation. Woodard (1963) studied in detail the 3,000 meters of Palm Spring Formation stratigraphy and separated the section into four members. The thickest, basal unit of the formation was named the Diablo Member. Christensen (1957) described the Palm Spring Group along the southern flank of the

Coyote Mountains as a conformable and gradational deposit of tan to brick-red sandstones and claystones. Winker (1987) further described the Diablo Formation as a pale orange to reddish brown friable sandstone. The very fine to fine grained unit is moderately well to well sorted of subrounded quartz grains (Winker, 1987). The Diablo Formation is the only member of the Palm Spring Group that was previously mapped in the study region.

Marine deltaic units grade upwards to the nonmarine fluvial units of the Colorado River. The transition is marked by the contact between the Deguyños Formation of the Imperial Group and the Diablo Formation of the Palm Spring Group. The fine-grained quartzose sandstones were deposited in the Salton Trough region at 4.25 Ma in the Pliocene (Dorsey et al., 2011). Upward fining cycles in the mature sandstone is consistent with meandering fluvial systems (Winker, 1987). Tectonic subsidence continued in the region, but the influx of the Colorado River-derived Diablo Formation filled the basin until 2.8 Ma and led to ocean regression.

Pleistocene/Quaternary Units

High-Elevation Alluvial Gravels. Several younger alluvial units have been described by previous studies throughout the Salton Trough. The unconsolidated units are difficult to differentiate and are typically categorized by location and elevation. Older alluvial units previously mapped in the Coyote Mountains will be described below with their previous unit labels. The alluvial nomenclature used in this study will be introduced in the Results section.

As stated earlier, the alluvial units found along the crest of the Coyote Mountains were originally named the “Garnet Formation” by Christensen (1957). The high elevation alluvial unit is comprised of buff to brown sandstones and pebble to cobble conglomerates with basement-derived metamorphic clasts. Ranging in thickness from one foot to sixty feet, it is differentiated from other alluvial units in the region by its lack of desert patina (Christensen, 1957). While the capping conglomerates are found in small deposits locally, Christensen estimated that they once covered about nine square miles in the region.

On the flanks of the range, Christensen (1957) described another alluvial unit as pebble to cobble brown to buff conglomerate with a poorly sorted arkosic arenite matrix. The unconsolidated sands, silts, and gravels have not been uplifted to the extent of the Christensen's Garnet Formation and can be found cut by mountain drainages containing modern alluvium (Todd, 2004). The unit is covered by a well-developed layer of desert pavement (Christensen, 1957). The unit contains metamorphic, igneous, volcanic, and fossil fragments from older units in the Coyote Mountains (Christensen, 1957). The poorly consolidated unit is typically considered age-equivalent with the Quaternary alluvial conglomerates covering the Fish Creek-Vallecito basin and has been named the terrace conglomerates because it is found up to 75-300 meters higher in elevation (Todd, 2004).

Deposition of the alluvial units marked the end of "C"-suite sedimentation as the Colorado River delta system prograded out of the region. Quaternary alluvial fan units found in the Coyote Mountains and Fish Creek-Vallecito basin were derived from local high points in the region (Todd, 2004). The provenance for Christensen's Garnet Formation at the crest of the range is believed to be fanglomerates from the ancestral Coyote Mountains during rapid uplift in the Pleistocene (Christensen, 1957; Woodard, 1963). This is evidenced by the lack of desert patina on the capping member of the range (Christensen, 1957). A less arid climate of the Salton Trough region in the Pleistocene prevented the formation of desert varnish on the older alluvial unit. The terrace alluvium deposits on the northern and southern flanks of the range are believed to be alluvial plain deposits derived from a more mature mountain system (Christensen, 1957).

Canebrake Conglomerate. The Canebrake conglomerate unit was used to describe margin conglomerates prior to recognition of the detachment system. Coeval deposition of the Canebrake conglomerate is found along the western margin of the Salton Trough and interfingers with Imperial and Palm Spring Formations (Winker, 1987). While not used to describe units in this study, Christensen (1957) mapped a sliver of the Canebrake conglomerate south of the Elsinore Fault and classified the exposure as a conglomeratic arkosic arenite (Christensen, 1957). Fossil fragments present in the conglomerate create serrated ridges to the west Fossil Canyon. This anomalous outcrop will be discussed later in the study.

Structure

The structure of the Coyote Mountains was originally interpreted as a large-scale anticline by Dibble (1954) based upon the sedimentary dip directions to the north and south of the range. Christensen (1957) believed the reversals in bedding orientations were the result of drag folding from displacement along the northwest trending Elsinore Fault. Cross sections drafted of the mountains reveal large east-west trending synclines in the basin deposits to the north and south of the range. Christensen hypothesized that the syncline in the north basin was formed from northeast tilting of the Coyote Mountain complex in the mountain block. Resilient units of the lower Imperial Formation responded rigidly to translation whereas less indurated mudstones and siltstones of the Colorado River prodelta were more pliable during deformation. In the desert basin to the south of the range, uplift along the Elsinore Fault created a large-scale feature named the Ocotillo Syncline. This structure is partially hypothetical and is based on southwest dipping units adjacent to the range and northwest dipping Alverson deposits across the desert valley (Christensen, 1957).

While bedding attitudes and fault orientations mapped in previous studies are observable in outcrop, the thicknesses of the stratigraphic sequence are purely hypothetical due to the uncertain basement profile prior to deposition (Christensen, 1957). An accurate basement paleotopography is unattainable under the sedimentary cover without more advanced techniques. Estimations of the basement structure in Christensen's cross sections are based upon unit thicknesses elsewhere in the region.

Christensen (1957) interpreted the faults within the Coyote Mountains as a small-scale reflection of regional stresses in the Salton Trough. The fault array was the result of clockwise torsional stress from dextral displacement along the Elsinore Fault. Tension and compression stress vectors were derived from fault orientations to create a regional right lateral deformation ellipsoid included in Christensen's research. The deformational ellipsoid included the north-south compression and east-west tension typical of a pure dextral fault system mentioned earlier.

Within the mountain block, Christensen described two faults that do not fit the torsional model for mountain deformation. He mapped a northwest-southeast and a west-east striking faults to the south of Red Rock Formation in West Canyon and the Alverson deposits in northern Fossil Canyon, respectively. Described as pre-Imperial deformation, the faults are mapped due to the truncation of the southward dipping conglomeratic and volcanic homocline against the basement complex to the south (Christensen, 1957). Christensen proposed that the marine strata of the Imperial Group have since buried the older faults and older stratigraphic sequence. His cross sections display the faults as vertical structures and are mapped as linear contacts striking through the Coyote Mountains. The existence of the faults is disputed by this mapping project and will be discussed later in the study.

Although faults and folds are easily visible in the Tertiary sedimentary and volcanic units, deformation in the basement complex is not as well understood. Basement exposures lacked the depth required for plastic deformation of the metamorphic complex at the time of Cenozoic deformation (Sylvester and Smith, 1976). It is hypothesized that cataclasis occurred within the rigid mountain block and allowed for ductile deformation in the younger sedimentary units.

Other interpretations for mountain block deformation are found in more recent literature of the region. A paleomagnetic study by Marshall et al. (2006) presented a wide range of rotational values between outcrops of the Alverson basalt throughout the mountain range. To accommodate the variable amounts of torsion in the system, it was hypothesized that the basement complex was fractured into small tectonic blocks. Independent rotation of the basement blocks allowed for translation and tilting of the sedimentary deposits without large-scale ductile deformation of the mountain system. Increased compressional stresses with proximity to the Elsinore Fault uplifted the mountain block to higher elevations than the basin sediments of the north basin (Marshall, 2006).

CHAPTER III

METHODOLOGY

The first task in the structural study was selecting the mapping area in the Coyote Mountains. Taking previous work into consideration, the central section of the range was chosen due to excellent exposure of geologic units and reliable access during winter months. Mapping scales differ greatly between previous studies, and none are more detailed than a 1:24,000 scale. The map created for this study, at a scale of 1:6,000, allows for more detail on individual outcrops and faults than maps for larger, regional stratigraphic or tectonic studies.

Reliable access points to the mountain range allowed for a large area to be mapped and studied on foot. Stratigraphic units from all stages of mountain development are found within the study region. Field measurements of fault planes and bedding orientations were used to determine the structure of the range as well as estimate the mechanism and stresses involved in mountain formation. Determining the timing and nature of deformation will aid in the creation of a specific geologic history for the central Coyote Mountains.

Aerial photos of the field area were acquired from Google Earth Pro for mapping purposes. Approximate one-kilometer-wide sections were printed and laminated. Eight weeks of field mapping were completed in seven trips to the Coyote Mountains. With three different access points on the southern flank of the range, the entire field area was reached through major canyons and drainages. Geologic mapping of unit contacts and faults was recorded on the aerial photos. Strikes and dips of bedding and fault planes were measured using a Brunton compass. The rakes of slickensides on fault surfaces were measured using a standard protractor. Photos of important outcrops, structures, and large-scale features were taken with a camera for review and inclusion in the study. GPS locations were recorded for all measurements and photograph sites to be included in the final map. Samples of each stratigraphic unit were collected for geologic description and interpretation.

After data acquisition in the field, geologic mapping was digitalized using ArcMap 9 and 10. Elevation contours were superimposed to the map and the aerial photos were removed. A printed "working" version of the map was used to draft structural cross sections of the mapping region. Cross sections were originally created on graph paper. Bedding and fault measurements from field mapping were extrapolated and used to estimate the subsurface structure. The cross sections were then scanned to a computer and digitalized using Adobe Illustrator and the freeware GNU Image Manipulation program.

Other figures, such as the stratigraphic columns and schematic drawings, were created using a similar hand-drawn technique. Original drafts were created on paper before being scanned and digitalized using the GNU Image Manipulation program. The smaller location maps were drafted over screenshots from Google Earth Pro to maintain proper scale within the region.

Stereonet projections of faults and sedimentary beds were created using Rick Allmendinger's freeware programs for fault and bedding analysis. The program Stereonet

7 was used to plot bedding in the west mountain front. Structural geology techniques were used to determine the geometry of the fold. Other stereonet projections for fault planes and primary stresses were created using the freeware program FaultKin 5. Measured faulting and displacement orientations were plotted onto a stereonet to show the preferred orientations in the study area.

The primary stress orientations for the mountain system were determined using the program’s kinematic tensor axes calculation. Using the right dihedra method for fault analysis, a fault plane solution for the pressure and tension quadrants based upon field measurements was included on the stereonet projection. Five measured fault planes with displacement lineations were used to determine the paleostress orientations. The lineations for a sixth fault plane were estimated from visible offset in outcrops. Smaller faults without accurate displacement vectors were not included. Assuming orthogonal motion along several smaller-scale faults would greatly skew results for the primary stress orientations. Further explanation for the kinematic tensor axes is included in the Results section of the study.

CHAPTER IV

RESULTS

The Results section will present the data collected from the field. First, the stratigraphic organization of the central Coyote Mountains used in this study will be introduced and described for unit characteristics and distributions in the region (Plate 1). Next, the faults mapped will be discussed for physical orientations and displacement magnitudes. A stereonet projection of the fault array will be presented along with an associate stereonet projection for paleostress estimates based upon the field measurements. Similarly, orientations for stratigraphic bedding will be introduced and plotted to visualize trends and folds within the study region. Finally, geologic cross sections of the mountain range will be presented and described based upon the observations and measurements.

Stratigraphy

The columnar representation of the stratigraphic sequence in this study portrays the unit relationships observed in the central Coyote Mountains (Figure 6). The nomenclature for the sequence is based upon recent research of the Coyote Mountains and Salton Trough. Primarily using unit labels from Winker and Kidwell (1996), the overall stratigraphy has been simplified from the regional depositional study of the western Salton Trough to only include units deposited in the mapping area. The Split

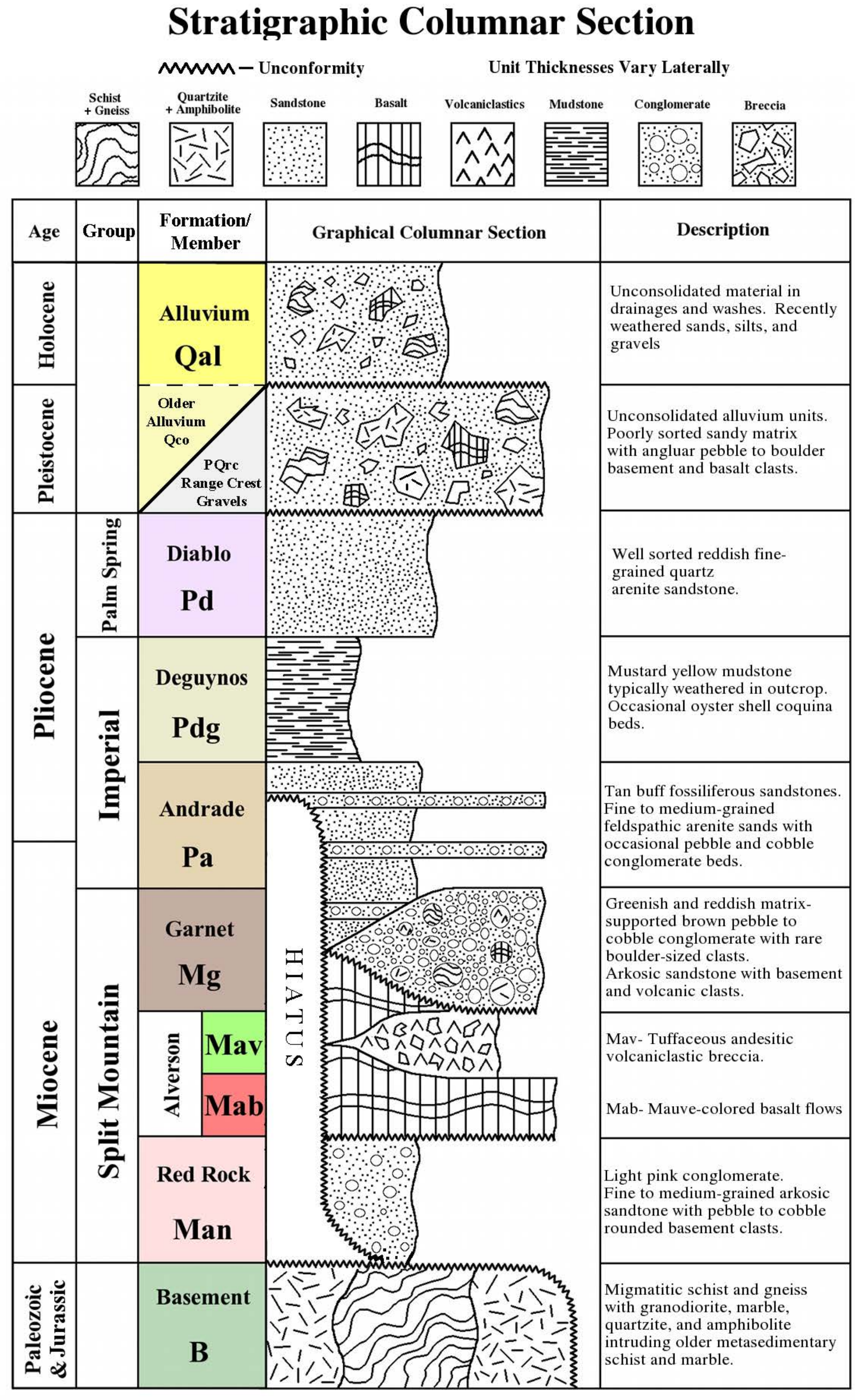

Figure 6. Stratigraphic columnar section of the central Coyote Mountains.

Mountain and Imperial Groups within the Coyote Mountains lack the lateral diversity observed in the larger basins. Several units and members found within the Fish Creek-Vallecito basin and surrounding mountains have been omitted because they do not crop out within the mapping region. Differences in stratigraphic interpretations between this study and previous works will be presented as well as new unit additions later in the Discussion section.

Thickness measurements are problematic in the study region and will not be included in stratigraphic descriptions. In the mountain block, the discontinuous outcrops typically lack distinct lower or upper contacts due to erosion or burial under Quaternary alluvial units. Estimates are also difficult due to the rarity of bedding orientations in the highly weathered and faulted sedimentary units. Noticeable variances in thicknesses within the mapping region will be noted.

Basement (B)

The erosion-resistant basement complex creates the core of the Coyote Mountains. Although the basement material is composed of Paleozoic and Jurassic units, this study does not differentiate between the two age groups. A sliver of the banded Paleozoic metasedimentary rocks can be found to the north and northeast of Fossil Canyon (Figure 7). Basement exposures in the rest of the mapping region are composed of the younger Jurassic schist, amphibolite, granodiorite, quartzite, and marble. Schist and granodiorite units comprise the largest exposures and create the majority of depositional contacts with the younger stratigraphic units. Quartzite and marble units are less extensive and can be found in 5-10 foot thick linear structures typically exposed in high angle or near vertical orientations. The steeply dipping “beds” compose many of the

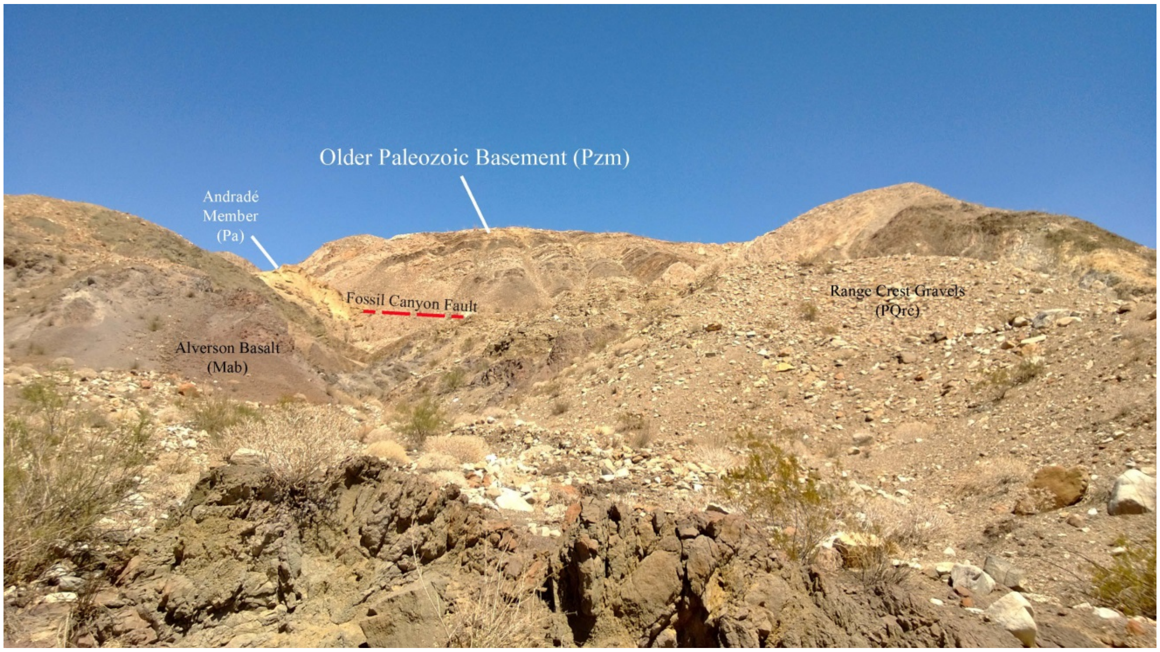

Figure 7. Banded Paleozoic metasedimentary basement (Pzm) on the eastern ridge of Fossil Canyon with outcrops of Alverson Basalt and Range Crest gravels in the foreground.

high elevation ridges and create dry waterfalls in mountain drainages (Figure 8). Larger exposures of the quartzite and marble units are visible in the mountain block, but do not create distinct linear features as in the thinner structures.

The basement complex is primarily observed in the mountain block. Basement units can also be found in the north basin along fault escarpments. Sedimentary and volcanic units of the sedimentary sequence are deposited as a nonconformity; however, the oldest formation of the Split Mountain Group are not exposed in the north basin.

<u>Split Mountain Group</u>

<u>Red Rock Formation (Man).</u> The basal member of the Split Mountain Formation is a matrix-supported conglomerate with a whitish-pink color composed of fine to medium-grained arkosic sand grains. The matrix is poorly sorted, and outcrops are

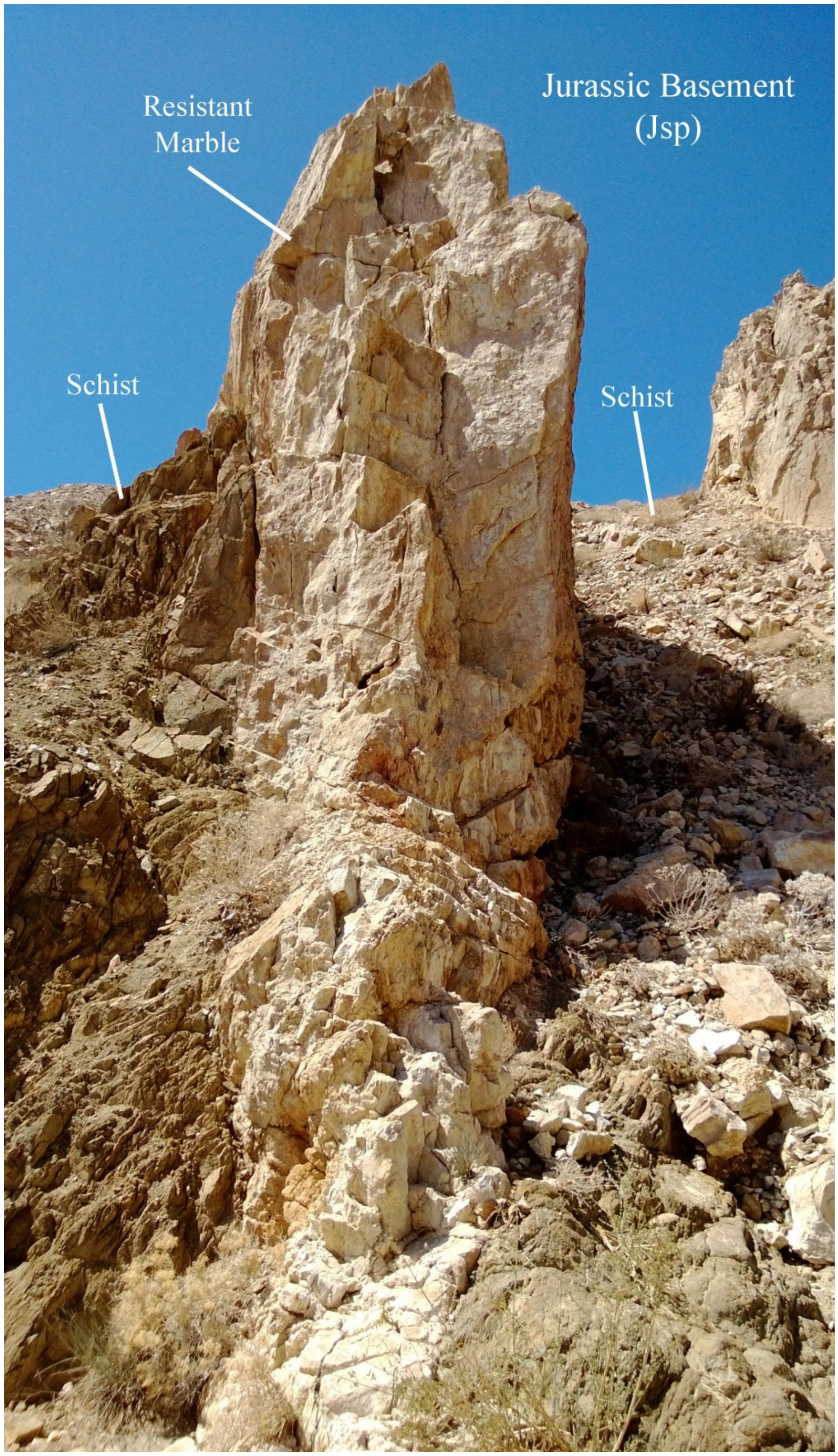

Figure 8. Jurassic basement (Jsp) - Resistant marble “beds” between eroded schist in northern Fossil Canyon.

typically found massively bedded. Linear clast structures may suggest faint bedding with possible imbrication. The steeply dipping depositional structures may represent an angular discordance with younger units of the Split Mountain Formation described later. The conglomerate contains pebble to cobble clasts of rounded to subrounded basement material. Rarely, larger boulder clasts are present within the unit. Clasts include marble, diorite, quartzite, and schist. As the oldest sedimentary unit in the region, the Red Rock Formation is always deposited as a nonconformity on the basement. The conglomerates are interpreted as fluvial or braided stream environments described by Dorsey (2005).

Within the mapping region, the Red Rock Formation is exposed exclusively in the mountain block with the thickest deposits located in West Canyon (Figure 9). The east-west trending unit is located between steep basement escarpments to the north and the south and taper out to the west approximately 3,000 feet from Fossil Canyon. The drainage in West Canyon bisects the conglomeratic unit and exposes the stratigraphy on the southern edge of the channel. The conglomerates appear to have a depositional contact with the steep basement escarpments as evidenced by a lack of fault displacement or gouge. Rather, the thick conglomerates in West Canyon are deposited as a buttress unconformity against the steep basement escarpments. The Red Rock Formation is also capped by the younger and more erosion-resistant Alverson basalt to the east.

Another deposit of the Red Rock Formation is found further north in Fossil Canyon. The whitish-pink conglomerates are highly weathered in outcrop and show no signs of bedding (Figure 10). A small deposit of the conglomerate is found in Fossil Canyon and extends to the west exposed along an east-west trending canyon. The unit is found in a similar east-west distribution as in West Canyon, but the conglomeratic

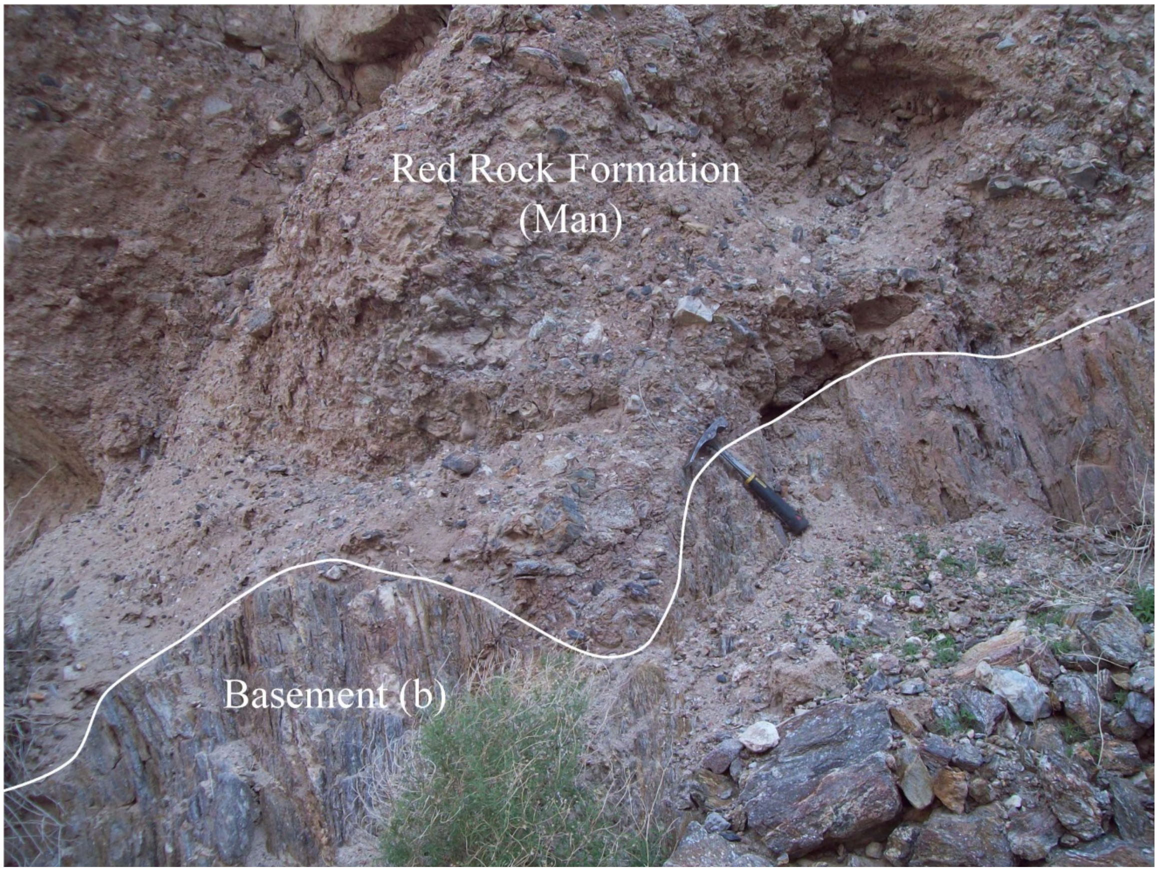

Figure 9. Red Rock Formation (Man) in West Canyon deposited as a nonconformity on the basement complex.

deposits are capped by the basalts to the south. Similarly, the Red Rock Formation in northern Fossil Canyon tapers out to the west.

Alverson Formation (Mab and Mav). In the central Coyote Mountains, the Alverson Formation is dominated by the dark reddish-brown to mauve-colored massive basalt (Mab). Sections of the basalt can be seen with a rough to vesicular texture. White diagenic minerals infill the vesicular texture and can be observed along sections in Fossil Canyon (Figure 11).

The Alverson Basalt is only exposed within the mountain block of the mapping region. As with the Red Rock Formation, the volcanic flows are observed in

Figure 10. Weathered Red Rock Formation (Man) in northern Fossil Canyon.

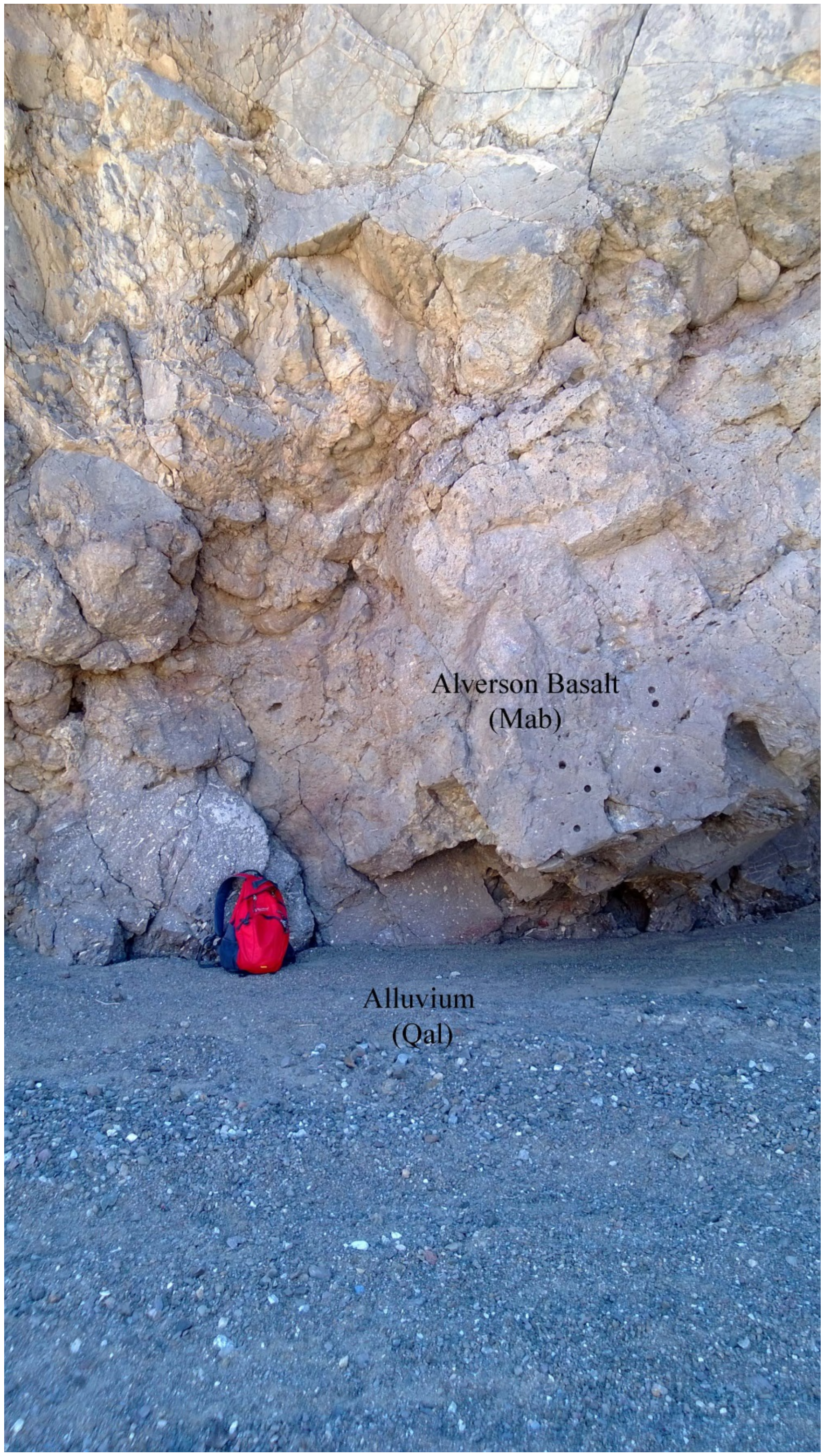

Figure 11. Alverson Basalt (Mab) in southern Fossil Canyon.

east-west trending deposits with depositional basement contacts to the north and south. To the east, the basalts are truncated by the Fossil Canyon Fault against a northwest trending basement escarpment. To the west, the deposits become thinner with distance from Fossil Canyon, and only two isolated exposures are observable to the west of Cahuilla Canyon. In West Canyon and Fossil Canyon, the Alverson Formation is deposited as an unconformable, capping unit on the Red Rock conglomerates and creates buttress unconformities with the metamorphic basement complex. Elsewhere, the basalts are typically deposited as a nonconformity directly on the basement. A north-south trending drainage to the east of Cahuilla Canyon slices through the basalt exposures and reveals the depositional contact. The buttress unconformities created on the southern contacts of the Alverson Formation were previously mapped as east-west trending faults by Christensen (1957) and Winker (1987) and will be discussed in greater detail later in the study.

The less extensive Alverson volcaniclastic submember (Mav) is also exposed in the mountain block (Figure 12). The tuffaceous volcaniclastic breccia is observed in 10-20 foot thick deposits in southern Fossil Canyon. The reddish tan to gray breccia is matrix-supported and contains subangular volcanic clasts. Clasts are typically pebble to cobble-sized and compose approximately 40% of the unit. Within the mapping area, the Alverson Volcaniclastics are conformably deposited above the basalt flows. In southern Fossil Canyon, the volcaniclastic submember is a continuous unit in the stratigraphic sequence. Further north in Fossil Canyon, however, the distribution is less extensive and

Figure 12. Alverson Volcaniclastics (Mav) in southern Fossil Canyon.

only seldom crops out above the basalt submember. The Alverson volcaniclastics are interpreted as reworked tuffaceous and volcanic material deposited during hiatuses of basalt flows in the region.

Garnet Formation (Mg). In the mountain block, the non-marine Garnet conglomerates unconformably overlie the Alverson Formation and the basement complex. Along the southern margin of the north basin, the Garnet Formation is only observed deposited as a nonconformity with the basement. Individual outcrops vary greatly in thickness throughout the mapping area. Although the conglomerates are mapped as a single unit in this study, the Garnet Member is differentiated into two lithologies based upon color, which are red and green. While stratigraphically similar, depositional characteristics are distinct between the two lithologies, and they typically occupy separate areas of the range.

The red Garnet conglomerates are primarily deposited on the northern side of the range and are exposed along the southern flank of the north basin (Figure 13). The reddish rust-colored pebble to cobble conglomerate is composed entirely of subangular to subrounded basement clasts. Supported by a coarse arkosic matrix, the massive red Garnet subunit does not possess bedding structures. The thickest section of the red Garnet subunit is found in the eastern section of the north basin at approximately 40 feet thick. Typically, the red conglomerates are found in discontinuous sections about two feet thick throughout the north basin. The red Garnet conglomerates are always found deposited as a nonconformity on the basement complex. The massively bedded and oxidized red Garnet Formation is interpreted as alluvial deposits derived from local basement irregularities.

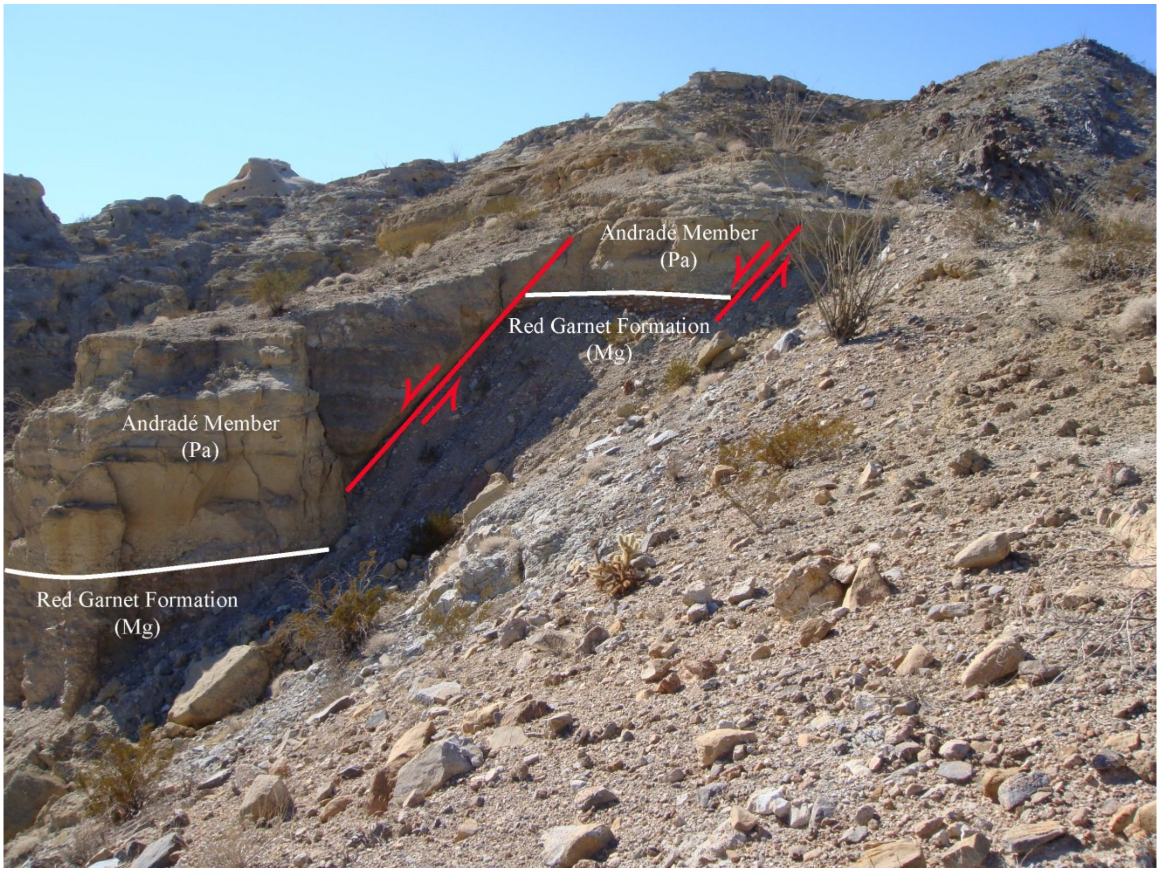

Figure 13. Deposits of the Red Garnet Formation (Mg) offset by normal faults in the north basin.

The green Garnet conglomerates are deposited within the mountain block and are exposed along Fossil Canyon and northern Cahuilla Canyon (Figure 14). The conglomerate consists of both basement and volcanic clasts and is generally a dark brown to brown color. The “green” label is given to the subunit due to the apparent greenish-gray hue when compared to the red Garnet conglomerates. Clasts are found predominately pebble to cobble-sized with rare boulder-sized clasts. Bedding can be determined through apparent dips of linear gravel and cobble beds within the unit. The poorly sorted arkosic matrix becomes more prevalent higher in the section towards the

Figure 14. Green Garnet Formation (Mg) in northern Cahuilla Canyon with Range Crest gravels (PQrc) in the foreground.

conformable contact with the Imperial Group. The green Garnet Formation is interpreted as alluvial deposits derived from the footwall of the west Salton detachment fault.

While the two variations are typically separated in the mapping region, a small isolated outcrop at the crest of the range may show a transition between the two lithologies within the Garnet Formation. Just north of the Central Mountain Fault, red Garnet conglomerates grade upwards into the typical green Garnet Formation of the mountain block. Angular, boulder-sized clasts of marble at the base of the outcrop transition to the smaller, more rounded clasts of the green subunit (Figure 15). The

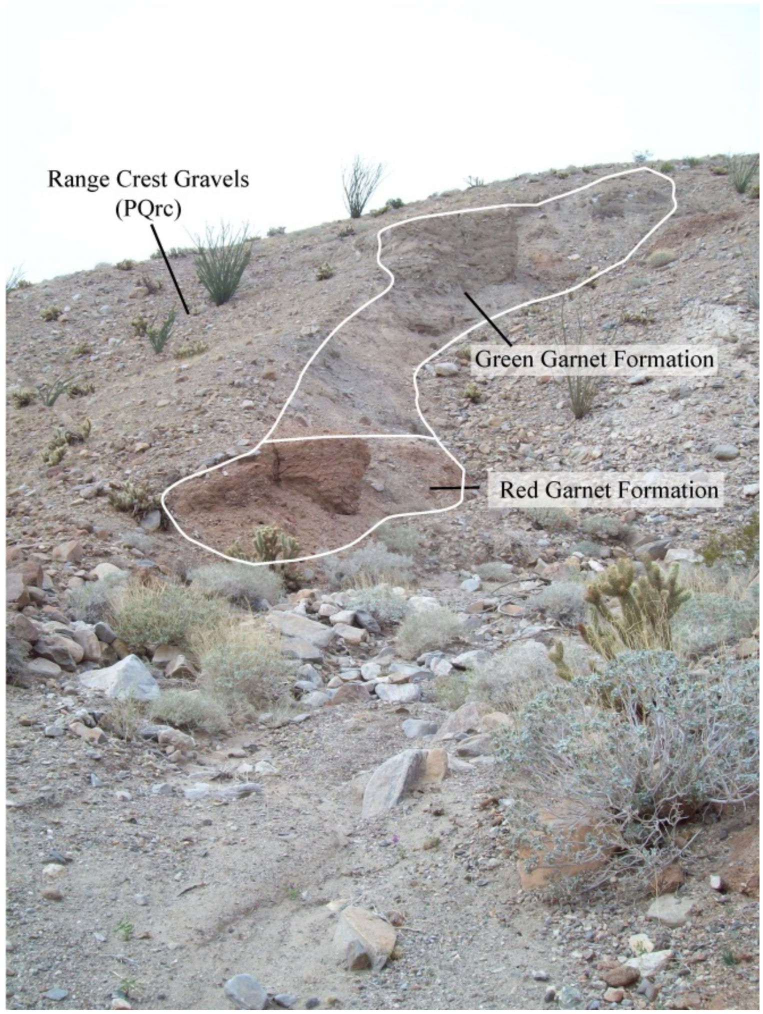

Figure 15. Transitional outcrop of red and green Garnet Conglomerates (Mg) at the range crest.

contact is also marked by the inclusion of plutonic and basalt clasts found throughout the mountain block.

In this location, Winker and Kidwell (1996) interpreted the Miocene conglomerates to be part of Christensen's (1957) original Garnet Formation from the Pleistocene. The green pre-marine variation of the conglomerates and the mountain-capping alluvial units look similar in this region but can be differentiated by the amount of cementation and induration. Winker and Kidwell's interpretation is problematic as it implies that both alluvial conglomerates in the central Coyote Mountains are laterally continuous with the Imperial Group. This study agrees with Christensen's original interpretation that the capping alluvial unit along the crest of the range is Pleistocene in age and post-date uplift and erosion of the younger stratigraphic sequence. However, the misinterpretation resulted in a fundamental change in the nomenclature. This study will retain the Garnet label from Winker and Kidwell's work in the Salton Trough to be consistent with recent studies in the region. The Miocene-aged conglomerates once included in Christensen's Imperial Formation and have now become a distinct pre-marine alluvial unit in the Split Mountain Group.

Imperial Group

Latrania Formation: Andradé Member (Ma). The Andradé sandstones are the only mappable member of Winker and Kidwell's (1996) Latrania Formation within the study region. The Latrania Formation is found throughout the Salton Trough and includes diverse members deposited during marine incursion in the Miocene. However, the asymmetrical Salton Trough allowed for lateral facies changes. Therefore, this study only includes the Coyote Mountain-specific Andradé Member within the stratigraphic sequence. The buff-tan to yellowish-tan feldspathic arenite sandstones are composed of fine to medium-sized sand grains (Figure 16). Pebble to cobble-sized clasts are visible in sedimentary layers near the base of the unit in Fossil Canyon and have a similar composition to the green Garnet conglomerates. The sandstones can be significantly weathered in outcrop and are easily friable. Other stratigraphic horizons are highly cemented and create dips slopes in the north basin. Fossiliferous zones are common and contain the remains of shallow marine bivalves, echinoderms, and gastropods. Large

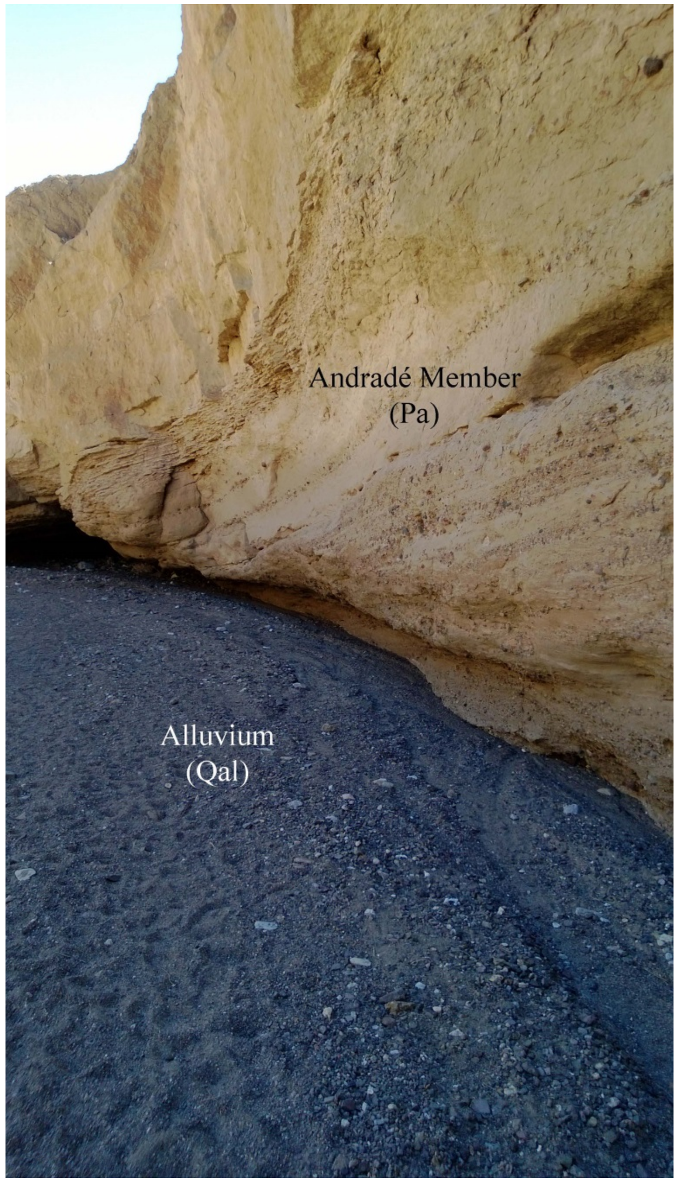

Figure 16. Andradé Member (Pa) in southern Fossil Canyon.

sections of the unit are immeasurable due to microfaulting and intensive weathering. The Andradé Member is interpreted as shallow marine sandstone in a near shore wave-dominated environment consistent with the elongate Gulf of California seaway.

The marine sandstones are found throughout the central Coyote Mountains and are deposited on the Garnet Formation, the Alverson Formation, and the basement complex. South of the Elsinore Fault, the uppermost section of the Andradé sandstone is truncated by the Elsinore Fault, and the sedimentary beds dip about 45° to the south. In the mountain block, the Andradé Member is exposed primarily in Fossil Canyon but is visible in an east-west trending distribution beneath the unconsolidated alluvial unit near the range crests. An isolated outcrop is deposited to the west of West Canyon on a flat bench within the typically steep basement escarpment.

In the north basin, the Andradé Member is deposited on the basement or red Garnet conglomerates. The deposits are found in large, continuous distributions than the channelized and highly eroded exposures in the mountain block. The sandstone beds create northeast-trending dip slopes in the region. Fossils beds within the Andradé Member are common in the north basin and create cliff forming strata within the sandstone sequence.

<u>Deguyños Formation (Pdg).</u> The Deguyños Formation is exposed in the central Coyote Mountains region as extremely weathered outcrops of dark mustard-yellow mudstone. Conformably deposited on the Andradé sandstones, precise unit contacts and bedding attitudes are typically obscured through erosion of the outermost surfaces. Unweathered mudstone is exposed along major drainages in the mountain block beneath the outermost weathered zone (Figure 17). The yellowish-gray mudstone appears massively bedded with a consistent fine grain size. Gypsum-filled fractures in the unweathered mudstone create a lattice-like pattern (Figure 18). Bedding can be inferred through large coquina beds within the Deguyños Formation. Typically 3 to 6 feet thick,

A

B

Figure 17. A. Weathered Deguyños Formation (Pdg) in northern Fossil Canyon. B. Outcrop of unweathered mudstone.

Figure 18. Gypsum lattice within Deguyños Formation (Pdg).

the coquina beds provide the only observable bedding structure in the formation. Occasional larger coquina beds are present in the northern mapping region. Although coquina beds are visible in the stratigraphy to the north and south of the mountain range, correlation was not achievable in this study. The Deguyños Formation is interpreted as turbidity currents from the introduction of the Colorado River prodelta. The thick sections of coquina may have been deposited during shallower periods in the Gulf of California seaway.

The Deguyños mudstone is predominately found in the basin deposits to the north and south of the mountain block. Smaller exposures crop out in Fossil Canyon and north of Cahuilla Canyon. Mapped outcrops may be larger than the actual distributions due to the weathering and sloughing of the outermost surfaces. In the north basin, large mounds of the mudstone are cut by sinuous drainages and dominate the topography. Dip slopes of the fossiliferous coquina beds within the Deguyños Formation dip to the northeast. To the south of the Elsinore Fault, mudstones outcrop in the west range front directly on the Andradé sandstone near the fault trace. Steep coquina beds visible within the mudstone dip approximately 60° to the south. In the east range front, the Deguyños Formation is exposed between the two segments of the Elsinore Fault. The mustard-yellow mudstones are juxtaposed with the basement escarpment of the mountain block to the north and the Palm Spring Group to the south.

Palm Spring Group

Diablo Formation (Pd). The Diablo Formation is the only unit of the Palm Spring Group mapped within the study area. The reddish-tan fine-grained quartz arenite sandstones are well-sorted and crop out south of the Elsinore Fault in the west and east range fronts. Outcrops of the Diablo Formation are highly weathered and resemble the rolling hills of the Deguyños mudstones. Bedding planes are difficult to measure in the poorly cemented and easily friable unit. Cross-bedding is faintly visible in certain outcrops in the east range front (Figure 19). To the south of the mapping area, the Diablo sandstones become buried by Quaternary alluvial units of the desert basin. The Diablo Formation is interpreted as the delta front from the Colorado River during delta progression through the region.

Alluvial Units

Range Crest Gravels (PQrc). This study herein names the Quaternary unit along the peaks of the Coyote Mountains as the Range Crest gravels. The unconsolidated gravels are unconformably deposited above the entire stratigraphic sequence and basement complex (Figure 20). Poorly sorted tan and brownish-buff sands and silts

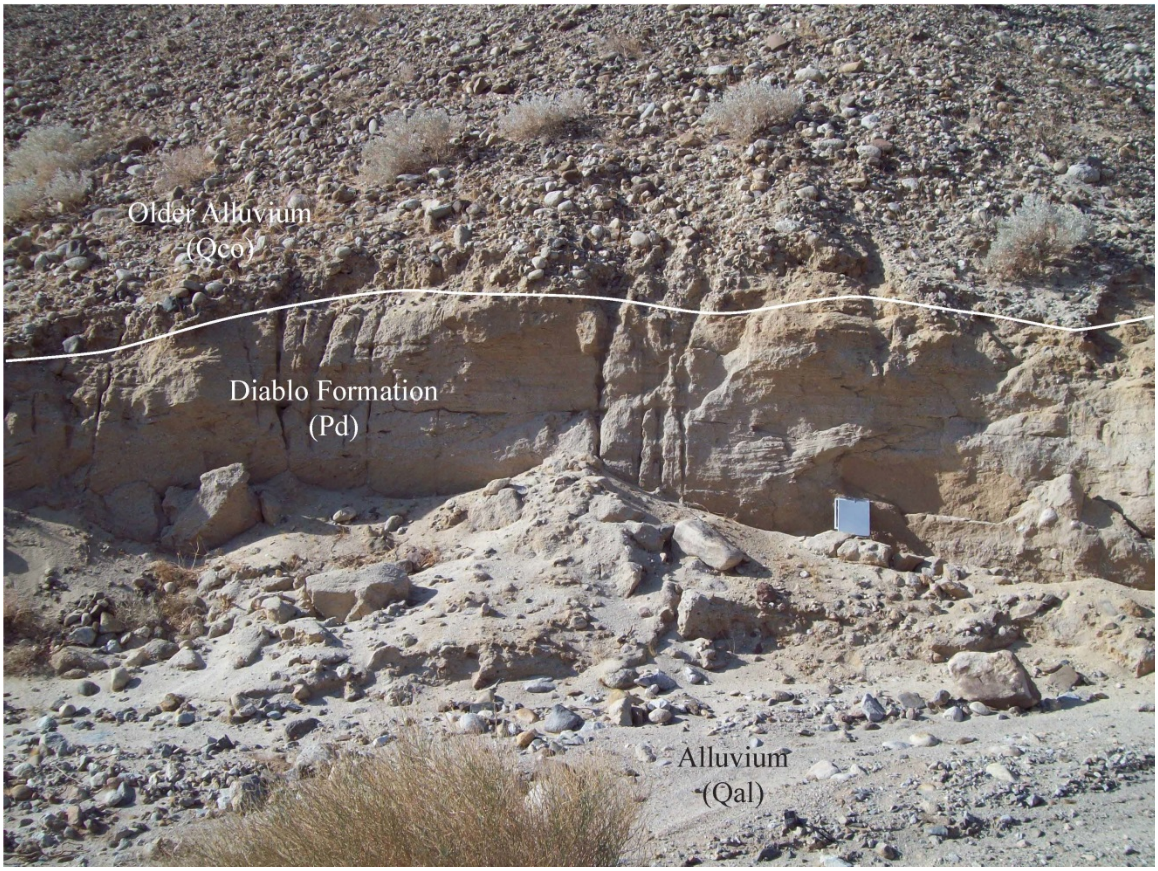

Figure 19. Cross-bedding in the Diablo Formation (Pd) in the eastern range front.

support the angular to subangular pebble to boulder clasts. Clasts are derived from basement material and are primarily composed of marble and schist. The Range Crest gravels are found in east-west trending deposits along the crest of the range. Due to the unconsolidated nature, some deposits may have been reworked during mountain formation and uplift. Bedding in not typically visible in outcrop but can be observed in the steep drainages near Fossil Canyon in subhorizontal orientations.

The Range Crest gravels are equivalent to the original Garnet Formation found in Christensen's (1957) stratigraphy of the Coyote Mountains. The unit lacks the

Figure 20. Range Crest gravels (PQrc) deposited on the Garnet Formation (Mg) at the range crest.

pediment surfaces and desert varnish observed in the other alluvial units on the flanks of the range presented below.

Older Alluvium (Qco). Uplifted alluvial deposits elsewhere in the mapping region are named older alluvium in this study. The older alluvium is similar to the Range Crest gravels in lithology but is typically deposited on the north and south flanks of the mountain block with upper pediment surfaces still intact (Figure 21). Relative ages between the two units cannot be determined; however, older alluvium deposits are probably younger than the Range Crest gravels due to the preservation of the desert patina. The provenance of the alluvial sediments may also be similar as they were

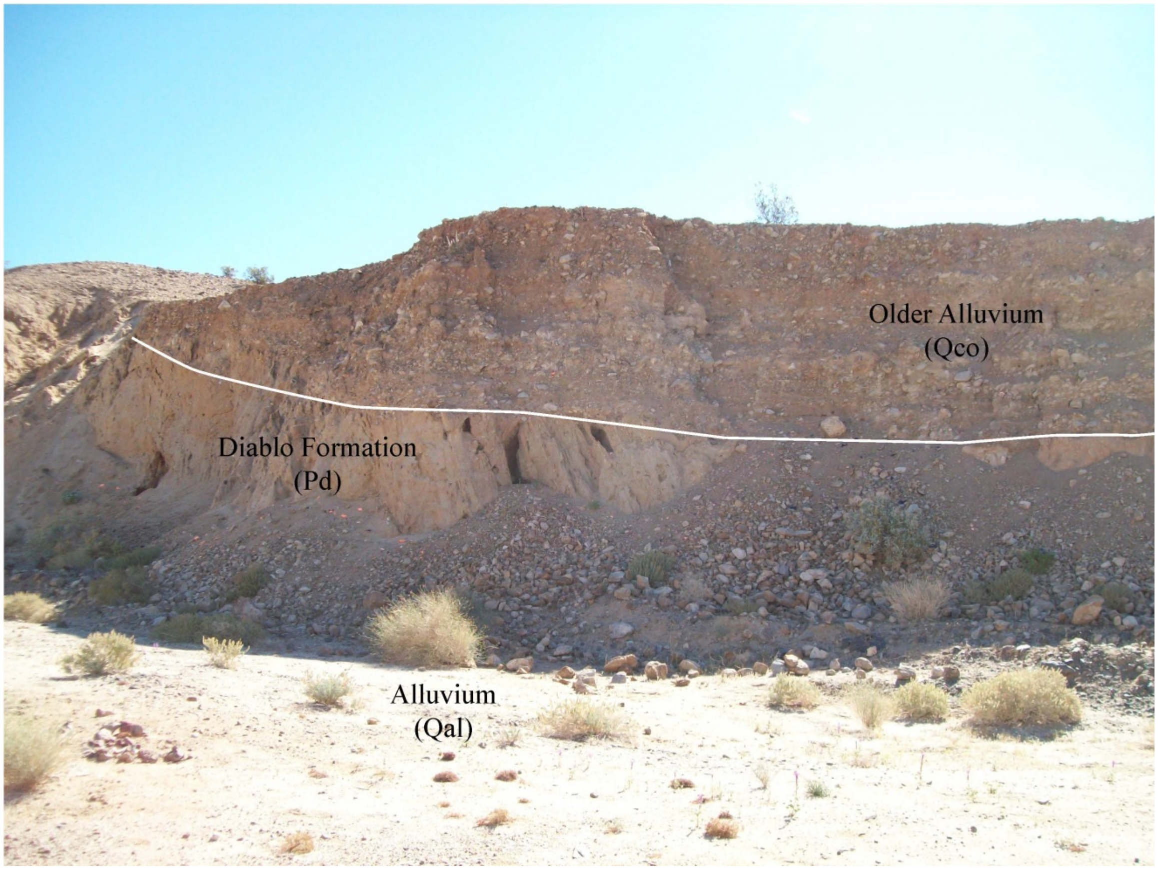

Figure 21. Older Alluvium (Qco) deposited at an angular unconformity with the Diablo Formation (Pd) in the east range front.

deposited during mountain uplift. Certain older alluvium exposures have been deposited more recently from eroding basement escarpments due to displacement along mountain faults.

An anomalous deposit of steeply dipping older alluvium is found in the east range front deposited above the Diablo Formation as an angular unconformity. Serrated ridges of reworked coquina cap the section of alluvial conglomerates (Figure 22). The unit is composed of medium-sized quartz sand grains and support granule to pebble sized basement clasts. The isolated coquina and conglomerate beds may be the remains of a

Figure 22. Serrated ridges of reworked coquina beds deposited stratigraphically above the Diablo Formation (Pd) in the east range front.

separate unit during mountain formation but are included with the older alluvium in this study.

Alluvium (Qal). Quaternary alluvium consists of the unconsolidated young material in present-day drainages and washes. Recently weathered sands, silts, and gravels fill the mountain's intermittent streambeds and fan out in coverage as they reach the desert floor. In the mountain block, alluvium is isolated to Fossil Canyon, West Canyon, and Cahuilla Canyon. Large deposits of alluvium are visible between the uplifted range fronts and stem from major mountain drainages. Within the north basin, Quaternary alluvium is mapped within the largest drainage in the region, but is omitted from smaller drainages in the Deguyños Formation, which are filled with eroded and reworked mudstone.

Faults

The current structure of the Coyote Mountains is heavily influenced by faulting in the region. Faulting of various magnitudes and orientations is found within the study area. Although faulting is readily apparent in the Tertiary stratigraphic sequence, displacement along smaller scale faults is rarely discernible in the basement. Large faults can be seen in the metamorphic complex as brecciated and gouged segments approximately 1-3 feet wide. Brecciation typically occurs in the marble units, whereas gouged sections are visible in basement schists. Occasionally, polished surfaces are seen on basement fault planes with large "slickengrooves" carved into the rock face. Faulting can also be interpreted from the juxtaposition of sedimentary units with basement escarpments. This is not to be confused with steep depositional contacts that are common in the mountain block as degradation of the basement material is not observed. Juxtaposition of the Deguyños mudstone with the basement always in inferred as a fault due to the burial of the metamorphic complex prior to Colorado River delta sedimentation. Faulting within the sedimentary units is easily recognized by well-defined fault planes typically found with measurable displacement lineations. Sections of the Andradé Member are disturbed by pervasive microfaulting, but patterns or preferred orientations were not recognized in the microfault array.

Displacement estimates are based upon observations and mapped exposures within the central Coyote Mountains. Bedding attitudes and inferred subsurface structure from the geologic cross sections are used to determine the magnitude for fault movement on larger faults (Plate 2). Determining the amount of displacement for certain faults is problematic, however, due to the ambiguous and hypothetical thicknesses of units in the mountain range.

Elsinore Fault

The largest fault in the region is the northwest-southeast striking Elsinore Fault. In the mapping area, the Elsinore Fault is primarily exposed as two vertical strands striking parallel to the Coyote Mountains. Creating the southern margin of the range, the fault separates sedimentary units of the desert floor to the south from basement exposures of the mountain block to the north. Strands of the Elsinore Fault crops out along the range front within deposits of the Imperial and Palm Spring Groups. In areas mapped as older alluvium and Quaternary alluvium, the fault trace is buried.

Vertical displacement along the Elsinore Fault has resulted in the abrupt basement escarpment along the southern edge of the mountain range. With each strand of the Elsinore Fault, units to the north are stratigraphically older than material to the south. In the eastern range front, the southern strand of the Elsinore Fault juxtaposes the Diablo Formation of the Palm Spring Group with a section of the Deguyños mudstone. The northern strand of the fault separates the marine mudstones from the Jurassic basement of the mountain block. The total vertical displacement of the Elsinore Fault in the study area is estimated at approximately 4.95 kilometers based upon unit thicknesses described in previous work of the Salton Trough. It is assumed that the Palm Spring Group and upper Imperial Group were previously deposited above the basement prior to fault initiation and have since been eroded during mountain uplift. This has exposed the basement complex and older stratigraphic units at their present elevations. Younger Quaternary units such as the Range Crest gravels were deposited after the erosion of the older stratigraphic section. In the Salton Trough region, the Fish Creek Mountains to the north have experienced a larger 5.7 km of uplift since the initiation of the San Jacinto Fault since 0.95 MA at a rate of approximately 6 millimeters/year (Dorsey et al., 2011). Horizontal displacement on the Elsinore Fault is not directly observable in the mapping region, but dextral motion of a maximum 7 km is estimated from previous studies of the region mentioned in the literature review (Johnson et al., 1983). Oblique movement along the trace of the Elsinore Fault adjacent to the Coyote Mountains may have lessened the amount of horizontal motion from the estimates derived from the basin units. This would also affect the magnitude of rotation.

Central Mountain Fault

In the mountain block, a large fault strikes to the northwest-southeast just south of the crest of the range. Displacement is observable within the sedimentary units and basement complex, and the linear structure is easily recognizable in aerial photos of the Coyote Mountains. This study herein names the structure as the Central Mountain Fault. In the western mapping area, the fault strikes between Tertiary sedimentary members and uplifted basement exposures along the southern margin of the north basin. To the southeast, the fault trace is lost in the extreme basement topography but crops out along strike northwest of Cahuilla Canyon. At this location, the Central Mountain Fault is visible as a thin strand of brecciated material within the typically undisturbed basement complex (Figure 23). In the sedimentary units to the north of Cahuilla Canyon, the fault is exposed as three segments slicing through the Garnet and Andradé deposits. The main

Figure 23. Brecciated marble basement complex along the trace of the Central Mountain Fault.

trace creates a slickenside-covered fault plane between the basement and Andradé sandstones. Further southeast along strike, the fault truncates Imperial bedding against gouged schists. This contact differs from the depositional relationship viewed elsewhere in the mountain block due to highly disturbed basement material and the lack of sedimentary onlap. The fault continues to strike to the southeast before the trace is lost in the Alverson basalt.

The nature of displacement along the Central Mountain Fault is similar to the Elsinore Fault but at a lesser magnitude. The three segments in northern Cahuilla Canyon suggest progressive north-side uplift (Figure 24). The polished fault plane on the basement complex dips steeply to the north with slickensides plunging 25° to the northwest. The two other strands of the fault are near vertical and lack displacement

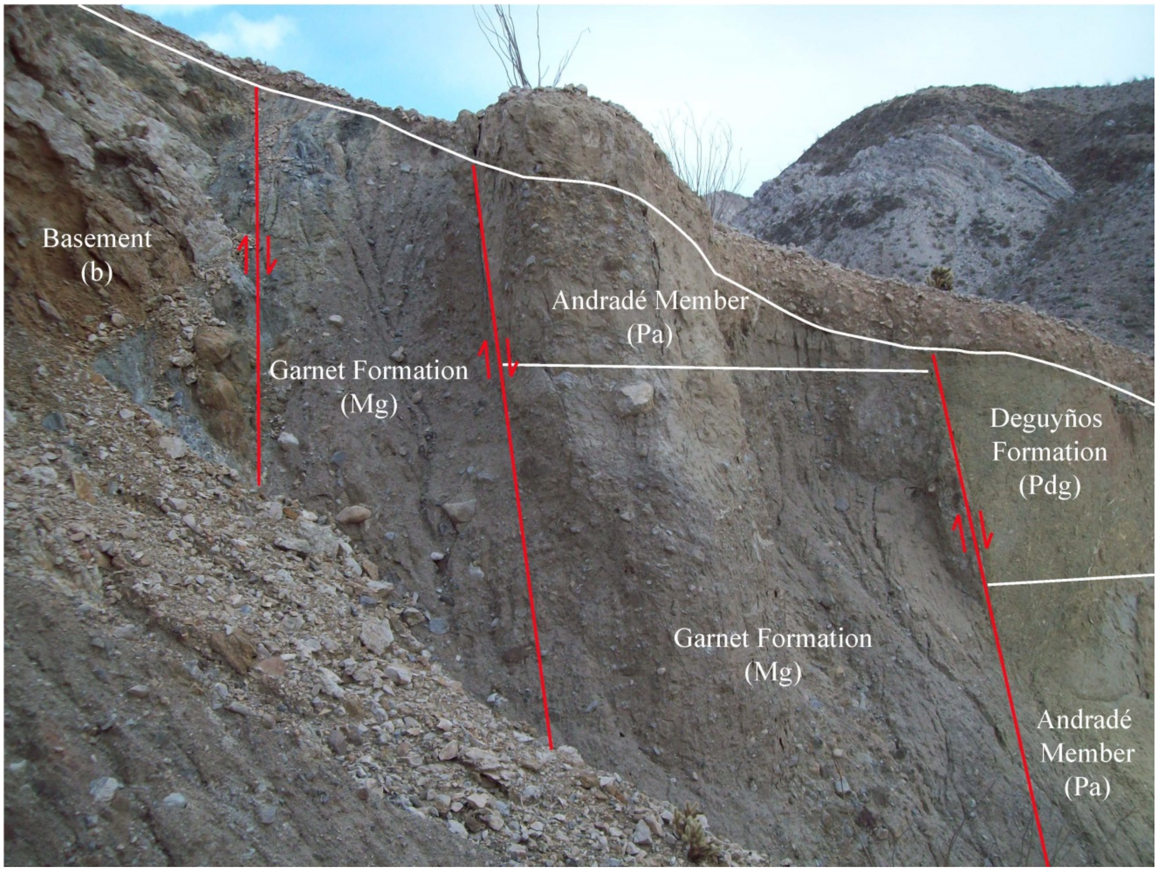

Figure 24. Three segments of the Central Mountain Fault in northern Cahuilla Canyon.

lineations. Vertical displacement is apparent in the stratigraphic relationships across fault segments. Dextral motion is inferred from the displacement lineations on the northern fault plane. However, the displacement amount is unattainable. Within the mapping region, the magnitude of vertical displacement is greatest in the northwest and gradually diminishes along strike to the southeast. This is evidenced by exposures of Deguyños mudstone against the basement complex in the western mapping area. Based upon observations in northern Cahuilla Canyon, uplift along the Central Mountain Fault is approximately 80-100 feet at the crest of the range. This is dependent on the thickness of the Garnet conglomerates in the area (Plate 2). To the north of the fault, isolated Garnet conglomerates crop out at the crest of the range at elevations well above the sedimentary units to the south. Outside of the mapping area to the northwest, a prominent northwest-southeast trending basement escarpment is visible along the strike of the Central Mountain Fault.

Fossil Canyon Fault

A second large northwest-southeast striking fault is found along the east side of Fossil Canyon. This study herein names the fault as the Fossil Canyon Fault. The fault trace curves slightly to the west as it progresses northward in the canyon. Thick exposures of volcanic and sedimentary units in Fossil Canyon abruptly end against the basement escarpment to the east. In a small drainage adjacent to the basement, the fault trace is visible dipping steeply to the west-southwest at approximately 70° (Figure 25). The basement complex to the east of Fossil Canyon Fault is heavily gouged. Further north, the fault strikes through a basement saddle before the exposure is buried by older alluvium. At the northernmost point in Fossil Canyon, the fault appears to splay in two directions. A fault plane is visible in the basement complex near the edge of the mapping region. Striking to the north, the fault creates a polished surface with 1.5-foot wide “slickengrooves” carved into the rock face. This fault dips steeply to the west at 72° and the “grooves” plunge 43° to the north. The steepness of the terrain prevents viewing the fault segment to the north. The second fault trace strikes to the northwest under the older alluvium and continues through a basement contact between schist and pinkish marble. The marble outcrop has a thin strand of highly brecciated material consistent with basement faulting along the Central Mountain Fault. The fault breccia continues to the canyon floor to the west where the trace is lost.

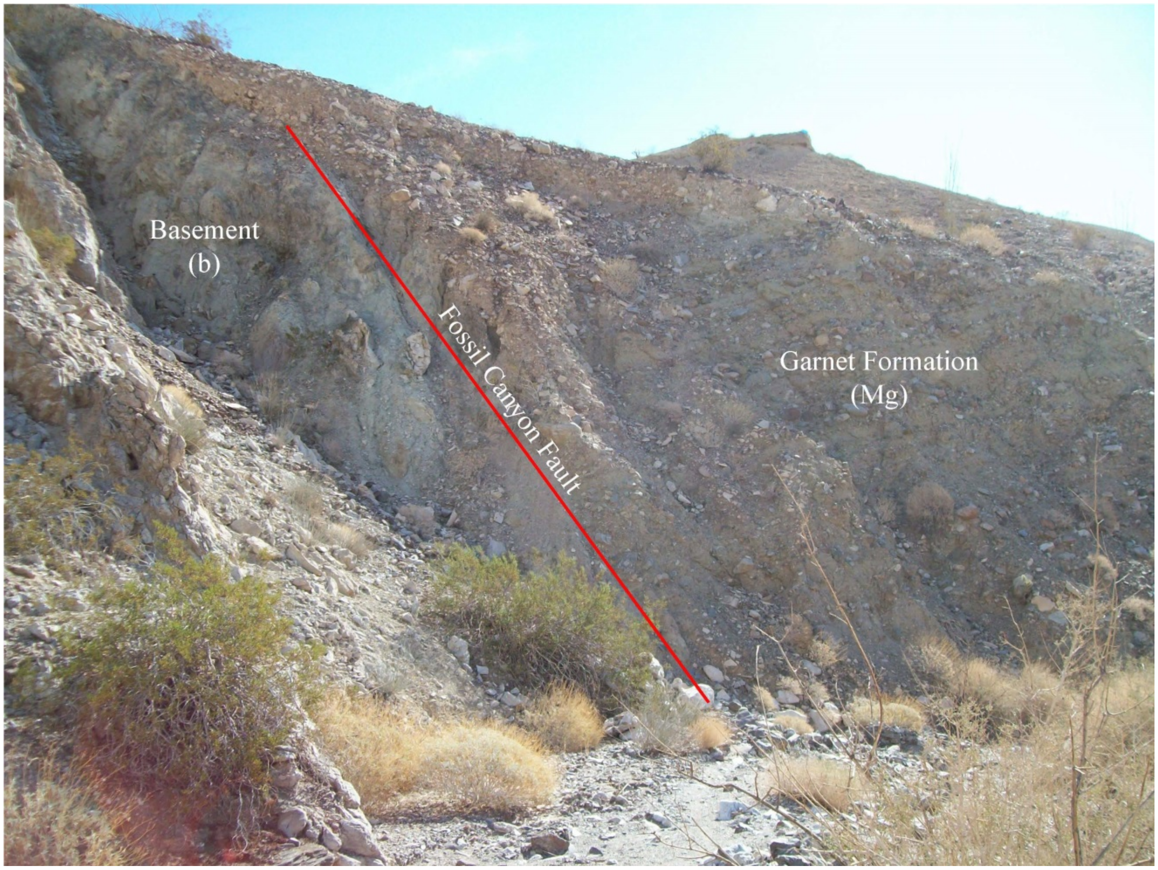

Figure 25. Exposure of the Fossil Canyon Fault in northern Fossil Canyon.

Minor splays of the fault are exposed along strike in Fossil Canyon. In a drainage perpendicular to the fault trace, two minor faults strike through the Imperial Formation with similar orientations as the major Fossil Canyon Fault. However, observable displacement is minor with only a few feet of offset. The fault splays do not appear to strike a significant distance away from the Fossil Canyon Fault but may be covered by older alluvial units.

As with the Elsinore Fault and Central Mountain Fault, the Fossil Canyon Fault exhibits oblique displacement. Dextral movement is inferred through offset in Alverson basalt outcrops on either side of the fault, and displacement is estimated at about 1,500 feet based upon mapping by Winker (1987). Approximately 400 feet of vertical displacement is estimated from Imperial Group sandstones and Range Crest gravels deposited on the basement ridge to the east of the mapping area (A. Bykerk-Kauffman, personal communication, September 2013). These estimates are problematic, however, due to the irregular paleotopography in which the basalt flows were deposited. Vertical displacement estimates may also be an issue. Marine sandstones may have been deposited at differeing elevations on the basement complex. Unlike the other two major faults, the curviplanar Fossil Canyon Fault is not vertical and dips approximately 70° to the west-southwest. Exposures of Deguyños mudstone in the hanging wall are capped by shattered material eroded from the basement escarpment from the footwall to the east (Figure 26). Although measurable lineations from the Fossil Canyon Fault are not present along the fault trace, an estimated displacement vector of 15° to the northwest is derived from horizontal and vertical displacement estimates using trigonometric functions.

North Basin Fault

North of the mountain block, fault orientations shift to northeast-southwest striking high-angle normal faults. Faulting is apparent in the Andradé sandstones but is also visible in the Deguyños Formation as evidenced by displacement in coquina marker beds. The most prominent fault crops out in the westernmost portion of the map and is herein named as the North Basin Fault. The west-northwest dipping normal fault creates a sandstone-capped basement scarp against weathered mudstone exposures of the Deguyños Formation (Figure 27).

While the fault trace is buried by weathered mudstone of the hanging wall, the angle of the basement escarpment is visually measured to be 70°, which is consistent with

Figure 26. View of the Fossil Canyon Fault from northern Fossil Canyon. Eroded basement from the footwall capping the Deguyños Formation (Pdg) of the hanging wall.

smaller faults in the north basin. The southern tip of the fault ends in the basement complex with no observable displacement or fault gouge. To the north, offset is apparent between outcrops of Andradé sandstone. At this location, the Andradé exposures are displaced vertically by approximately 40 feet as evidenced by cross section estimations and measurements. Displacement increases to over 100 feet along strike, and may continue to get larger to the north. The fault trace eventually becomes buried in the weathered Deguyños mudstones of the north basin.

The steady increase in vertical displacement on the North Basin Fault is also observed in all other faults in the north basin. Motion along the fault planes is found to be

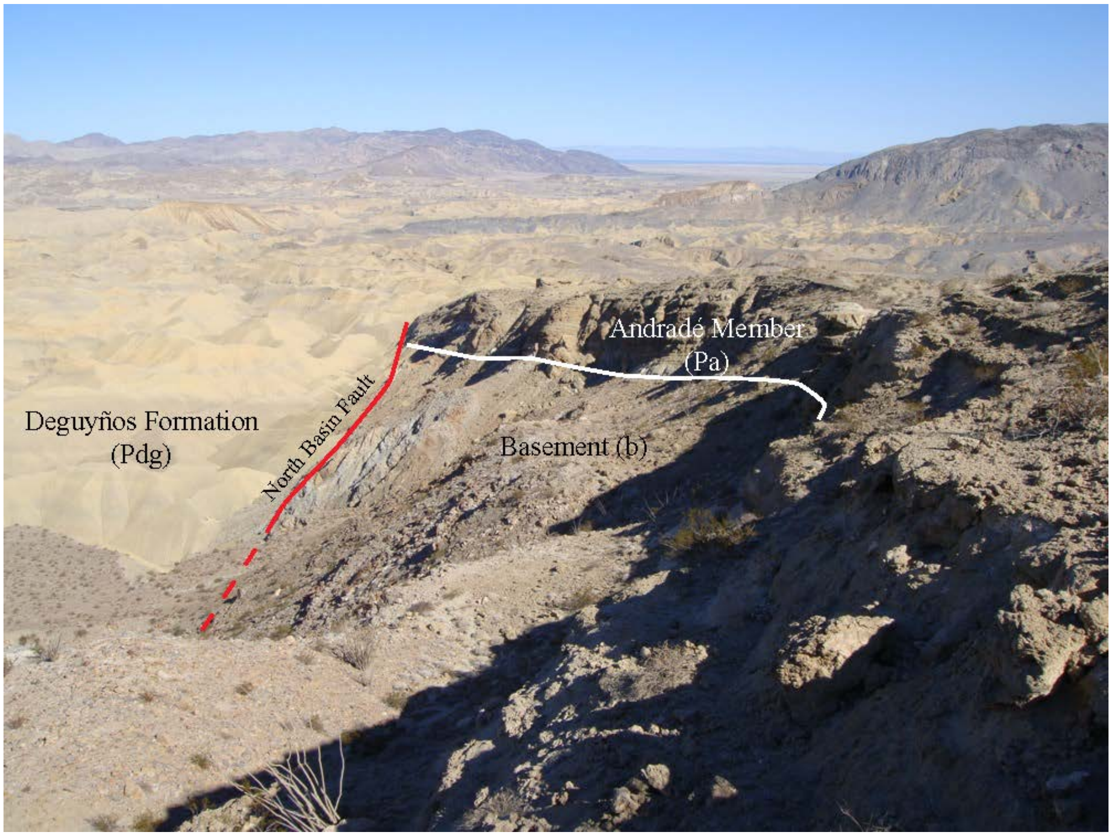

Figure 27. Exposure of the North Basin Fault in the north basin.

hinged with no observable displacement at the southern margin of the north basin. Fault escarpments increase in height to the north with larger displacement magnitudes. Although it is difficult to determine the true nature of the faults due to erosion of large sections of sedimentary units from uplift, torsional stresses from the Elsinore Fault may have created the structures. The nature of faulting in the north basin will be discussed in greater detail later in the study.

Other Faults

Another large normal fault creates the boundary between the mountain block and north basin. Striking northeast-southwest, the fault truncates sandstone and mudstone beds against the uplifted basement complex. The dip of the fault can be measured using visual approximations at 70° to the northwest (Figure 28). At the fault exposure, vertical displacement is estimated at approximately 575 feet based upon apparent dips from the

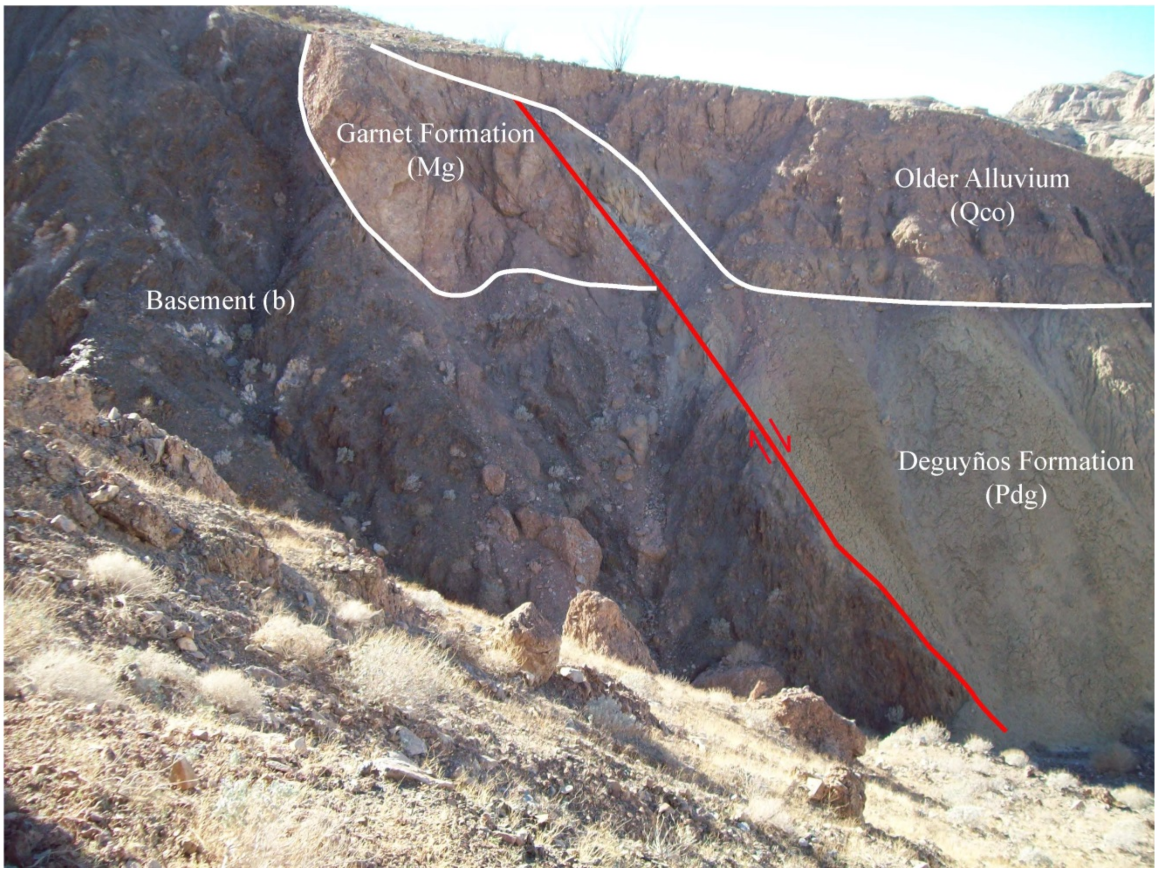

Figure 28. Normal fault separating the mountain block from the north basin.

geologic cross sections (Plate 2). Offset is estimated to vary along strike with minimal displacement to the southwest as it approaches the Central Mountain Fault. Bedding orientations shift between the hanging wall and the footwall of the fault. Red Garnet conglomerates deposited at the northern margin of the mountain block dip at approximately 20° to the north, whereas Deguyños mudstones of the basin dip at 25° to the northeast. Similar to the North Basin Fault, the trace is buried in the weathered Deguyños mudstone to the northeast.

Several other high-angle normal faults are prevalent in the north basin. Dipping primarily to the southeast, the smaller-scale faults offset Andradé sandstones by 5-20 feet based upon visual approximations. As with the larger basin faults, offset appears to increase along strike towards the northeast. Exposures of the faults in the Deguyños mudstone are visible in thick sections of coquina beds (Figure 29). Elongate exposures of the basement complex are exposed in the footwall of several normal faults in the north basin.

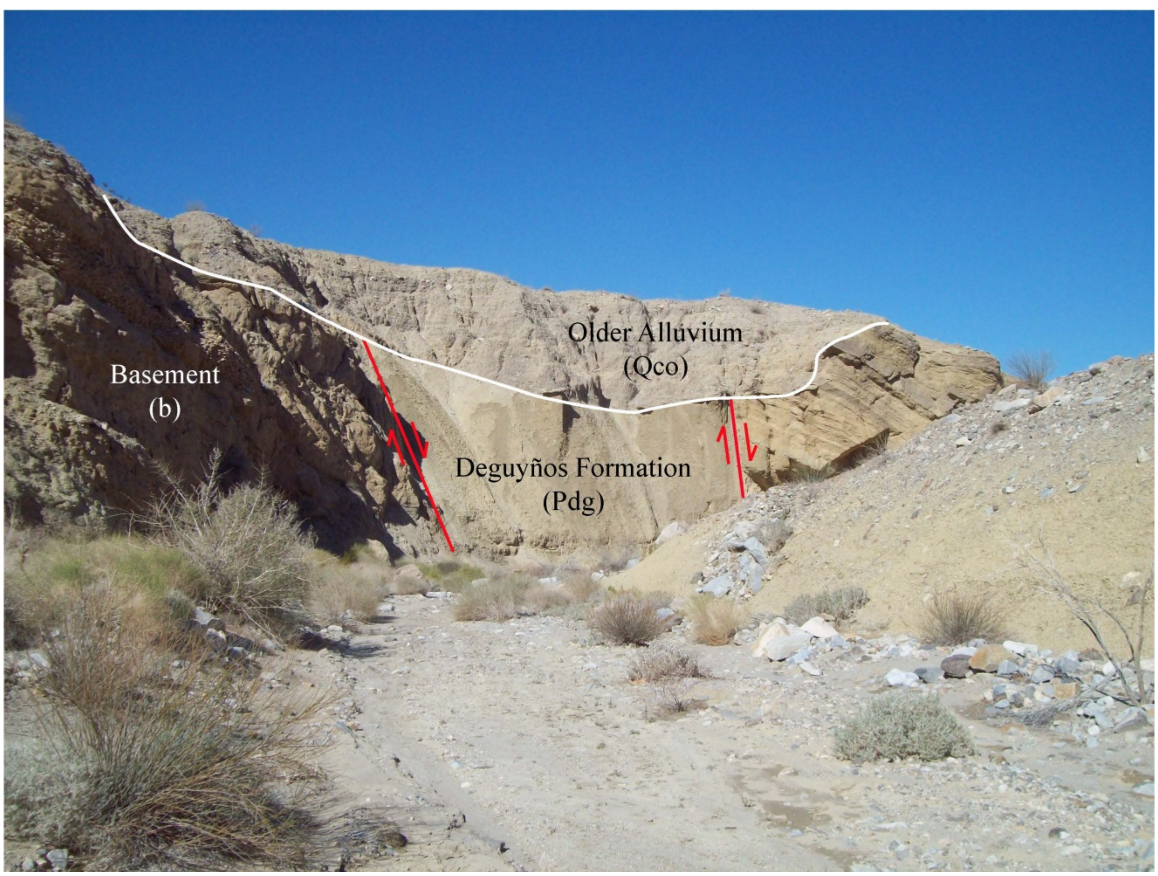

Figure 29. Hinged normal faulting in the north basin offsetting the Deguyños Formation (Pdg).

Smaller faults in the mountain block are found with similar orientations. Northeast-southwest striking oblique faults are primarily exposed in the Garnet and Andradé units. Displacement lineations are commonly seen on fault planes and display both normal and left-lateral displacement based upon stratigraphic offset. The smaller mountain faults do not strike into the basement complex, but larger faults juxtapose the sedimentary units with basement of the footwall. Most faults dip to the northwest, with a few having opposite orientations. The structures are crosscut by the major Central Mountain and Fossil Canyon Faults. Two vertical fault planes are visible in West Canyon with displacement lineations, but do not strike a significant distance within the Red Rock Formation. The amount of offset is unclear and may be minimal.

The largest antithetical striking fault in the mountain block is found in northern Fossil Canyon. Dipping at 50° to the northwest, Andradé sandstones of the hanging wall are juxtaposed with the older Garnet conglomerates (Figure 30). Slickensides on the fault plane have a rake of 60° to the west. Following the fault to the east, the fault down drops Deguyños mudstone against the Garnet conglomerates. Despite the limited length of the exposure in the mountain block, this may represent a hinged fault with increasing displacement along strike similar to the antithetical faults of the north basin. The amount of displacement is difficult to determine due to variance in unit thicknesses but is estimated between 30-70 feet. This is based upon visual approximations and the limited bedding orientations measured in the region. Other antithetical faults in the mountain block exhibit less displacement as is estimated at approximately 5-20 feet. Slickensides on exposed fault planes express similar oblique motion.

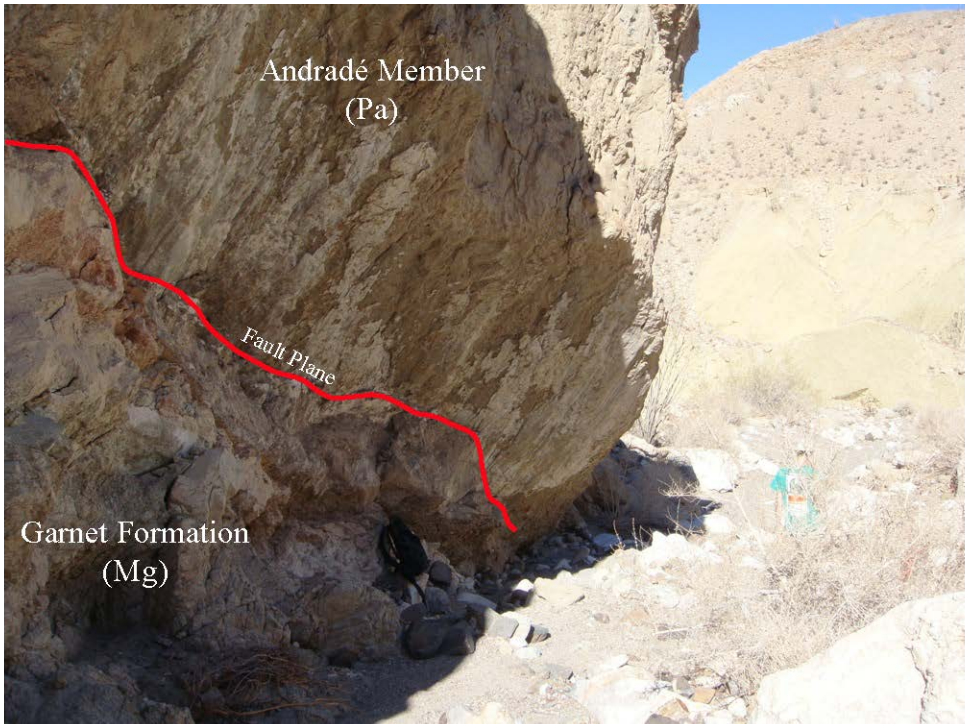

Figure 30. Oblique normal fault in northern Fossil Canyon.

Stereonet Projections of Faults

A stereonet projection of faulting in the Coyote Mountain region portrays the dominant orientations for brittle fracture in the system. The majority of faults in the mountain block and north basin fall within two dominant strike directions (Figure 31a). Despite appearing vertical throughout the study area, the Central Mountain Fault was plotted from the only exposed fault plane with lineations near the crest of the range, which dips steeply to the northeast. The Fossil Canyon Fault was plotted from approximations of strike and dip at the most prominent exposure in the eastern mapping region. Displacement vectors for horizontal and vertical motion were plotted from estimated offset along the fault discussed earlier. The smaller northeast-southwest trending faults vary slightly in strike based upon location, but generally possess similar

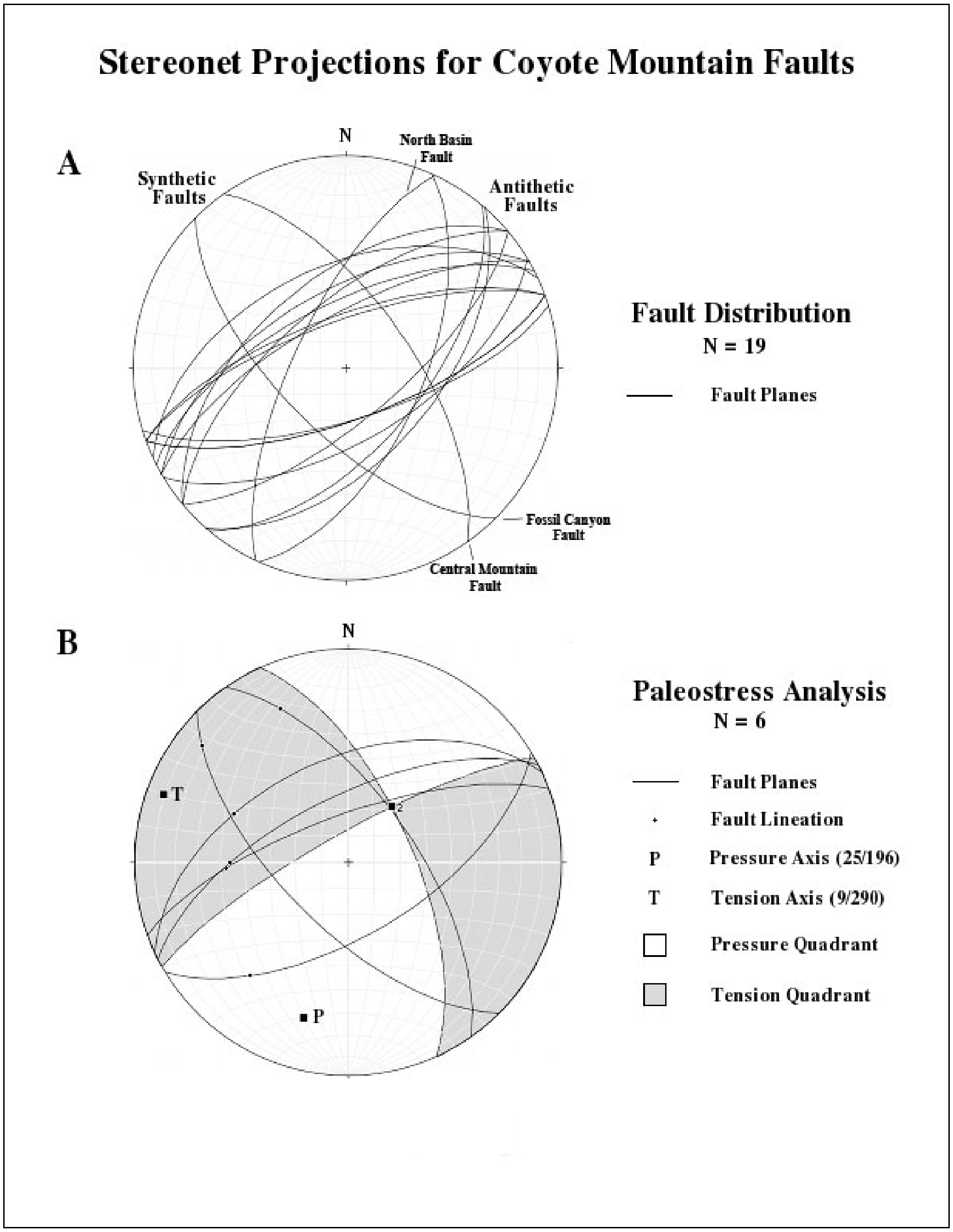

Figure 31. A. Stereonet projections for faults measured in mapping region; B. Paleostress estimates for measured fault lineations.

orientations. Faults in the western edge of the north basin strike more north-south compared to faults further east. The major Elsinore Fault was not included in the plotted fault array.

Paleostress estimates for the Coyote Mountains were also plotted on a stereonet projection based upon the measured displacement lineations (Figure 31b). Faults lacking slickensides were not included in the estimate as incorrect assumptions for displacement vectors could greatly skew the results. The paleostress estimate for the system was achieved using the right dihedra method. Pressure and tension quadrants were first plotted for each fault individually based upon fault plane solutions. Common intersections within the fault array determine the system-wide paleostresses in the region. Using this method, the pressure axis in the central Coyote Mountains trend 196° and plunges 25°. The tension axis trends 290° and plunges 9°. The estimated paleostresses orientations will be discussed for their influence on the structure of the mountains later in the study.

Bedding Structure

Bedding orientations differ significantly throughout the study region. Within the mountain block, sedimentary units in southern Fossil Canyon dip about 25° to the southeast. Dip magnitudes shallow in the sedimentary sequence further north. At the peaks of the range, bedding is found with dips less than 25° in various directions. This may be related to the intensely fractured and faulted material. A stereonet projection of bedding attitudes in the mountain block portrays the irregular orientations measured within the central Coyote Mountains (Figure 32)

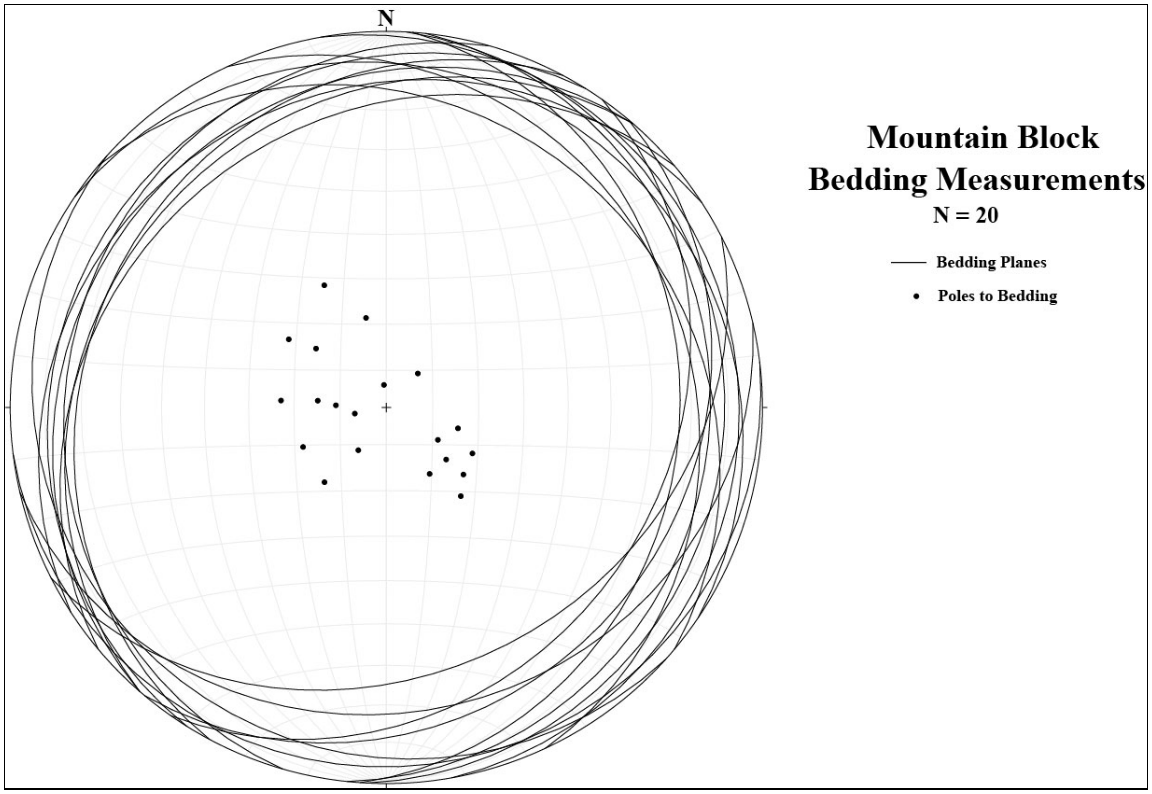

Figure 32. Stereonet projection for bedding attitudes in the mountain block.

In the north basin, bedding within the Imperial Group dips to the northeast at approximately 25° or less. To the east, dip orientations shift to the north with similar dip magnitudes. Although bedding is difficult to measure in the highly fractured sandstone of the Andradé Member, measurements in the coquina beds of the Deguyños Formation appear consistent and lack significant deformation or folding across the basin.

To the south of the range, sedimentary bedding is found in opposite orientations to the north basin. In the west range front, Andradé sandstone beds adjacent to the Elsinore Fault dips to the south at 40°. Dip angles increase to 64° away from the fault in coquina beds within the Deguyños mudstone. Although bedding planes are difficult to measure in the highly weathered Deguyños and Diablo Formations, they appear to approach horizontal away from the fault trace. Diablo sandstones at the southern margin of the mapping area dip slightly to the north and create a wide syncline. The axial trace of the syncline strikes at 277° and dips approximately 70° to the north. The fold axis trends to the east and plunges at 10° (Figure 33).

In the east range front, the southern strand of the Elsinore Fault separates the Deguyños mudstone from the younger sandstones of the Palm Spring Formation. Bedding in the Deguyños Formation is measured from an isolated exposure of coquina. The bed dips gently at 21° toward the range but probably does not represent overall bedding of the mudstone. The mudstone unit is found between the two strands of the Elsinore Fault and may be heavily disturbed from fault displacement.

To the south of the Elsinore Fault, beds of the Diablo Formation typically dip steeply to the south at approximately 70°. A few anomalous bedding orientations may show a tight fold in the Colorado River-derived sandstones, but the abrupt change in bedding orientations is only observed at the single location. Dip magnitudes lessen to approximately 25° further south in the east range front away from the Elsinore Fault. An angular unconformity separates the Diablo sandstone from the older alluvium exposures to the east. Bedding in older alluvium is measured from the serrated ridges of reworked coquina. Adjacent to the fault, the beds dip about 65-75° to the southeast. Measurable bedding of the older alluvium shallows to 30° away from the Elsinore Fault.

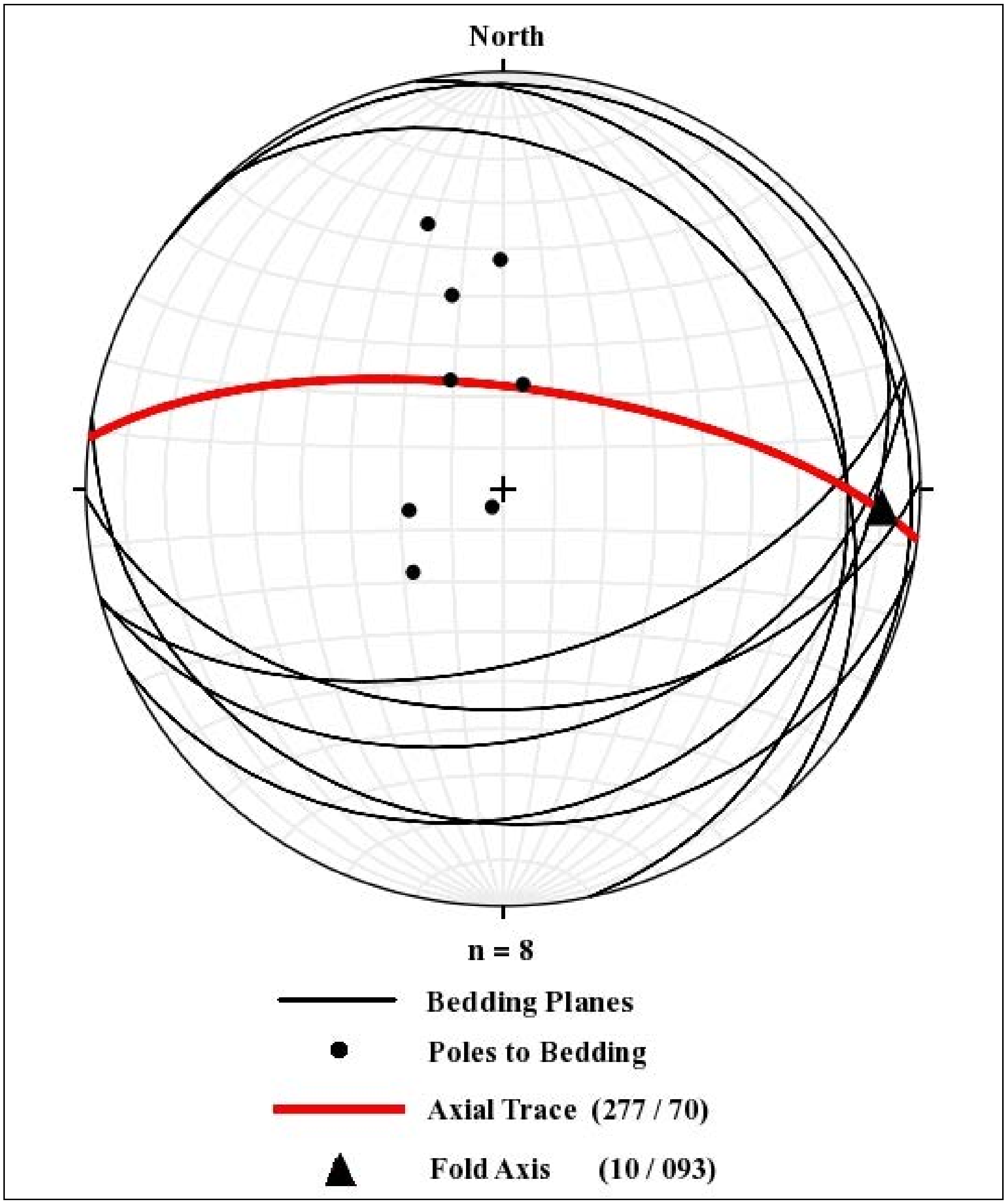

Figure 33. Stereonet projections for folding in the west range front.

Cross Sections

Measurements of faults and bedding attitudes in the region were used to create cross sections of the predicted subsurface geology (Plate 2). The highly irregular basement topography creates difficulties in correlating units throughout the range.

The depths to the basement complex are typically hypothetical under the sedimentary and volcanic cover. Unit thicknesses vary greatly within the region and cannot be assumed to be consistent between outcrops. Deposition within the same unit could have occurred at varying elevations on the irregular paleotopography prior to uplift and deformation. This problem is magnified within the early marine sequence of the Imperial Group as the Andradé sandstones blanketed the region in the shallow marine environment. Also, at a scale of 1:6,000, the Tertiary rocks of the mountain block are especially thin when compared to the basin material to the north and south of the range. The thickness of mountain block bedding and hypothetical contacts create significant challenges when predicting and portraying the complex subsurface structure.

Based upon mapped distributions, sedimentary and volcanic units in the mountain block appear to have accumulated in paleocanyons within the basement material. Three east-west trending infilled paleocanyon deposits are bound by basement exposures within the mountain block. The sedimentary sequences are truncated to the east by the Fossil Canyon Fault and taper out near Cahuilla Canyon to the west. Faults found in the mountain block crosscut the structures. Similar paleotopography could exist in the basins to the north and south of the range below the thick sections of Imperial and Palm Spring Groups.

The cross sections also display the changes in bedding attitudes across the system. Bedding reversals occur between the northern and southern flanks of the range. Orientations are more difficult to portray in the thin units of the mountain block. The geometry of the only major fold in the region is displayed from measurements of the syncline in the west range front. Smaller-scale drag folding is shown along faults contacts in the north basin.

CHAPTER V

DISCUSSION

The current structure of the Coyote Mountains is dependent on the original geology of the Salton Trough basin and the subsequent deformation from regional and local faulting. The reorganization from detachment-influenced subsidence to transpressional uplift has exposed the stratigraphic units and basement rock to their current elevations. Interpretations based upon observations in the central Coyote Mountains will be discussed to determine the geologic structure and history of the area. Firstly, the structure of the original basin will be presented based upon mapped exposures with a focus on the depositional characteristics for individual units. Specific attention will be given to the isolated distributions of the stratigraphic sequence in the mountain block to recreate the unaltered basin prior to deformation in the Pleistocene. Secondly, the younger alluvial units deposited syn- and post-uplift will be discussed for relative ages for deposition as well as provenance during mountain formation. Finally, the nature of deformation will be discussed based upon fault and bedding orientations observed within the mountain system.

Pre-Deformation Stratigraphy

Throughout previous studies on the Coyote Mountains, the true structure of the basement complex remains a mystery during emplacement of the Tertiary stratigraphic sequence. It is difficult to determine the original structure due to tectonic subsidence and burial of the basement under the marine and fluvial sediments. Only through uplift has the basement complex been exposed for geologic interpretation. While the basement provided the substrate for stratigraphic deposition, the paleotopography is predominantly hypothetical. Previous studies agree that the fluvial units of the Red Rock Formation were deposited in basement channels prior to subsidence in the region, but the extent of topographic irregularity is not well understood during emplacement of the younger volcanic and sedimentary units.

Paleotopographic interpretations of the basement are based upon observations in the mountain block. Uplift of the range and erosion of the stratigraphy have exposed the metamorphic complex and provided a window into the basement structure prior to Salton Trough deposition. It is assumed that the Deguyños Formation of the Imperial Group and subsequent Colorado River deposits of the Palm Spring Group were deposited without the influence of the basement complex in the region. This is apparent in the unit distributions in the mountain block, which will be discussed later.

Within the mountain block, this study interprets the three east-west trending stratigraphic distributions of Split Mountain and Imperial Groups as infilled paleocanyons in the basement complex. Christensen (1957) originally interpreted the structures as fault-bound deposits created prior to the introduction of the Imperial Group. Although the faults mapped by Christensen are based upon the truncation of bedding planes, no evidence for the faults is observable in the field.

Within the mountain block, faults juxtaposing the basement complex with the younger stratigraphic cover create gouged or brecciated material. This degradation can be observed along the major Elsinore Fault as well as the Central Mountain Fault and Fossil Canyon Fault in the mountain block. Along Christensen's proposed faults, the basement complex and Split Mountain units are intact and appear depositional.

Further evidence for non-faulting is observable in the shape of the mapped exposures in the mountain block. The detailed mapping from this study displays erratic contacts between the Split Mountain Group and basement along the presumed depositional surface. Christensen mapped linear fault contacts striking at the southern edge of the Red Rock and Alverson Formations. The questionable faults are also found on many of the younger maps of the Coyote Mountains in future studies. This study maps more complexity in the Split Mountain Group distributions that would be expected at a depositional contact with an irregular basement surface.

The infilled paleocanyon model suggested in this study has implications for the stratigraphic sequence not previously addressed. Individual units can be interpreted based upon their distributions and depositional environments. Although erosion has removed large sections of the stratigraphy, the infilled paleocanyons preserve units not typically observed in other regions of the study area.

Prior to detachment faulting, a braided stream environment flowed through the topographic lows in the metamorphic basement complex. The fluvial conglomerates are found within the two southern paleocanyons of the mountain block that would have contained the river system and its sediments. Basalts of the Alverson Formation are deposited in similar distributions and cap the Red Rock conglomerates in both paleocanyons. The basalts may have been connected to the east as suggested by the large exposures mapped by Christensen outside of the mapping region. Significant portions of the Alverson Formation may have also been eroded during the long unconformity between basalt deposition and introduction of the Garnet Formation during detachment faulting. However, unlike the sedimentary units of the stratigraphic sequence, the basalt is more erosion resistant and was not as dependent on the basement structure for preservation in the mountain range. This is evidenced by the high-elevation ridge of Alverson basalt along the central paleocanyon. Basalt outcrops are found above the basement elevations, which is not typical of the younger Tertiary sedimentary units that once buried the formation.

A thick section of sedimentary units in the northernmost section of Cahuilla Canyon represents the third east-west trending infilled paleocanyon (Figure 34). As opposed to the two southern paleocanyons, the Garnet Formation is the oldest unit found in outcrop. The units are bisected by the Central Mountain Fault, which affects the sedimentary thicknesses in the area. In the northernmost paleocanyon, it is unclear whether the older units of the Split Mountain Group are deposited beneath the Garnet Formation. However, to the north of the Central Mountain Fault, the Garnet Formation is deposited directly on the basement complex. A small distribution of the Red Rock and Alverson Formations may be buried under the younger stratigraphy to the south of the fault. This relationship is impossible to prove through field mapping. Deposition may have been contained within the two other paleocanyons.

The Garnet Formation marks the first influence of the detachment system in the Salton Trough. It is assumed that the conglomerates were also deposited primarily within the paleocanyons of the mountain block due to the locations preserved in outcrop. Unlike older stratigraphic units of the Split Mountain Group, the Garnet Formation is

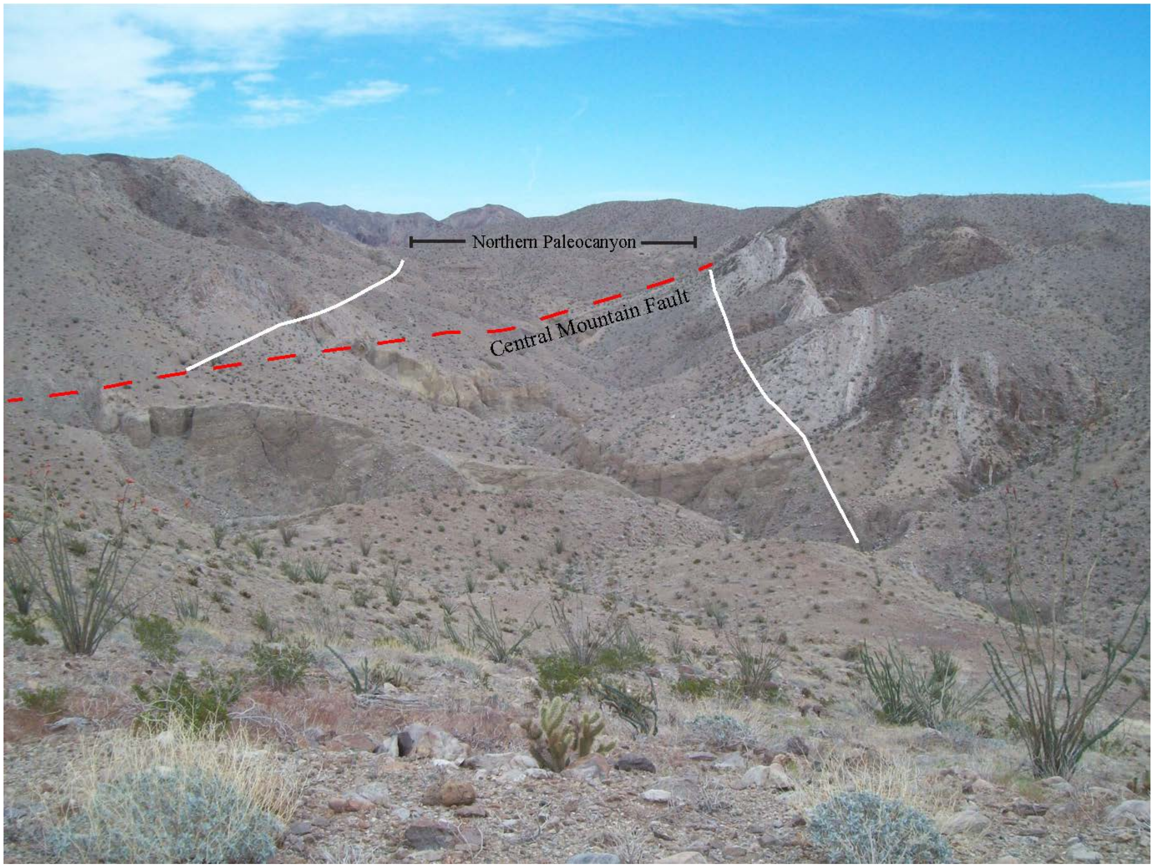

Figure 34. Infilled northern paleocanyon in northern Cahuilla Canyon with the approximate trace of the Central Mountain Fault.

found outside of the mountain block in the study region. This can be resolved with the two lithologies that comprise the unit. The red and green variations of the Garnet Formation typically occupy separate areas and differ by provenance. The red Garnet conglomerates are believed to have been an alluvial unit derived from erosion of the local basement complex, whereas the green Garnet conglomerates are derived from the alluvial fans stemming from the west Salton detachment fault. The outcrop located at the peak of the range grades from red to green and may be evidence of a transition in Garnet Formation deposition. The red lithology may be found at the base of the green conglomerates throughout the mountain block, but this relationship is only observed at the single location.

In the north basin, the red Garnet Formation is deposited on the basement complex as a nonconformity. Thicknesses within the unit vary by location and change significantly within the region. This may be directly related to the irregular topography of the basement. Conglomeratic exposures are typically only a few feet thick and create a thin buffer between the basement complex and the Imperial Group. The thickest sections at the southern margin of the north basin may represent paleotopographic lows in the basement complex that allowed for increased deposition of the alluvial unit. The thinner sections may have been more continuous and may have also covered the basement complex of the mountain block prior to uplift and erosion.

While the red Garnet Formation is found in both the mountain block and the north basin, the green Garnet Formation is only located within the infilled paleocanyons. The green conglomerates may differ from other outcrops in the Salton Trough due to contained deposition within the irregular topography. Likewise, the green conglomerates may not have been deposited in the north basin due to accumulation in the paleotopographic lows of the mountain block. It is unclear whether or not the green Garnet conglomerates are deposited in other paleocanyons buried beneath the uneroded stratigraphic sequence in the adjacent basins.

The Garnet Formation is only found within two of the three paleocanyons. The absence of the conglomerates in the central paleocanyon may be related to the thick deposits of the Alverson basalt. This is evidenced by the stratigraphic relationship observed on the eastern edge of Fossil Canyon. The marine sandstones of the Andradé

Member are found deposited directly on the Alverson basalt (Figure 35). Large rounded clasts of the Alverson subunit can be found within the base of the Imperial Group.

Figure 35. Andradé Member (Pa) with Alverson Basalt inclusions in the central paleocanyon.

Miocene alluvial conglomerates are observed along the margins of the central paleocanyon in Fossil Canyon. This suggests that the central paleocanyon may not have been a paleotopographic low during the initiation of the west Salton detachment fault. Rather, the erosion-resistant basalt infilled the central paleocanyon prior to the development of the alluvial fan systems to the west.

As with the geologic understanding of the unit, the nomenclature for the Garnet Formation has been a constantly changing characteristic throughout studies of the Coyote Mountains. The pre-marine alluvial conglomerates were originally included as the basal section of the Imperial Group by Christensen (1957). The red and green lithologies were considered separate subunits, but the relationship observed at the crest of the range was not discussed. The unit was eventually separated from the Imperial Group when Winker and Kidwell (1996) incorrectly correlated the Miocene-aged unit with the range-capping conglomerates from the Pleistocene. This stratigraphic interpretation renamed the youngest unit of the Split Mountain Group after Christensen's Pleistocene conglomerates at the crest of the range. This study agrees with the separation of the non-marine conglomeratic unit from the marine Imperial Group, but the stratigraphic misinterpretation increased confusion in the nomenclature. As stated earlier in this study, the Garnet conglomerates can be differentiated from the Range Crest gravels by clast content and induration. In northern Fossil Canyon, the contact between the two units can be clearly identified as an angular unconformity (Figure 36). This study retains the Garnet moniker for the Miocene conglomerates for continuity with recent stratigraphic studies of the Salton Trough.

Sedimentation after ocean transgression allowed for a more regionally continuous depositional framework. Andradé sandstones are found throughout the mountain range and surrounding basins, and outcrops are deposited on both older sedimentary units and the basement complex. The marine sandstones would have buried the entire irregular paleotopography prior to mountain uplift in the Pleistocene. This is evidenced by the large exposures of undisturbed Andradé Member in the north basin

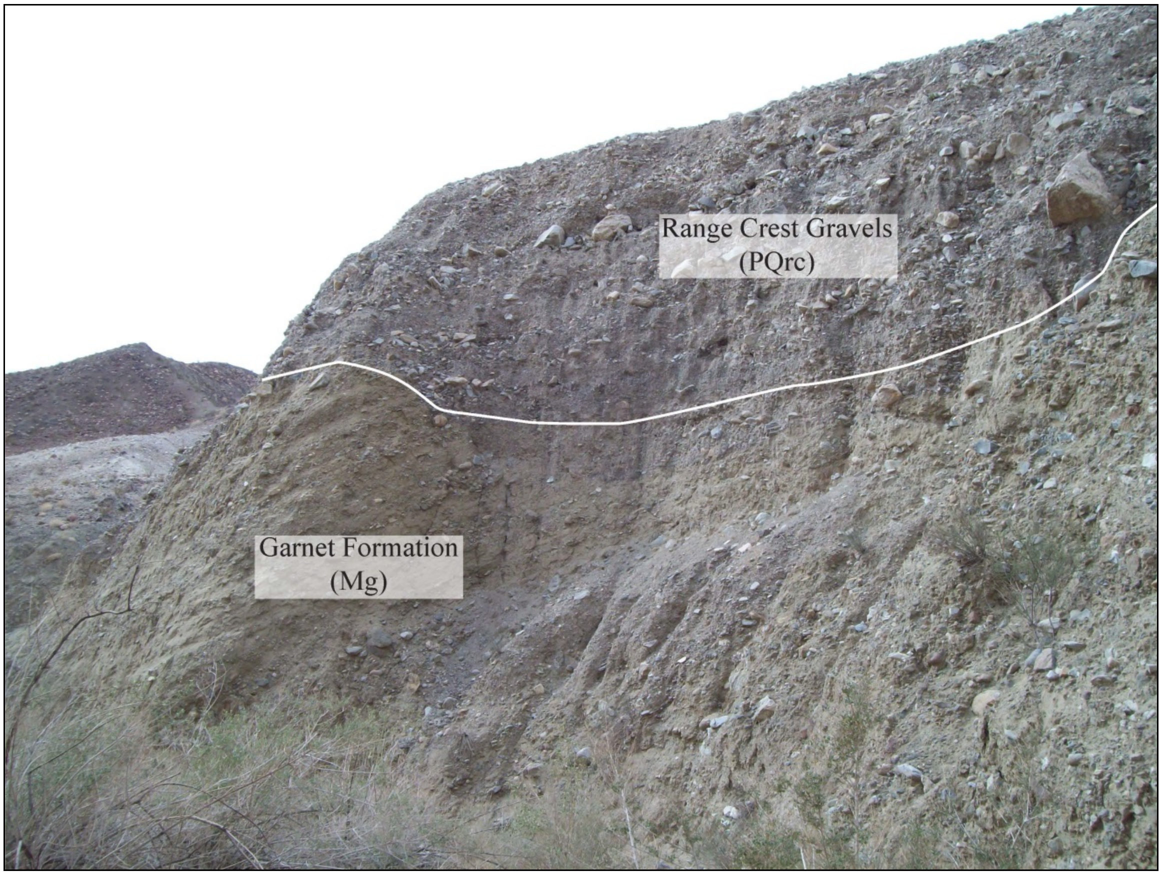

Figure 36. Range Crest gravels (PQrc) deposited at an angular unconformity with the Garnet Formation (Mg) in northern Fossil Canyon.

above the basement complex. In the mountain block, outcrops of the Split Mountain Group observed at the crest of the range in the central and northern paleocanyons would have been buried by the entire Imperial Group. Therefore, it is assumed that the entire basement complex in the mountain block would have been once covered by the marine sandstones of the Andradé Member prior to uplift as well. In the mountain block, Andradé sandstones are preserved within the infilled paleocanyons.

The Deguyños mudstones mark the first influence of the Colorado River within the system. Prodelta muds and silts were deposited out of the sediment load and turbidity currents in the narrow marine basin. Like the Andradé sandstones, the unit would have buried the entire stratigraphic sequence. However, the irregular paleotopography that dictated the distribution of older geologic units would have been covered by the Andradé Member. This is evidenced by the current locations of the mudstone deposits within the mountain block. Only small outcrops of the once regionally continuous prodelta unit are observed. Unlike older stratigraphic units, the Deguyños Formation is not found within the paleocanyons because they would have been infilled by the marine sandstones prior to the introduction of the Colorado River delta system. Rather, mudstone deposits are only preserved along fault escarpments in the mountain block. While the paleotopographic structure protected the older units from erosion, the younger mudstones would not have been preserved during uplift without the creation of basement escarpments along the Fossil Canyon Fault and the Central Mountain Fault.

Fluvial units of the Diablo Formation would have also been deposited above the Imperial Group prior to the initiation of the Elsinore Fault. Erosion has completely removed all evidence of the Palm Spring Group in the mountain block. Despite a lesser extent of uplift, the fluvial sandstones have also been removed from the mapped region in the north basin. The Deguyños Formation is only located on the southern side of the Elsinore Fault. Although the Palm Spring Group is not directly observed in the majority of the study region, the measured thicknesses from previous stratigraphic studies of the Fish-Creek Vallecito basin were used to estimate the amount of uplift from the Elsinore Fault during the formation of the Coyote Mountains.

Uplift of the region has eroded large sections of the stratigraphic sequence, thus exposing older units once buried by the marine and delta units. However, the magnitude of uplift in the mountain block has removed a majority of the previous deposits in the area. Only units adjacent to basement escarpments have been preserved for geologic interpretation.

Basement-related preservation of the stratigraphic sequence is most clearly apparent in the isolated Andradé deposit found on the basement escarpment to the west of West Canyon. The anomalous outcrop of the Andradé Member may represent a submarine ledge in the southernmost paleocanyon. Prior to mountain uplift, the area would have been infilled by sediments of the Split Mountain and Imperial Groups. Erosion has since removed most of the section above the Alverson basalt during mountain formation. Unit removal may have also been greater due to channelized erosion within the mountain block. Despite this, the thin section of the Andradé Member remains higher in the section. The majority of the original deposit has been removed from the area along with the older Garnet Formation assumed to have also been deposited in the paleocanyon. The steep basement protected the deposit on the relatively flat ledge in the basement complex.

While the paleocanyons have protected large sections of the stratigraphy, the majority of exposures in the mountain block are found proximal to fault scarps in the mountain system. Unit thicknesses in the Split Mountain and Imperial Groups become thinner with distance from the Fossil Canyon Fault. In the northernmost paleocanyon, outcrops south of the Central Mountain Fault are significantly thicker than the uplifted, isolated Garnet conglomerates on the mountain ridge to the north. In the western mapping region, a large section of the Andradé sandstone is found south of the Central Mountain Fault at the margin of the north basin. This may be due to the steepness and size of the basement escarpments created through faulting compared to the natural irregularity prior to stratigraphic deposition in the region.

To review, the stratigraphic units in the Coyote Mountains were deposited on an irregular basement topography. The oldest units were most likely contained in the three paleocanyons exposed in the mountain block. Other infilled paleocanyons may be buried in the adjacent basins, but uplift in the mountain block allowed for increased erosion and exposed the structures. The introduction of the Gulf of California to the region infilled the remaining basement topography with sandstones of the Andradé Member. Deltaic units of the upper Imperial Group and Palm Spring Group were emplaced above the earlier stratigraphic section without any topographic constraints that affected the older stratigraphy. Transpressional uplift eroded the majority of the stratigraphy sequence. Only outcrops within the paleocanyons or along fault traces were protected from erosion by the erosion-resistant basement complex. A schematic diagram illustrating the depositional relationships and uplift-induced erosion is found in Figure 37. The timing and nature of uplift and faulting will be discussed later in the section.

Post-Deformation Stratigraphy

Although stratigraphic units deposited in the Salton Trough were significantly eroded during the creation of the Coyote Mountains, the younger alluvial units at the crest and flanks of the range were deposited during uplift. The two units are similar, but occupy different areas of the mapping region. They may have also been deposited at different times in mountain formation, but relative age dating is difficult as they do not interact. Problems also occur when attempting to correlate the units with other alluvial

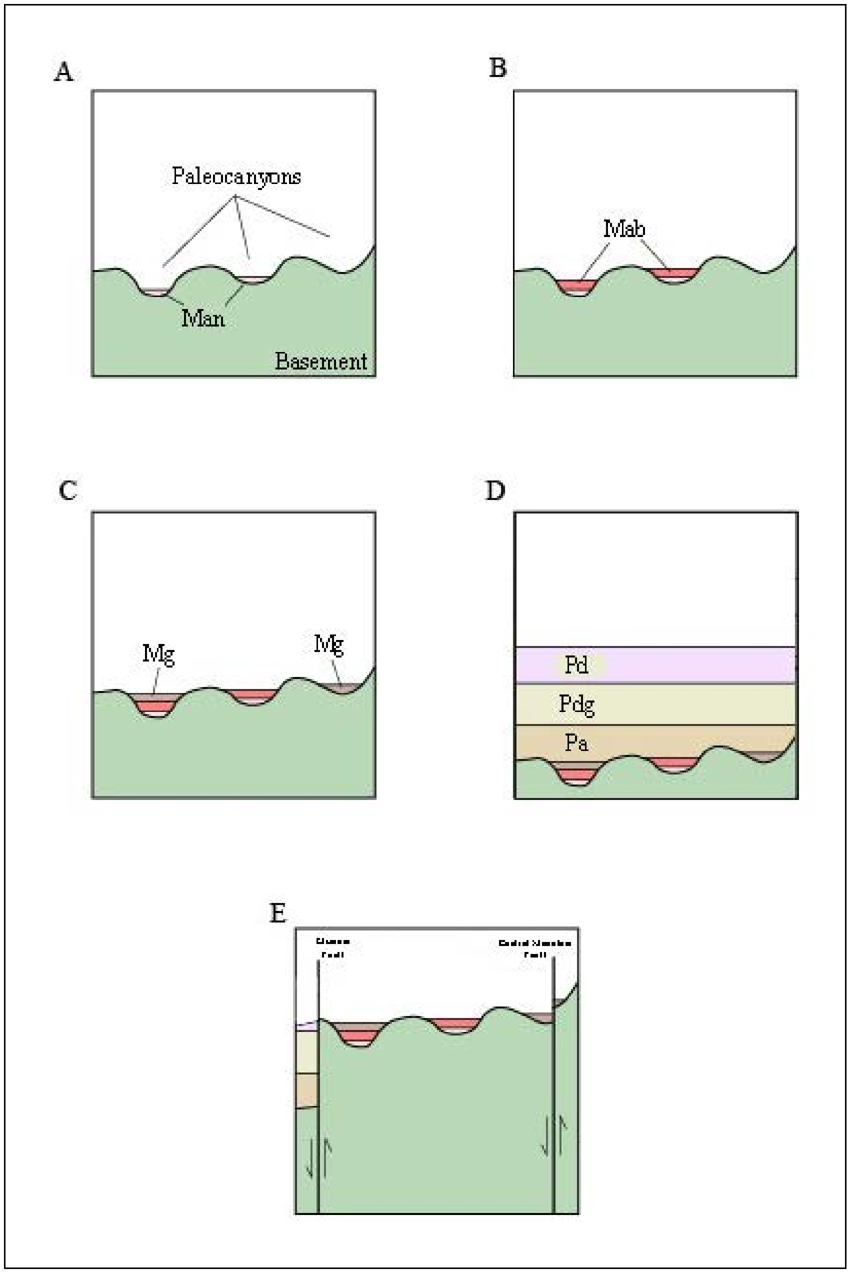

Figure 37. Schematic diagram for stratigraphic deposition on the irregular basement complex during the formation of the Coyote Mountains.

units found in the surrounding basins in other studies due to the young age and unconsolidated nature of the deposits. This report will only discuss the units within the system.

The Range Crest gravels are likely the older of the two alluvial units found in the mapping area. The Pleistocene/Quaternary unit resembles the Miocene Garnet Formation in the northernmost paleocanyon but is significantly less consolidated. The range-capping unit is most likely derived from alluvial fans created during early uplift of the Coyote Mountains. This is evidenced by the coverage of the older stratigraphic sequence and basement complex along the entire distribution of the unit. Alluvial fans would have developed from local uplift of the stratigraphic section and eventual exposure of the basement complex to the east and northeast outside of the mapping region as evidenced by the marble clasts within the unit. Greater amounts of uplift in the range are observed east of the Fossil Canyon Fault and create the highest elevation basement exposures in the mountain range. Over time, a majority of the unit has also been eroded away, leaving only the basal remnants of the unit. The remnant Range Crest gravels were uplifted with the mountain block to their present-day elevations. Unlike the pre-deformational stratigraphy, the relatively young age of the Range Crest gravels has allowed for exposures to remain at high elevations without protection from the erosion-resistant basement complex. However, the unit is eroding quickly as Christensen (1957) hypothesized that the unit once covered nine square kilometers. The Range Crest gravels also lack the original pediment surface observed in the older alluvium. Desert patina at the surface may have been removed by erosion during uplift or was never formed due to a differing climate during emplacement. While climatic differences were suggested by Christensen, this hypothesis cannot be confirmed or denied in this study.

The older alluvium is found on the northern and southern flanks of the range and retains the original pediment surfaces. Unlike the Range Crest gravels, the unit was likely derived from the mountain block during uplift based upon its distribution parallel to the Coyote Mountain range. Current drainages and channels stemming from the Coyote Mountains bisect the older alluvium deposits and are filled with current alluvium at lower elevations. Because of this relationship, Todd (2004) described the unit as Terrace alluvium, which had been uplifted from its original elevation during the formation of the Coyote Mountains. Although minor, uplift has clearly placed the unit above the current desert floor. Possible remnants of the older alluvium are observed to the north of Elsinore Fault along the margin of the mountain block. Similar to the Range Crest gravels, the older alluvium is deposited above the remaining stratigraphic sequence at an angular unconformity. This is evidence that deposition must have occurred after the onset of deformation in both units.

The anomalous deposit of the older alluvium in the eastern range front has a distinctly different lithology than other post-deformational units in the region. The section may be part of a separate unit not recognized in this study. The layers of reworked coquina beds may be the remains of the Deguyños Formation eroded from the mountain block during uplift. The steep bedding attitudes adjacent to the Elsinore Fault show a significant amount of cementation and translation not observed in other exposures of the older alluvium. More work is needed on this unit to recognize its place in the geologic history of the Coyote Mountains and Salton Trough.

Deformation

The stratigraphic units of the Salton Trough have since been exposed and deformed during the creation of the Coyote Mountains. As mentioned earlier, large sections of the stratigraphy have been preserved due to fault escarpments created in the basement complex. While oblique motion along the Elsinore Fault is considered the major factor in the formation of the range, transpressional stresses from the large dextral fault have resulted in smaller-scale structures in the mapping area. The differing orientations for faulting will first be discussed, followed by bedding and folding in the region.

Faulting

The onset of faulting occurred during either of the two major tectonic episodes in the geologic history of the Coyote Mountains. It is currently recognized that displacement along the west Salton detachment fault created tectonic subsidence and formed the Salton Trough. The initiation of the Elsinore Fault is believed to have uplifted the Coyote Mountains to their current elevations. Determining which tectonic event created the smaller-scale faults will be critical in developing an accurate geologic history of the region.

One hypothesis suggests that normal faulting in the north basin could have occurred in the hanging wall of the west Salton detachment fault prior to the initiation of the Elsinore Fault. Extensional normal faulting would have occurred parallel to the detachment system and created the half-grabens visible in the basin units. Subsequent clockwise rotation from strike-slip tectonism would have rotated the faults to their current northeast-southwest orientations. The new transpressional stress regime could have also reactivated older extensional features and created new antithetical shear structures along the former traces. This would be similar to the Elsinore Fault, which activated along the strike of the former west Salton detachment fault. Faulting could have also been synchronous with deposition of the upper Deguyños Formation and Palm Spring Group as suggested by rotational data from the Fish Creek-Vallecito Basin. This would place the beginning of deformation within the ambiguous geologic history between subsidence and uplift in the system.

Detachment-related faulting opposes assertions made in previous studies. The hanging wall of the detachment system was believed to be undisturbed during basin subsidence due to nonorthogonal fault displacement (Dorsey, 2005). This study agrees as evidenced by the lack of faulting to the south of the Elsinore Fault in the mountain fronts. Outcrops of the Imperial and Palm Spring Groups would have been faulted in a similar fashion to units in the mountain block and north basin if the structures were created during detachment. Prior to uplift, the basin units of the Salton Trough would have experienced similar stresses during continental rifting and thus possess pre-Elsinore Fault deformational characteristics. Coquina beds in the Deguyños Formation do not show evidence of faulting and create a continuous feature in the western range front.

On the contrary, evidence for Elsinore Fault-related deformation is very strong. Regional right-lateral transpression has resulted in strain partitioning and created the fault array observed within the Coyote Mountains and north basin. The Central Mountain Fault and the Fossil Canyon Fault differ by ~10° and ~20° off of the trace of the Elsinore fault, respectively, and represent synthetic shears structures consistent with dextral fault motion. However, transpressional stresses and uplift along the Elsinore Fault have resulted in oblique displacement along the two large mountains faults in the system. The significant vertical displacement in the synthetic faults has created basement escarpments and preserved large sections of the Tertiary stratigraphy in the mountain block for geologic interpretation.

Although the two synthetic faults have similar strike orientations in the Coyote Mountains, the nature of displacement between the two is very different. This could be the result of increasing transpressional stresses from the Elsinore Fault based upon location. Pure dextral displacement is recorded in the fault trace adjacent to the Fish Creek-Vallecito basin. In this area, the Elsinore Fault lacks vertical displacement apparent in the mountainous region to the southeast. Uplift magnitudes steadily increase along the strike of the transpressional bend. This is evidenced by elevation changes in the basement complex across the range as seen in the profile of the Coyote Mountains. The highest elevations in the area are located to the east and northeast of the Fossil Canyon Fault. Within the study area, the amount of uplift is estimated at approximately 5 kilometers along the crest of the range. Different estimates are predicted to the northwest and southeast based upon these assumptions.

The Central Mountain Fault has not been recognized in previous studies of the Coyote Mountains. Christensen (1957) mapped a portion of the fault along the southern margin of the north basin, but the fault is truncated by a northeastern-striking normal fault prior to reaching higher elevations to the north of Cahuilla Canyon. Subsequent maps of the area have also omitted the large structure despite a distinct fault exposure in the sedimentary sequence and brecciation in the typically undisturbed basement complex at the crest of the range. A complete trace of the Central Mountain Fault is necessary in understanding the true structure and formation of the mountain range. Recognizing the feature also explains the preservation of sedimentary units that would normally be eroded during uplift. To the north of the fault, only thin, discontinuous outcrops of the basal Garnet conglomerates are found deposited on the basement complex buried under Quaternary alluvium. As evidenced by fault lineations and stratigraphic relationships between the fault strands, the structure possesses oblique displacement similar to the Elsinore Fault.

In the eastern mapping region, the Fossil Canyon Fault lacks observable displacement lineations along strike. The curviplanar fault trace stems directly from the Elsinore Fault and has a general strike consistent with synthetic faulting in the dextral system. Unlike the Central Mountain Fault, normal displacement is apparent based upon the non-vertical fault plane and sedimentary units deposited on the basement escarpments to the northeast. The large vertical component observed in the fault may have accommodated the increasing uplift within the basement complex of the eastern Coyote Mountains. As dextral displacement in the Elsinore Fault decreased along the transpressional bend, greater magnitudes of vertical movement uplifted the basement block to the northeast of the fault. The synthetic Fossil Canyon Fault mirrored the changing stresses in the mountain block.

Dextral displacement along the Fossil Canyon Fault is inferred from offset in Alverson basalt outcrops on either side of the fault in southern Fossil Canyon. The exact estimate is problematic due to the erratic fault trace and channelized distributions of the Miocene basalt exposures. Splays observed in Fossil Canyon may be more prevalent and record more dextral motion than the two small faults mapped in this study; however, due to normal displacement and erosion, they would be buried under in the footwall by Quaternary alluvium. Christensen (1957) mapped two parallel fault structures along

Fossil Canyon as opposed to the single Fossil Canyon Fault in this study, but this may have been interpreted from the minor fault splays exposed in the drainage.

The two synthetic fault structures exposed in the Central Coyote Mountains may be part of a larger system-wide synthetic fault array on the northern side of the Elsinore Fault. The Central Mountain Fault trace has the largest magnitude of displacement in the northwestern mapping region. The fault trace eventually ends in the mountain block to the southeast, which is laterally consistent with the northwestern exposure of the Fossil Canyon Fault at the margin of the north basin. Changing transpressional stresses may have created a rightward step between the two *en echelon* faults. To the west of the mapping area, other northwest-striking synthetic faults may be exposed within the mountain system with similar relationships. Due to a lesser extent of uplift along the Elsinore Fault, the hypothetical synthetic faults would also display smaller degrees of vertical displacement. This could be related to the lower elevations of basement exposures in the western Coyote Mountains as well as the distance between the Elsinore Fault and the sedimentary units of the north basin.

Previous maps in the Fish Creek-Vallecito basin lack the northwest-southeast trending synthetic faults adjacent to the Elsinore Fault. Quaternary alluvial units cover a significant area where the proposed synthetic faults would occur. In this region, the Elsinore Fault exhibits pure dextral displacement without transpressional uplift. Synthetic faults stemming from this section of the Elsinore Fault would also display pure dextral motion. A continuation of the synthetic fault array may continue outside of the mountain block in the Fish Creek-Vallecito basin but remain buried due to the absence of vertical displacement.

The length of the synthetic faults may also be related to the geomorphology of the Coyote Mountains. Oblique displacement along the major structures appears to define the extent of the mountain block. The Central Mountain Fault creates the southwestern boarder of the north basin in the western mapping region. The initiation of the Fossil Canyon Fault begins at the margin of the north basin at the proposed step over in synthetic faulting. The extent of transpressional uplift and synthetic faulting may end with distance from the Elsinore Fault, and units of the north basin would have been subjected differing stresses.

While the two major faults in the mountain system are consistent with synthetic faulting, the many smaller-scale faults in the region can be attributed to antithetical faulting from the dextral Elsinore Fault. As seen in Figure 31, fault orientations in the mountain block and the north basin fall within the necessary boundaries for antithetical shear structures. However, the nature of displacement between faults in the mountain block and north basin is very different. This is explained through differing stresses with proximity to the major Elsinore Fault.

Within the mountain block, the antithetical faults are most noticeable in the sedimentary units of northern Fossil Canyon. Similar faults are found throughout the Tertiary stratigraphy, but the majority of faulting with measurable lineations is located in this region. This study predicts that faulting was pervasive in the sedimentary cover prior to erosion of the stratigraphic sequence during mountain uplift, but the smaller features did not create the brecciated basement material observed along the synthetic faults. As with the major Elsinore Fault, antithetical faults have oblique displacement but with opposite orientations as the structures possess both a left-lateral and normal component.

Because most of the antithetical faults are found in northern Fossil Canyon, they would be subjected to similar stresses. This is apparent when compared to the antithetical faults located in the north basin.

North basin faults are observable with similar strike orientations as the antithetical faults in the mountain block but lack the sinistral displacement measured in the Fossil Canyon structures. The basin region was subjected to differing stresses due to its distance from the Elsinore Fault. Significantly, less uplift has occurred in the area compared to the mountain block, and the region is not influenced by the larger synthetic faults. As suggested earlier, these two characteristics may be related and define the boundaries of the uplifted mountain block. Despite the distance to the north, Elsinore Fault-related transpression has still deformed the north basin. Uplift and tilting has occurred in the basement complex and sedimentary units, which will be discussed later. North basin faults are the result of dextral torsional stresses from the transpressional system. The rotational stresses along with uplift of the southwestern margin of the basin created the hinged faults with increasing displacement along strike. As with the synthetic faults found in the mountain block, the antithetical faults of the north basin are characterized by their location with respect to the Elsinore Fault.

Fault orientations shift between the western and eastern portions of the mapping region. Along the western border, faults strike to the north-south, whereas faults further east strike to the northeast-southwest. The longer fault traces also curve to the north with distance from the range. The shifting orientations are related to the changing vertical displacement on the Elsinore Fault. In the west and north, antithetical faults such as the North Basin Fault are found closer to orientations expected from a purely dextral system. This is due to the lesser extent of uplift affecting the area. Antithetical faults to the east are more closely associated with the transpressional uplift as evidenced by the similar strikes to antithetical faults in the mountain block. It is predicted that antithetical faults within the north basin and adjacent Fish Creek-Vallecito basin continue to rotate to the west due to the changing stresses along the strike of the Elsinore Fault.

Influence from the Elsinore Fault is also apparent in the primary dip directions of the antithetical faults of the north basin. A majority of the hinged normal faults dip the southeast, but the largest magnitude faults possess opposite dip directions. This is true of the North Basin Fault and the mountain block margin fault, which dip to the west and northwest, respectively. The large normal faults down drop the basin units from the uplifted basement complex of the uplifted mountain block. As seen in Figure 30b, the paleostress tension axis trends to the northwest and plunges below horizontal. This would have preferentially formed the larger antithetical pull-apart structures to have northwest dip directions as well. The smaller normal faults with opposite orientations may have been formed to accommodate the significant amount of displacement from the larger faults in the system.

Synthetic and antithetical faulting is only found to the north of the Elsinore Fault. In the desert basin to the south of the range, faulting is not present in the exposed units of the upper Imperial and Palm Spring Groups. This supports the hypothesis that all faulting in the study region is related to transpressional stresses and strain partitioning from the Elsinore Fault. Ductile deformation observed in the units is related to uplift of the adjacent mountain block, which will be discussed later.

Bedding Structure

The changing bedding orientations observed throughout the Coyote Mountains can be explained through two hypotheses. Either the observed units in the region were gradually deformed and folded during transpressional uplift and mountain creation, or blocky fracture in the basement complex has translocated the younger stratigraphic units to their current orientations. Dibblee (1954) originally believed that the Coyote Mountains were the remnants of a large anticline based upon opposite bedding orientations on the northern and southern flanks of the range. Christensen (1957) went into further detail by suggesting that ductile deformation occurred within the younger, less indurated sedimentary units, but brittle fracture deformed the older stratigraphic sequence and basement complex. This more detailed deformational idea was strengthened due to the fact that the basement complex was too shallow during mountain formation to undergo ductile deformation (Sylvester and Smith, 1976). Although basement cataclasis was suggested, it was not observed in this study and will not be included in the deformational model for the central Coyote Mountains.

As stated in the Results chapter, bedding is generally found in two primary orientations. Units in the southern mountain block and both mountain fronts dip to the south and southeast, whereas the sedimentary units of the north basin dip to the north and northeast. In Figure 32, general bedding in the mountain block is found in several orientations, but the measurements may be skewed due to the amount of faulting in northern Fossil Canyon and the northern paleocanyon. Ductile deformation is only directly observed in the changing dips of the mountain fronts within the Diablo and Deguyños Formations. Younger units in the north basin may also possess gradual changes in dip magnitudes, but faulting and ambiguous bedding planes are prevalent in the region.

Similar to the fault array in the Coyote Mountains, bedding orientations measured in the study area are directly related to displacement on the Elsinore Fault. The southern dips in the mountain block can be explained through the tilting of the entire basement complex. Although uplift occurred from displacement on the Elsinore Fault along the southern margin of the range, the magnitude is the greatest along the range crest. This is evidenced by the Garnet Formation deposited at the highest elevations in the mapping region. The southern dip orientations observed in Fossil Canyon represent the translocation of the stratigraphic sequence with movement of the basement complex. Paleostress estimates plotted in Figure 30b show the pressure axis trending perpendicular to the mountain block and plunging approximately 25°, which may be indicative of regional tilting from the Elsinore Fault. Similar displacement along the synthetic faults in the mountain block may have also contributed to the orientation of the mountain block.

On the northern side of the range, bedding is found with opposite orientations. Units of the Imperial Group dip to the northeast and north depending on location in the north basin. Bedding orientations shift slightly across the hinged fault traces and may be the result of torsion in the system. Regardless, the sedimentary bedding orientations differ significantly from other regions in the mapping area. Along the southern margin of the north basin, stratigraphic cover is relatively thin, and the Andradé Member of the Imperial Group creates dip slopes on the exposed escarpments of the basement complex. Based upon this relationship, it is also assumed that the sedimentary cover was translocated with the tilting basement complex similar to the mountain block to the south.

However, due to major antithetical faults and distance from the Elsinore Fault, bedding orientations are found generally to the north.

Anomalous bedding orientations are observed in the red Garnet conglomerates at the southern margin of the north basin. The conglomerates dip to the north despite being clearly deposited on the mountain block. Dips measured in the outcrop could be the result of the hinged normal fault mapped to the east, which may have continued to the southwest and translocated the units with the basement complex. The trace creates large “slickengrooves” in the basement, but is ultimately lost along strike. Therefore, faulting is not considered the major factor in bedding orientations at this location.

A significant vertical distance is observed between the outcrop and the red Garnet conglomerates deposited at the crest of the range. The lack of fault evidence between the two outcrops suggests the relationship is the result of the highly irregular basement complex similar to the infilled paleocanyons further south. The thick section of the red Garnet Formation may be an uplifted and exposed edge of another paleotopographic low in the region. This would suggest that the stratigraphic complexity mapped in the mountain block could also be found below the marine mudstones of the north basin.

Christensen (1957) maps a syncline to the north of the range in the north basin. The extent of the mapping region in this study only contains the southern limb of the fold, and ductile deformation was not directly observed to the north of the range. Folding is measureable in the upper Imperial and Palm Spring Groups of the west and east range fronts. A wide syncline is found in the sedimentary units of the west range front, but the northern limb is truncated by the Elsinore Fault at the margin of the basin.

Bedding attitudes in the northern limb of the fold become steeper with proximity to the Elsinore Fault, but dip magnitudes lessen directly against the major oblique fault. This may represent drag folding from uplift of the basement complex to the north. Although a syncline is not formed in the east range front, a similar steepening in stratigraphic bedding is observed; however, drag folding cannot be measured in the highly weathered material.

As proposed by Christensen, ductile deformation may have only occurred in the younger sedimentary units of the stratigraphic sequence. This study cannot deny this claim as observations in the field area match these original conclusions. Outcrops of the older stratigraphy are too highly faulted and discontinuous to make conclusions on their deformational nature during early mountain uplift. Ductile deformation is clearly observed and measured in the younger units of the Deguyños and Diablo Formations. Both units are typically highly weathered in outcrop and lack consistent bedding planes in the region. The presence of ductile deformation in the younger stratigraphic units has implications for the early structure of the Coyote Mountains during the initiation of the Elsinore Fault.

The reversal of bedding orientations across the north-south transect in the mapping region may be the remnants of the large anticline originally hypothesized by Dibblee. Related to transpressional uplift along the Elsinore Fault, younger Colorado River-derived units of the upper stratigraphy would have been deformed during the initiation of the fault in the Pleistocene. A full anticline would have been short-lived as erosion of the uplifted sedimentary units above the present-day mountain block would have begun immediately after fault initiation. As hypothesized by Christensen (1957), older stratigraphic units would have fractured from the transpressional stresses and translocated with the basement complex from faulting to their current orientations. Synthetic and antithetical faulting would have occurred early in the geologic history of the Elsinore Fault and may have affected the geometry of the early fold in the system. After erosional unroofing of the mountain block, continued displacement on the Elsinore Fault would continue to deform the remnant fold limbs to the north and south of the mountain block. Deposition of the Pleistocene and Quaternary alluvial units would have occurred well after the onset of deformation in the region. This is evidenced by the angular unconformity between the Split Mountain Group and the high-elevation alluvial units in the mountain block viewed in Figure 36. A visual diagram of the proposed geologic history of the range based on observations in the field area can be found in Figure 38.

The smaller syncline observed in the western range front may have been an associate fold of the larger hypothetical anticline that was previously formed early above the mountain system. Along with Christensen's syncline in the north basin and his hypothetical "Ocotillo Syncline" in the desert basin to the south, folding in the region may have occurred from region-wide north-south compression during the transition from detachment faulting to dextral faulting from the San Andreas fault system. Although this hypothesis would fit into the larger deformation of the Salton Trough region, evidence is severely lacking in this study.

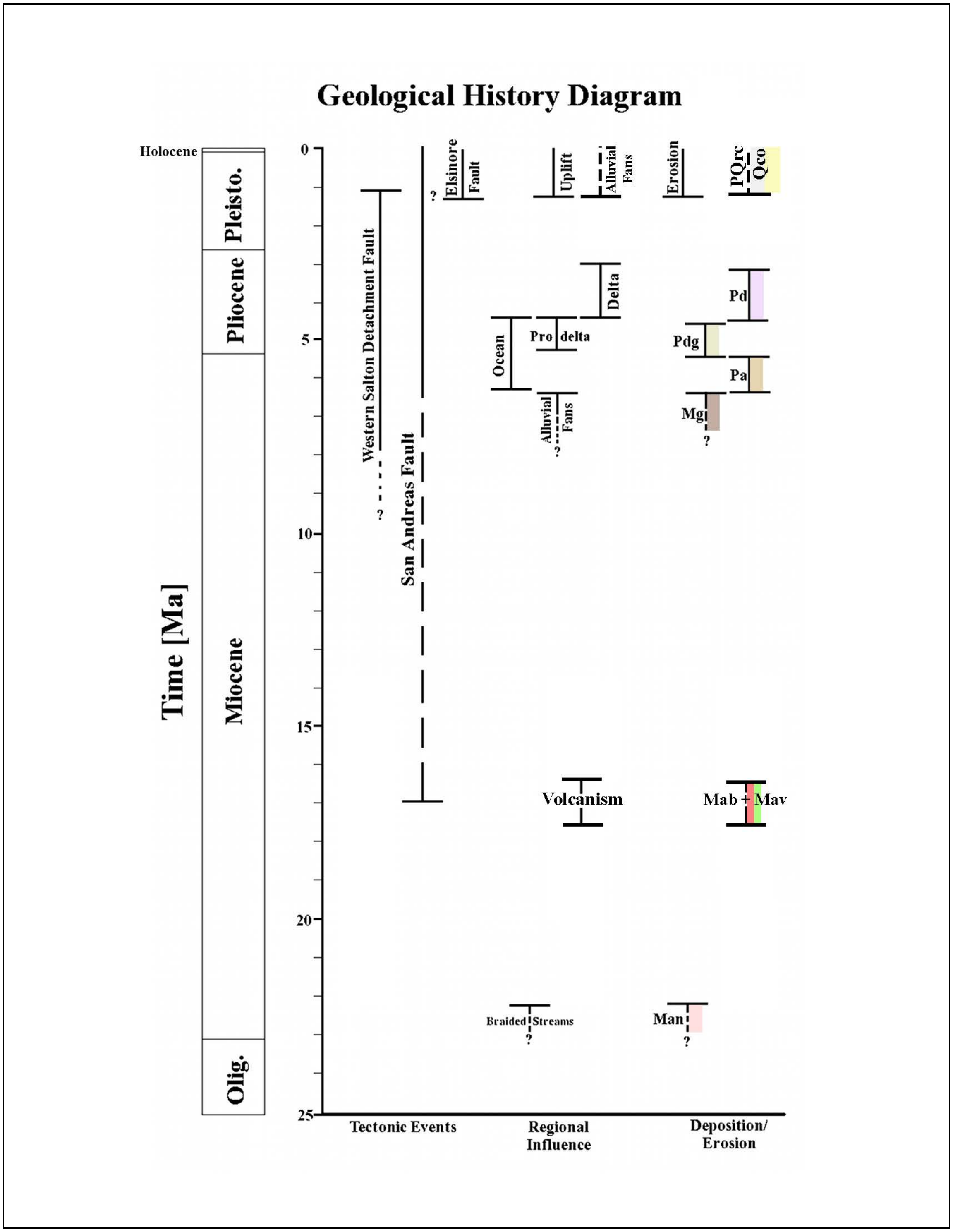

Figure 38. Geologic history diagram of the Coyote Mountains.

CHAPTER VI

CONCLUSION

The current structural geology of the central Coyote Mountains is dependent on the two major tectonic episodes to occur in the area. Regional detachment on the west Salton detachment fault allowed for tectonic subsidence and the deposition of the majority of the stratigraphic sequence. The initiation of the Elsinore Fault of the southern California San Andreas fault system uplifted and deformed the units of the basin and created the present-day Coyote Mountains. Based upon field mapping and observations in this study, new conclusions on the geologic structure of the Coyote Mountains can be made.

The stratigraphic sequence was deposited on an irregular basement paleotopography, which included three east-west trending paleocanyons found in the mountain block. While previous studies assert that most of the structure is hypothetical under the sedimentary cover, new assumptions of the basement complex can be made based upon distributions and depositional characteristics of the stratigraphic sequence in the mountain block. An irregular basement structure allowed for similar geologic units to be deposited at varying elevations, thus complicating unit correlation. The Red Rock and Alverson Formations are exposed in the two southern paleocanyons. Paleotopographic lows in the basement complex were infilled with the pre-detachment conglomerates and volcanics prior to any faulting in the region. Similar structures may be present under the thick basin units to the north and south of the range.

The initiation of the west Salton detachment fault resulted in the deposition of the Garnet Formation within the same paleotopographic lows in the region. The Miocene-aged alluvial conglomerates can be divided into separate subunits based upon provenance. The basal red Garnet conglomerate is a massive unit probably derived from local irregularities in the basement complex, and the green Garnet conglomerate is a relatively younger subunit derived from the footwall of the detachment system. The red Garnet Formation is also the oldest Tertiary unit exposed in the north basin and may have been more prevalent in the region prior to uplift and erosion. The green Garnet Formation is deposited within the southern and northern paleocanyons of the mountain block and may have a distinct lithology due to contained deposition in the extreme basement paleotopography.

The conformable Andradé Member of the Latrania Formation is the oldest unit of the Imperial Group and marks ocean transgression to the region. The marine sandstones are found throughout the mapping region and would have completely buried the basement irregularities that dictated the deposition of previous units. Younger sedimentary units of the Imperial Group and Palm Spring Group would have subsequently been deposited above the marine sandstones throughout the mapping region prior to uplift, deformation, and erosion.

The initiation of the Elsinore Fault in the Pleistocene introduced transpressional stresses to the previously undisturbed basin units. Oblique displacement along the typically dextral Elsinore Fault uplifted the stratigraphy and created the Coyote

Mountains. Strain partitioning resulted in a fault array consistent with synthetic and antithetical faulting for the transpressional Elsinore Fault. Two large synthetic faults strike to the northwest-southeast within the mountain block and may define the geomorphology of the uplifted basement region. Antithetical faults are found at a smaller magnitude and are present in both the mountain block and north basin. The nature of faulting in the region may be directly associated with location in respect to the Elsinore fault from changing stress regimes in the transpressional bend of the fault trace.

Faulting in the mountain block has also preserved the stratigraphic sequence at higher elevations in the mountain block. During uplift of the Coyote Mountain, most of the stratigraphy sequence in the mountain region was removed by erosion. Only units deposited within the infilled paleocanyons and adjacent to fault escarpments currently remain at higher elevations. Pleistocene and Quaternary alluvial units deposited during uplift, such as the Range Crest gravels, remain due to their relatively young age and cap the entire stratigraphic sequence at an angular unconformity.

As with brittle fracture, bedding orientations measured throughout the region is the result of displacement along the Elsinore Fault. In the mountain block and north basin, tilting and faulting within the basement complex has translocated the stratigraphic units to their current orientations. South of the Elsinore Fault, mountain uplift has resulted in the folding of the younger basin units and may imply regional folding in the upper sedimentary sequence during the initiation of the Elsinore Fault prior to erosion.

Future work is necessary in the region to confirm or deny assumptions made in this study. Due to the size of the mapping area, interpretations for deformation may change with increased data elsewhere in the range. Within the north-south transect, the nature of faulting appears to shift from west to east from changing stresses along the oblique Elsinore Fault. Although conclusions in this study are consistent with observations in the study region, changing conditions and stress regimes throughout the area could alter the model for mountain formation. Geologic mapping of the remainder of the range at the same scale would be necessary to obtain a better geologic structure and history during development of the Coyote Mountains. More detailed study of the basement complex as well may find deformational clues not readily observed in the Tertiary stratigraphic sequence.

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PLATES

Plate 1

Geologic Map of the Central Coyote Mountains

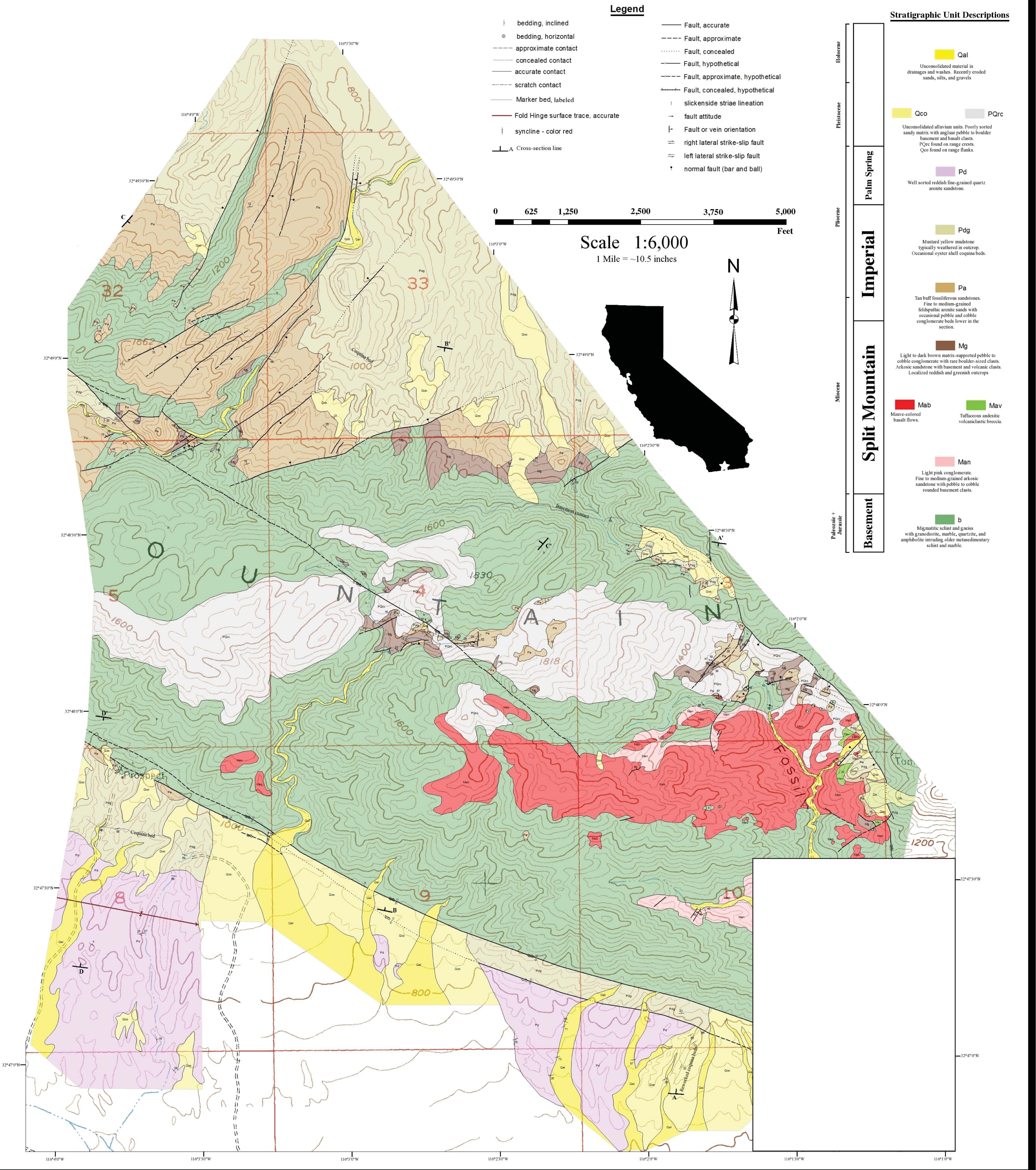
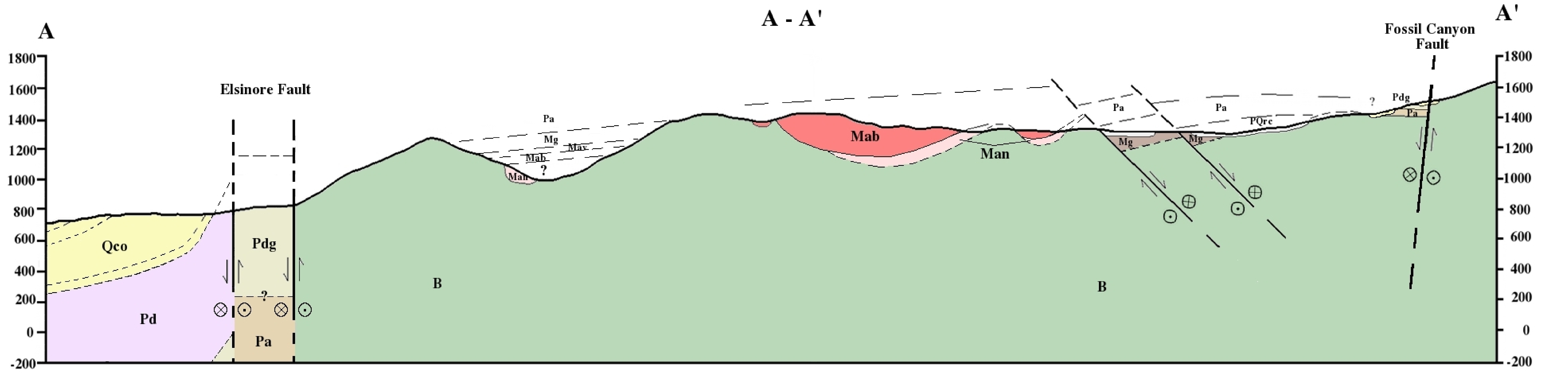
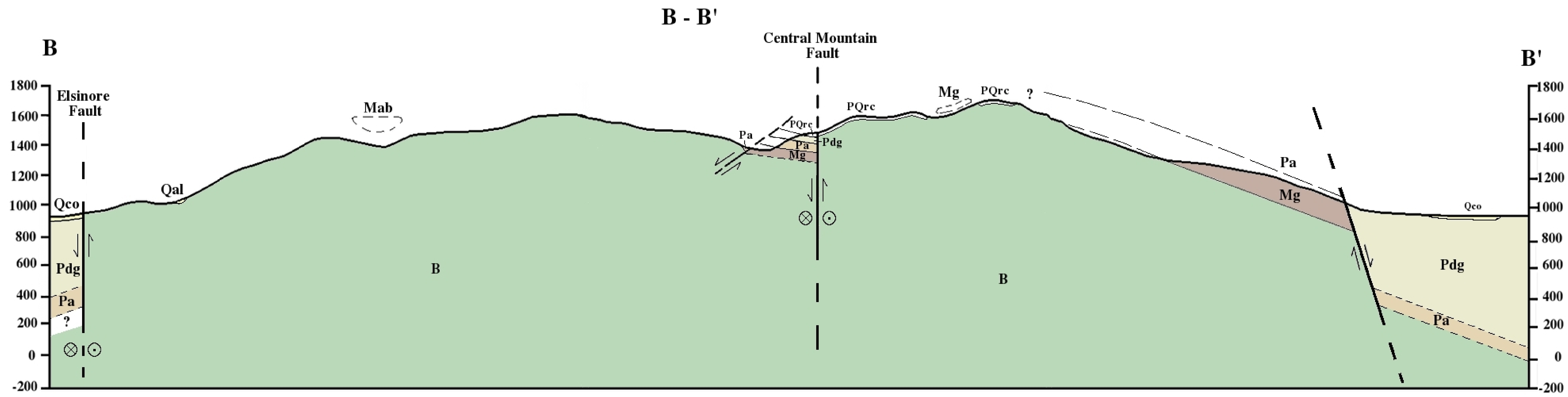
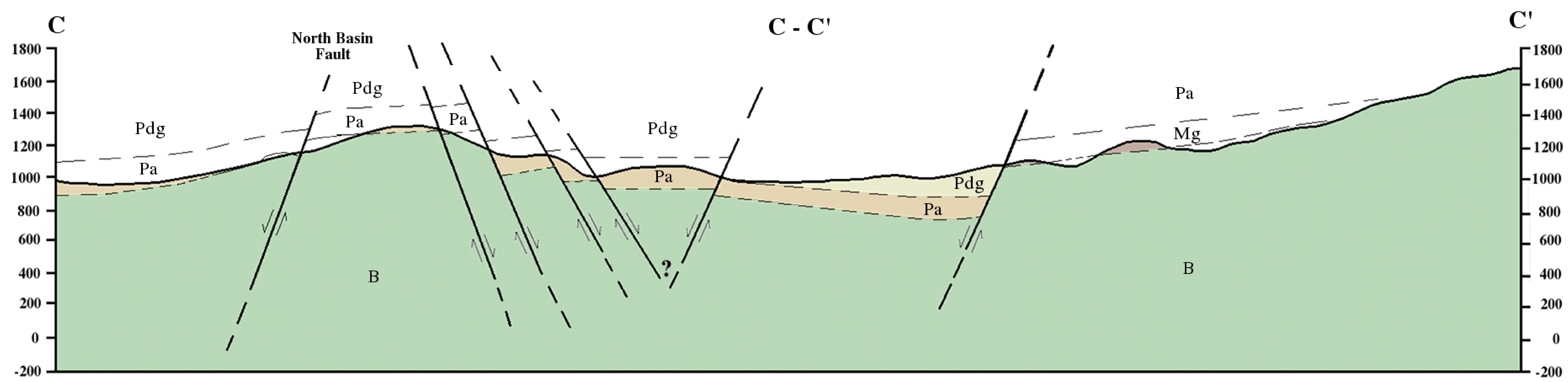


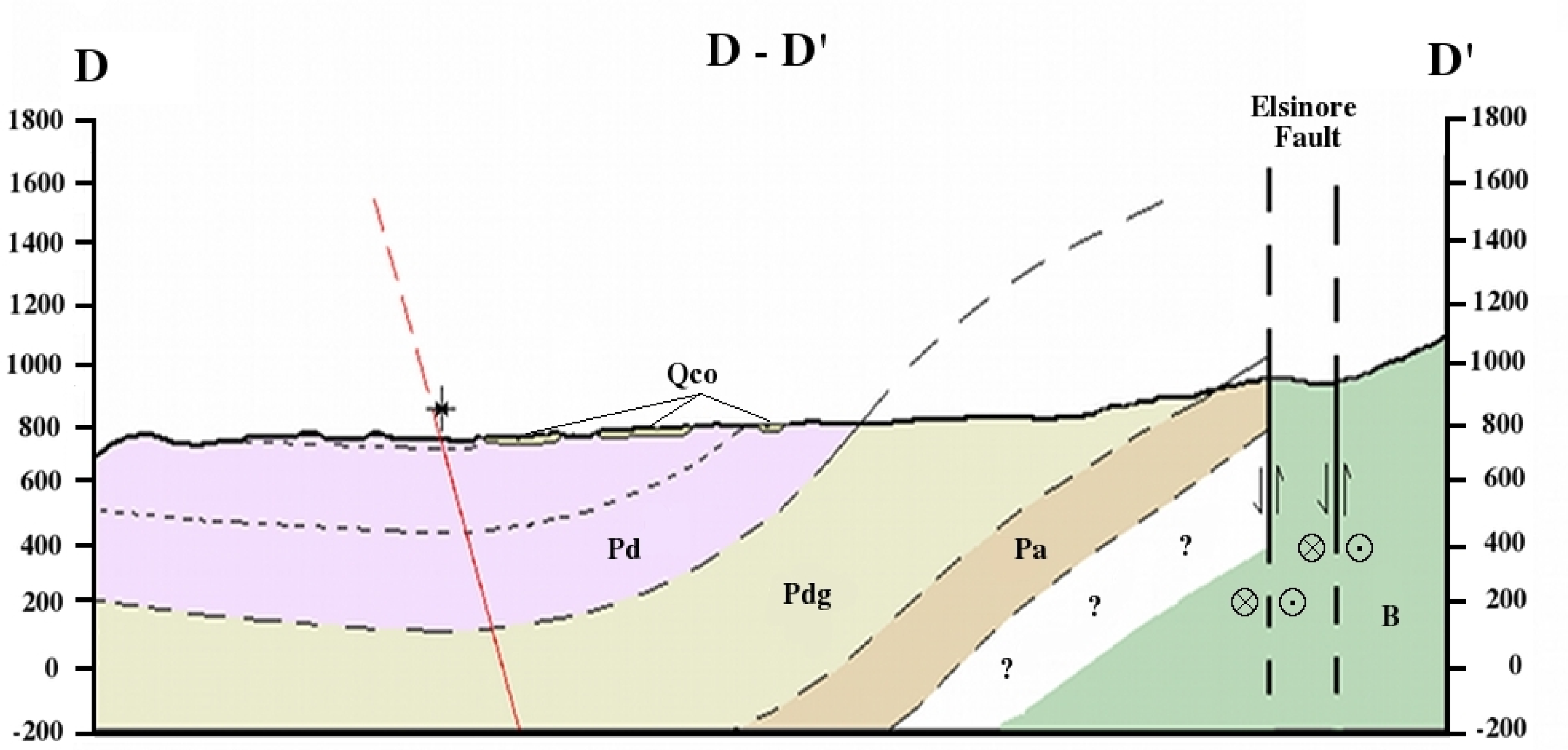
Plate 2

Structural Cross-Sections









0 625 1,250 2,500 3,750 5,000

Feet

Legend

Scale 1:6,000

1 Mile = ~10.5 inches

- Qal
- Qco
- PQrc
- Pd
- Pdg
- Pa
- Mg
- Mav
- Mab
- Man
- B

- Faults
- Vertical Displacement
- Horizontal Displacement
- Unit Contacts
- Axial Trace
- Syncline Axis