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Multi-stage exhumation history of the Orocopia schist of southern California and southwestern Arizona

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Multi-stage exhumation history of the Orocopia schist of southern California and southwestern Arizona

by

Rachel Elena Lishansky

A thesis submitted to the graduate faculty in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Geology

Program of Study Committee:
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Iowa State University
Ames, Iowa

2011

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ABSTRACT

The Pelona-Orocopia-Rand (POR) schists are metamorphic complexes that crop out along a belt extending from the southern Sierra Nevada to southwestern Arizona. The schists are considered to be correlated with the Franciscan subduction complex and believed to have been emplaced beneath crystalline basement of North America along a low-angle NE-dipping Late Cretaceous-early Cenozoic subduction zone related to the Laramide orogeny. Exhumation of the POR schists appears to have occurred in two main phases, as indicated by $^{40}$Ar/$^{39}$Ar thermochronology. A first episode of cooling of the schists during the Late Cretaceous to early Cenozoic may have been driven by both extensional faulting and erosion. A second phase of cooling during the middle Cenozoic is thought to be related to an extensional event that affected much of western North America.

One of the most critical places for understanding the tectonic evolution of the POR schists is the Gavilan Hills area of the southeasternmost California. The Orocopia Schist in that area forms the lower plate of the Chocolate Mountains fault and its exposed structural thickness is about 300 m. Above the schist is a thin slice of quartzofeldspathic to amphibolitic gneisses derived from middle to deep levels of the Mesozoic North American magmatic arc. The gneisses are, in turn, separated from overlying low-grade metasedimentary and metavolcanic rocks of the Winterhaven Formation by the Gatuna fault.

Previous $^{40}$Ar/$^{39}$Ar dating indicates that the Chocolate Mountains fault in the Gavilan Hills is early Cenozoic in age. The goal of this study was to constrain the age of the structurally higher Gatuna fault. To accomplish this, (U-Th)/He thermochronological analyses were performed on single detrital zircons from Orocopia Schist and Winterhaven Formation in the Gavilan Hills, an unnamed set of hills due east of the Gavilan Hills, and the Castle Dome Mountains. The ages obtained so far are 22.4-24.8 Ma for the Orocopia Schist and 39.7 Ma for the Winterhaven Formation. The dissimilar cooling histories of the Orocopia Schist and Winterhaven Formation prior to ca. 22 Ma confirm the hypothesis that the Gatuna fault is middle Cenozoic in age.
A further part of this study involved the creation of a publication-quality digital geologic map of the Picacho, Picacho NW, Picacho SW, and Hidden Valley 7.5’ Quadrangles in Arizona and California based on field mapping conducted by geologists of the U.S. Geological Survey. The ArcGIS software was used for this purpose. The map summarizes the findings of the research conducted in this area and therefore provides an important basis for further investigation.
CHAPTER 1. INTRODUCTION

The Pelona, Orocopia, and Rand Schists are Late Cretaceous–early Cenozoic graywacke-basalt-chert complexes that crop out along a belt that extends more than 500 km from the southern Sierra Nevada in California southeastward to Neversweat Ridge in the Sonoran Desert of Arizona (Fig. 1) (Ehlig, 1958, 1981; Haxel and Dillon, 1978; Haxel et al., 2002; Jacobson et al., 1988). This study focuses on the Orocopia schists, which form the southeast portion of the belt. In southern California, Orocopia-type schist crops out in the Orocopia Mountains, Chocolate Mountains, Peter Kane Mountain, Gavilan Hills, a small set of hills east of the Gavilan Hills, and a set of Hills east of Marcus Wash. In southwest Arizona, Orocopia Schist is exposed in five areas: the Trigo and Middle Mountains, southwest and southeast Castle Dome Mountains, and Neversweat Ridge (Fig. 2).

Orocopia-type schists have very distinctive lithology. They consist of metagraywacke, MORB-like metabasalt, ferromanganiferous metachert, siliceous marble, and ultramafic rocks (e.g. Ehlig, 1958, 1981; Haxel and Dillon, 1978; Haxel et al., 2002). Much research has been conducted studying the emplacement of the schist beneath crystalline basement of North America. Most authors consider that the schists were underthrust along a low-angle, NE-dipping Late Cretaceous–early Cenozoic subduction zone related to the Laramide orogeny, and are correlatives of the Franciscan subduction complex (“Franciscan subduction model;” Crowell, 1968, 1981; Yeats, 1968; Burchfiel and Davis, 1981; Hamilton, 1987, 1988; Jacobson et al., 1995, 1996) (Fig. 3). This model easily explains the oceanic protolith and relatively high pressure (~6–10 kbar; Graham and Powell, 1984; Jacobson, 1995)) and moderate temperature (400–600°C) metamorphism of the schists.

Related studies have also focused on the timing and nature of the processes involved in the exhumation of the Orocopia-type schist and three main models have been proposed (Fig. 4). Most workers consider that unroofing of the schist occurred primarily through normal faulting (Figs. 4A and 4B). This is based on the observation that low-angle faults that sit atop the schist are typically
Figure 1. Distribution of the Orocopia, Pelona, and Rand Schists (black areas) in southern California and southwest Arizona. Orange rectangle is the study area. Based on Jennings (1977).

Figure 3. Most widely accepted model for underthrusting of the Pelona-Orocopia-Rand schists (Franciscan subduction model) (based on Haxel et al., 2002, Fig.13).
Figure 4. Models for the exhumation of the POR schist: (A) Normal faulting, genetically related to the detachment faults and core complexes distributed through much of the Cordillera (middle Cenozoic); (B) Normal faulting, synchronous with subduction (Late Cretaceous–early Cenozoic), (C) Erosion of anticlinorium generated by passive-roof thrust/duplex structure within the subduction zone (Late Cretaceous–early Cenozoic). From Jacobson et al. (2007).
associated with retrogression of albite-epidote amphibolite facies of the uppermost schist to
greenschist facies (e.g. Haxel et al., 1985; Silver and Nourse, 1986; Jacobson et al., 1988, 1996).

Among those workers that postulate exhumation through normal faulting, there is a
disagreement regarding the timing. One view, the “synsubductional” model implies that exhumation
was synchronous with subduction, immediately following underplating of the schist (Fig. 4B) (e.g.,
Haxel et al., 1985; Jacobson et al., 1988, 1996, 2007; Jacobson, 1990). This interpretation is
motivated by analogy to models for the exhumation of the Franciscan Complex synchronous with
subduction (Platt, 1986). Also, K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological studies indicate significant
cooling of the schist and upper plate in Late Cretaceous–early Cenozoic time (e.g. Ehlig, 1981;

An alternative view is that these faults are largely middle Cenozoic in age and genetically
related to the detachment faults and core complexes distributed through much of the Cordillera (Fig.
4A) (Hamilton, 1987; Frost, 1989; Bishop and Ehlig, 1990). In fact, recent $^{40}\text{Ar}/^{39}\text{Ar}$
thermochronological studies of the Orocopia Schist indicate a major phase of cooling during the
middle Cenozoic, probably associated with normal faulting (Jacobson et al., 2002, 2007). However,
the middle Cenozoic cooling followed another rapid phase of cooling in the early Cenozoic,
indicating that the middle Cenozoic event was not the sole or even primary mechanism for unroofing
of the schist. Middle Cenozoic normal faulting probably did leave the schist at shallow structural
levels, from which it was exposed shortly thereafter (Sherrod and Tosdal, 1991; Jacobson et al.,
1996).

The third model for exhumation of the schist considers that the retrograde mylonitic contact
between schist and upper plate, rather than being a normal fault, is a passive-roof thrust capping a
duplex structure within the subduction zone (Fig. 4C) (Yin, 2002). The implication is that a regional
anticline of schist (Chocolate Mountains anticlinorium) was formed above the duplex structure, with
subsequent erosion of the anticline being the primary mechanism that brought the schist to the surface.

None of these models seem to be capable of explaining the whole structure that has been observed in the area; however each of them is appropriate for the explanation of certain phenomena. One of the major goals of our study was to discriminate between the above models and to better understand what makes their contribution particularly appropriate.

One of the most important places to study the tectonic evolution of the Orocopia-type schist is the Gavilan Hills area (Haxel, 1977; Dillon et al., 1990; Oyarzabal et al., 1997) (Figs. 1 and 2). This area is located in southeasternmost California, along the Chocolate Mountains anticlinorium. Here, the Chocolate Mountains fault divides the structurally deepest schist from overlying orthogneisses that were derived from the Mesozoic Cordilleran magmatic arc. The gneisses, in turn, are separated from overlying low-grade metavolcanic and metasedimentary rock of the Jurassic to Cretaceous Winterhaven Formation by the Gatuna fault. The above rock units and faults are exposed in a doubly-plunging anticline, with the schist in the core, and gneisses and the Winterhaven Formations exposed on the flanks (Figs. 5 and 6). Originally, the Chocolate Mountains fault was considered a thrust fault along which the schist had undergone prograde metamorphism (Haxel, 1977; Dillon et al., 1990). However, Jacobson et al. (1996, 2002) showed that Orocopia schist in the Gavilan Hills has undergone retrograde metamorphism, and the conclusion was made that the Chocolate Mountains fault is a normal fault responsible for the exhumation of the schist. Additional evidence for this interpretation comes from the fact that lineation and folds are parallel to each other in the uppermost schist and adjacent upper plate, but oblique to those in the deeper parts of the schist. Oyarzabal et al. (1997) and Jacobson et al. (2002) suggested that the deeper structures are related to the original underthrusting, with those in closer proximity to the Chocolate Mountains fault related to unroofing.
Figure 5. Geology of the Gavilan Hills area (after Haxel et al., 1985).

Figure 6. Lithotectonic sequence in Gavilan Hills (after Haxel et al., 1985).
Interpretation of the Chocolate Mountains fault as responsible for the exhumation of the schist in Gavilan Hills led to the question of its age, whether Late Cretaceous to early Cenozoic (Jacobson et al., 1996, Oyarzabal et al., 1997), or middle Cenozoic (Frost et al., 1982, 1989; Hamilton, 1987, 1988). In order to solve this problem, thermochronological analyses were performed (Jacobson, 2002). \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis of hornblende, muscovite, biotite, and K-feldspar, combined with previous apatite fission track measurements from the Gavilan Hills, indicated two major cooling events in the area (Fig. 7). For this analysis, closure temperatures were assumed to be 525 ± 50 °C for hornblende, 400 ± 50 °C for muscovite, and 350 ± 50 °C for biotite (McDougall and Harrison, 1999). Potassium feldspar records a continuous thermal history from ~350 °C to ~150 °C and is modeled using the multidiffusion domain technique (Lovera et al., 1997, 2001). Based on hornblende and muscovite thermochronology, the first phase of rapid cooling occurred from 55 Ma to 48 Ma and is thought to be related to slip on the Chocolate Mountains fault. These data support the hypothesis about Late Cretaceous to early Cenozoic timing of the exhumation, synchronous with low-angle subduction. The results of the potassium feldspar analysis in the Gavilan Hills indicate a second period of rapid cooling from 28 to 24 Ma, which was tentatively correlated with exhumation along the Gatuna fault (Jacobson, 2002). This second stage of exhumation is thought to reflect the early stages of a middle-Cenozoic extensional event known in the area.

The thermochronological results for the schist and gneiss in the Gavilan Hills were used to plot temperature-time paths (Fig. 7). These demonstrate that the schist and gneiss were justaposed against each other at 52–50 Ma, and after that time have had similar cooling histories. In particular, the rapid, synchronous cooling of the schist and gneiss at 28 to 24 Ma would seem to suggest a second phase of normal faulting that affected the schist and gneiss as a single unit. The likely candidate for this structure would be the Gatuna fault, but proof of this conjecture requires knowledge of the cooling path of the Winterhaven Formation overlying the Gatuna fault. However, the low grade
of metamorphism, and thus fine grain size, of the Winterhaven Formation has hindered its dating prior to this study.

A thermochronological analysis similar to that performed in the Gavilan Hills has also been conducted on the Orocopia Schist and related rocks in the Orocopia Mountains to the northwest (Jacobson et al., 2007). Results for the schist in the Orocopia Mountains showed a two-stage cooling history, similar to that of the Gavilan Hills area (Fig. 8). The older cooling event occurred at 52–50 Ma and was inferred to be associated with retrogression of the schist to greenschist facies. The younger event occurred at 24–22 Ma and was considered to be concurrent with mylonitization at the top of the schist. The early Cenozoic older event and middle Cenozoic younger event were interpreted as related to slip along Chocolate Mountains and Orocopia Mountains detachment faults, respectively. However, the Chocolate Mountains fault is not actually exposed in the Orocopia Mountains, presumably because it was cut out by slip on the Orocopia Mountains detachment fault.

In the Orocopia Mountains, thermochronological data show that the timing of juxtaposition of the upper plate against the schist, and thus the age of the Orocopia Mountains detachment fault, is 24–22 Ma. This has implications for the age of the Chocolate Mountains anticlinorium, which is defined by the folding of the Orocopia Mountains detachment fault. The anticlinorium must be younger than the detachment fault and thus younger than 24–22 Ma. This contradicts the theory of Yin (2002) that exhumation of the schist was caused primarily by erosion of an early Cenozoic anticlinorium.

The temperature-time curves for the Orocopia Schist from the Gavilan Hills and Orocopia Mountains are remarkably similar (Figs. 7 and 8). In the Gavilan Hills, the combined results for the schist and gneiss provide evidence that the early Cenozoic phase of cooling was caused by extensional movement on the Chocolate Mountains fault. The middle Cenozoic cooling of the schist probably relates to slip on the Gatuna fault, but without thermochronological results from the Winterhaven Formation, this cannot be proven. For the above reason, it is important to date the Gatuna fault in the Gavilan Hills, where both the early and middle Cenozoic structures appear to be
preserved (i.e., the Chocolate Mountains and Gatuna faults, respectively). Faults similar to the Chocolate Mountains and Gatuna fault are exposed in about a half dozen anticlinal structures extending for 100 km to the east of the Gavilan Hills. In each of these areas, the two faults are essentially parallel and separated from each other by only 10s to a few hundred meters of structural section. It is striking that two faults which seem to have formed in very different tectonic environments ~25 m.y. years apart would have such a close spatial association. It is thus important to directly date the Gatuna fault and its equivalents to test this hypothesis.

As mentioned above, dating of the Gatuna-type faults has been difficult to do in the past because of the low grade of metamorphism of the Winterhaven Formation and related rocks that overlie the faults. However, recent advances in (U-Th)/He dating now make this possible. Thus, a very important goal of this study was to perform such dating. Analyses were conducted in the Gavilan Hills and two additional areas to the east that expose the Orocopia Schist and related rocks (Table 1). One of these areas occurs in an unnamed set of hills east of the Gavilan Hills between White Wash and Little Picacho Wash just south of the Picacho State Recreation Area in California. The other is in the southeast Castle Dome Mountains of southwest Arizona. In addition to addressing an important tectonic problem, this allows us to test the (U-Th)/He thermochronological dating facility recently installed at Stanford University.

The other task of the thesis was to create a publication-quality digital geologic map of the Picacho, Picacho NW, Picacho SW, and Hidden Valley 7.5’ Quadrangles in Arizona and California based on work of D.R. Sherrod, R.M. Tosdal, and G.B. Haxel based on their unpublished mapping conducted for the U.S. Geological Survey supplemented by the work of Parker (1966), Haxel (1977), Pietenpol (1983), and Oyarzabal et al. (1997). The map includes exposures of the schist in the Gavilan Hills, unnamed hills east of the Gavilan Hills, and Trigo Mountains. These areas overlap with study area for (U-Th)/He dating and therefore provide additional information for understanding the tectonic evolution of the area.
Figure 7. Generalized temperature-time paths for Orocopia Schist and structurally overlying gneiss plate in Gavilan Hills (after Jacobson et al., 2007). Paths based upon apatite fission track data (rectangles), K-feldspar multidiffusion domain modeling (lines), and biotite (triangles), muscovite (circles), and hornblende (hexagons) bulk closure ages.

Figure 8. Generalized temperature-time paths for Orocopia Schist and upper-plate rocks in Orocopia Mountains (after Jacobson et al., 2007). Path based upon apatite fission track data (rectangles), K-feldspar MDD analysis (lines), and biotite (hexagons), muscovite (pentagons), and hornblende (diamonds) bulk closure ages.
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<td>Rocks of Slungullion</td>
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Table 1. Samples utilized for (U-Th)/He analysis.
CHAPTER 2. GEOLOGIC MAP OF THE PICACHO, PICACHO NW, PICACHO SW, AND HIDDEN VALLEY 7.5' QUADRANGLES IN ARIZONA AND CALIFORNIA

The goal of the project was the creation of a publication-quality digital geologic map of the Picacho, Picacho NW, Picacho SW, and Hidden Valley 7.5' Quadrangles in Arizona and California (Plate 1). The digital map summarizes the findings of research conducted in this area and provides a basis for further efforts. The source for the digital map was a 1:50,000 Mylar map based on field mapping conducted by D.R. Sherrod, R.M. Tosdal, and G.B. Haxel between 1982 and 1995 for the U.S. Geological Survey, supplemented by the work of Parker (1966), Haxel (1977), Pietenpol (1983), and Oyarzabal et al. (1997) (Figs. 9 and 10). The Mylar map contains a USGS topographic basemap produced by photographic means onto which line and point information was added by hand in ink. An early digital version of this map was created by Tian (1999) using the ArcInfo software. The goals were to (1) update Tian’s (1999) ArcINFO map to an ArcGIS 9 map, (2) check the accuracy of the line work, (3) add a topographic base, (4) add structure symbols and other features, and (5) finish the preparation of the map for publication. Details of the above procedures, particularly related to problems encountered in properly georeferencing the Mylar map, are described in the following sections.

Georeferencing the Mylar map

Using ArcINFO, Tian (1999) hand-digitized (traced) the inked lines on the Mylar map and stored them inside an ArcINFO coverage. In order to verify the fit of the lines, the Mylar map (showing the digitized inked lines) was scanned into a TIFF file, imported into ArcGIS 9.3, georeferenced, and compared the coverage lines with the ink lines. This revealed some discrepancies which needed to be corrected. These discrepancies could be traced largely to imperfections in the paper topographic basemap used as the source image transferred photographically to the Mylar map. This paper basemap was prepared from paper versions of four adjacent U.S. Geological Survey
(USGS) 7.5’ (1:24,000 scale) quadrangles: Picacho, Picacho NW, Picacho SW, and Hidden Valley. The borders of the quadrangles were removed with a razor, and the four trimmed paper maps were then manually joined into a single paper map. The four-quadrangle composite map was then photographed and printed onto a Mylar sheet at a scale of 1:50,000. The fact that a GIS system permits the user to enlarge the digital view of the map beyond the originally intended scale (zoom in) amplifies the small imprecision made when cutting and assembling the quadrangles, and shows them as mismatches along the contours of adjacent quadrangles (Fig. 11).

Ideally, the digitized lines from the 1999 coverage should perfectly match the inked lines on the Mylar sheet; in order to visually verify and correct them in ArcGIS, the digitized lines need to appear on top of the scanned tiff. However, the tiffs initially missed any spatial context and they needed to be georeferenced in order for ArcGIS to be able to draw them at their true geographic locations. The georeferencing process is based on matching certain key locations on the scanned Mylar tiffs to their real-world locations as given by the already georeferenced digital versions (DRGs) of the same topographic sheets that were “embedded” into the original Mylar sheet. The spatial juxtaposition of all these pieces has ramifications for the quality of the digital geological map.

Creating the new topographic basemap

In order to correctly georeference the Mylar scan, its embedded contours needed to match the digital (DRG) version of the 1:24,000 topographic sheets (USGS topographic sheets, 2009). A DRG is a digital version of the U.S. Geological Survey topographic paper maps, scanned at a minimum resolution of 250 dots per inch (dpi).

California DRG files are available to download from an Internet site maintained by the State of California (California DRGs, 2009) (Fig. 12). From a shapefile containing the index of USGS 1:24,000 sheets in California, codes were identified for the relevant quadrangles (Fig. 13). The Picacho quadrangle’s code is 33114a5, Picacho NW quadrangle’s code is 33114b6, Picacho SW
Figure 9. Scanned image of the Mylar map of the Picacho, Picacho NW, Picacho SW, and Hidden Valley 7.5’ quadrangles in Arizona and California used as the base for the digital version created in this study.

Figure 11. Mismatch of topographic contours at the boundaries of the quadrangles in the original Mylar map (the arrow is pointing to the problematic area).
Figure 12. Screenshot of the library of California topographic maps (California DRGs, 2009).

Figure 13. Four 7.5' quadrangles of interest highlighted (cyan) on California index map and their codes in the attribute table below.
quadrangle’s code is 33114a6, and the Hidden Valley quadrangle’s code is 33114b5. The DRG files are offered in both trimmed and untrimmed versions. The untrimmed versions show the scanned equivalent of the complete paper map, including margins around the map with all the typical additional information for printed maps, including the coordinate system, scale, title, labels, etc. The Libre Map Project (Libre Map Project, 2011) offers untrimmed DRGs for all states as geotiffs. The trimmed version only contain the data inside the boundaries of quadrangles (“frame”); i.e., the data necessary in order to digitally splice together the four DRGs. Although trimmed versions of the DRGs are available for Picacho NW, Picacho SW, and Picacho 7.5’ quadrangle maps, which all straddle the boundary between California and Arizona, the Hidden Valley 7.5’ quadrangle map, which lies entirely within Arizona, is only available in the untrimmed version (Arizona Geological Survey maps, 2009), and needed to be trimmed first with the outline of the quadrangle.

DRGs are typically 1-band, index-colored rasters with 15-20 different unique colors corresponding to the official USGS color palette used for printing the original paper topographic sheets (e.g. a certain shade of green for forest, blue for water, brown for contours, etc.). Differences in the process used for scanning the paper topographic sheet may result in slight color differences for DRGs. For example, the AZ DRGs uses a slightly darker brown tone (RGB value) for contour lines than the CA DRGs because they were created by different state agencies.

Setting a common projection and datum for the four 7.5’ quadrangle maps

ArcGIS is able to show data together that use different projections and datums. However, this requires an on-the-fly re-projection, which is less precise and may lead to artifacts. As a precise fit of all four DRGs is vital for the georeferencing of the Mylar scans, the decision was made to externally re-project all rasters and vector files used in this project into a common coordinate system, using the UTM Zone 11 North projection and the North American Datum of 1927 (NAD27). The North American Datum of 1927 and the North American Datum of 1983 (NAD83) are the two main North American datums currently in use. The California and Arizona DRGs use different coordinate
systems. The California DRGs use the Albers-NAD83 coordinate system, whereas the Arizona DRG uses a UTM11-NAD27 coordinate system. Using the ArcGIS “Project Raster” tool, the California DRGs were re-projected from their Albers projection to the UTM11N projection, and their datum was converted from NAD83 to NAD27, using the NADCON datum conversion method (Nadcon datum conversion method, 2011) (Fig. 14).

**Trimming the Hidden Valley quadrangle map**

To create a final version of the topographic basemap from the four 7.5’ quadrangles, it was necessary to prepare a trimmed version of the Hidden Valley 7.5’ map. The strategy was to overlay the outline of this quadrangle over the untrimmed version of the map and to use an ArcGIS tool to cut out the area inside the outline.

The outline (polygon) of the Hidden Valley quadrangle was extracted from the shapefile “USGS Quads.shp” and saved into a new shape file called “outline_for_trimming_AZ_b5.shp” (Figs. 15–17). The outline polygon was added on top of the untrimmed Hidden Valley DRG (Fig.18), with the intent to use it as a mask which would convert those DRG cells outside the polygon into Nodata (NULL) values and render them invisible.

Although it should have been possible to create a trimmed copy of the Hidden Valley DRG using the ArcGIS Spatial Analyst “Copy Raster” tool, this did not work, possibly due to the DRG raster type. After some experimentation, it was found that the “Raster Calculator” could be used to make a copy of the DRG that, in fact, honored the mask given by the outline polygon. First, in “Spatial Analyst/ Options/ General,” the “outline_for_trimming_AZ_b5.shp” polygon was set as “Analysis mask” (Figs. 19 and 20) and used as the output extent (“Spatial Analyst/ Options/ Extent”) (Fig. 21). The “Raster Calculator” (“Spatial Analyst/ Raster Calculator”) was used to make a copy of the DRG, in which the cells were first converted to whole numbers using the int() function: int(“o33114b5.tif”) (Fig. 22). The resulting integer GRID was exported into a geotiff raster (.tif file,
Fig. 23). As the copy process removes the USGS color palette, the trimmed DRG’s colors are initially random (Fig. 24). The colors were restored to those of the untrimmed DRG using “Properties/ Symbolize/ Import Symbology”. The final trimmed Hidden Valley DRG with the correct USGS colors is shown in Fig. 25. At this stage, georeferenced DRGs for the four 7.5’ quadrangles were trimmed, all using the same coordinate system, were displayed as separate, adjacent layers in ArcMap. The images were examined to verify that lines (contours, etc.) crossing quadrangle boundaries lined up and that the gaps between were only on the order of 6–10 meters wide (Fig. 26).

Once the quality of the fit was confirmed, the four separate images of the 7.5’ quadrangles were merged into a single 15’ quadrangle raster using the ArcGIS “Mosaic” tool (“Data management tools / Raster / Raster dataset/ Mosaic To New Raster”) (Fig. 27). As the color representation of the official USGS topographic sheet palette is slightly different between the AZ and CA DRGs, a correction was applied using “Match” for the “Mosaic Colormap Mode”; this matches the AZ DRG green to the CA DRG green, etc. The new composite DRG (Fig. 28) was given a color map that contains entries for both sets of slightly different colors, i.e. it has two slightly different tones of brown, two tones of green, etc. As a result the composite DRG shows slightly different colors for the AZ and the CA parts.

There are two more alternatives for creating a single basemap from all four quadrangles:

1. Download the four 1:24,000 topographic sheets as a single DRG from the USGS Seamless site (Seamless maps, 2011) as an 8-bit geotiff file. This requires entering the coordinates (latitude and longitude) of the basemap’s corners. The geotiff coordinate system is already set to UTM11N NAD27 and its four topographic sheets are already color matched. Except for small differences along the quadrangle boundaries, this looks identical to our basemap (Fig. 29).

2. Use the online version of the USGS topographic sheets by adding the USA Topographic Maps service as a layer (Fig. 30). This streams a seamless basemap DRG from the internet. It is
Figure 14. Re-projecting the California DRG maps using the “Project Raster” tool.

Figure 15. Close-up of California index map including Hidden Valley 7.5’ quadrangle.
Figure 16. Saving the quadrangle selected in Figure 15.

Figure 17. Exporting data with the selected quadrangle as shapefile.
Figure 18. Untrimmed Hidden Valley quadrangle topographic map in the form of the original TIFF file with USGS topographic colors as “Unique Values.”

Figure 19. Setting up the Spatial Analyst – Options tool.
Figure 20. Options that need to be set for trimming in “Options/General” tab.

Figure 21. Options that need to be set for trimming in “Options/Extent” tab.
Figure 22. The “Raster Calculator” tool used to create the trimmed copy of the raster.

Figure 23. Exporting and saving the trimmed version of the Hidden Valley raster.
Figure 24. Final view of the trimmed version the Hidden Valley topographic map generated with raster calculator. Note random color palette.

Figure 25. Trimmed version of the Hidden Valley topographic map with colors set to unique values equivalent to those in the untrimmed USGS map.
Figure 26. Comparison of the internal margin areas between quadrangles in the Mylar map (left image) to the newly created base topographic base map (right image), scale 1:15,000.

Figure 27. Creating the base topographic map using the “Mosaic” tool.
Figure 28. Final version of topographic base map that includes all four quadrangles.
Figure 29. Example of the non-hillshaded DRG (scale 1:10,000) (Seamless maps, 2011).

**USA Topographic Maps**

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</table>

Figure 30. Online map service version of the USGS topographic maps (DRG).
Figure 31. Online version of the same area (with embedded hill shading).

Figure 32. Georferencing the Mylar map. Crosses on the map represent the georeference points.
identical to the seamless DRG from USGS’ Seamless site but has hillshading embedded that cannot be switched off (Fig. 31).

**Georeferencing the Mylar map based on the new topographic basemap**

The next step was to georeference the scan of the Mylar map (tiff) so that its embedded line information matched the corresponding lines on the new basemap. Using Adobe Photoshop software, the scan was first cut into four pieces, each corresponding to one of the USGS quadrangles. Each of the four pieces was georeferenced independently to mimic the way the paper basemap was assembled and to improve fit at the margins.

Georeferencing requires the designation of a number of match (link) point pairs that link a location on the scan (image) to a physical location (Fig. 32). The first point of the pair match pertains to a pixel (X/Y Source) on the non-georeferenced scanned image, the second to the corresponding coordinate point on the basemap (X/Y Map). Points used for this purpose included the corners of the DRG, tick-marks along the outer (non-trimmed) boundaries of the four quadrangles, and additional points from pixels/locations from inside each quadrangle. An attempt was made to place the match points at equal spacing; however, the scan’s low contrast and lack of color, which were a result of the process used to embed the original topographic sheet onto the Mylar map, reduced good choices for points. Most often the interior match points used were at line intersections and other strong features that could be clearly identified on the scan and clearly connected to their corresponding location on the basemap. Roughly 20 match points were used per quadrangle, which were stored in a text file. This number of match points allowed the consideration of several transformation methods for rectification. First, second, and third order polynomial and the spline methods were all looked at. The polynomial transformations describe how to “warp” the scanned image into an optimal fit by minimizing the difference (residual distance) between the two parts of a match point, i.e. how far away, after the transformation, each pixel is from its true location. By minimizing the pixel-location distance for the match points all other pixels of the scan are automatically moved close to their true,
but unknown location. A first-order polynomial transformation can only move, rotate, and scale the scanned image (affine transformations). Higher-order polynomial transformations afford the algorithm more degrees of freedom and enable different types of warping. The higher the order, the more points are needed. The minimum number of match point pairs necessary for a given order of polynomial \( p \) is: \((p + 1)(p + 2)\), i.e. 6 for first order, 12 for second order, and 20 for third order polynomials (ESRI data management, 2009).

Provided that the points are evenly spaced, higher order polynomials typically provide better matches with smaller overall RMS Errors based on pixel/location differences (residuals) (Figs. 33-35). However, they have the potential to grossly distort areas that are not well sampled. The third order polynomial transformation was used primarily to gauge how the residuals change as more and more match points were added, with a difference of 10 m or less considered desirable. High residuals typically indicate a mistake in the choice of corresponding points for the pair. If, after a new match point was added its residual was higher than 10 m, the point was removed and a different pixel/location match was chosen.

After using the polynomial method for quality control, the spline transformation was implemented for the final rectification (i.e. the permanent transformation of the scanned tiff image into a raster file). The spline transformation is a rubber sheeting method, i.e. it is based on a piecewise polynomial that changes locally while maintaining continuity and smoothness between adjacent polynomials. The spline transformation provides better local accuracy than the polynomial methods but does not provide a metric for global accuracy (such as an RMS Error) (Fig. 36). At match points, the spline transformation guarantees that the pixels exactly match the true location, but misidentification mistakes can not be identified directly. Adding more control points does increase overall accuracy of the spline transformation, as for the polynomial transformation. The spline transformation requires a minimum of ten control points (ESRI spline transformation, 2009). The
Figure 33. Link table of georeference points based on 1st Order Polynomial transformation.

Figure 34. Link table of georeference points based on 2nd Order Polynomial transformation.
Figure 35. Link table of georeference points based on 3rd Order Polynomial transformation.

Figure 36. Link table of georeference points based on spline transformation.
rasters “rect_ne_sp2.img,” “rect_nw_sp2.img,” “rect_se_sp2.img,” “rect_sw_sp2.img” contain the georeferenced (rectified) versions of the four scanned tiff images.

**Data conversion from ArcInfo (Coverage) to ArcGIS (Shapefiles, Geodatabase)**

After georeferencing the scan of the original Mylar map, the previously digitized line and point data (Tian 1999) were imported from their ArcInfo Coverage format into ArcGIS 9.3 in order to verify their fit to the features inked on the Mylar map and to perform the necessary updates for the final version of the digital map. The coverage “fifteen_orig” created by Tian (1999) contains feature classes (files) called “arc,” “label,” and “polygon” parts, which contain the various types of features (geometry), and standalone tables called “line_code” and “q_geounit.”

The “arc” file represents the digitized line features – boundaries of the geological units, faults, dikes, etc.; the type of line is encoded in its attribute table as LINE_CODE. The “polygon” file contains polygons, which share their boundaries with the “arc” file’s lines, representing the spatial extent of geological units, the “label” file contains locations (points) inside the polygons, and stores information about the type (including age) of each geological unit (called GEOUNIT_CODE in the attribute table). In theory, each polygon is spatially defined via one or more lines (arcs), with the polygon’s “type” given by the value of the label point it encloses. However, some polygons are defined by a combination of faults and unit boundaries, which can lead to complicated topological situations (Fig. 37). As polygons share lines, changing any part (of the geometry) of a line invalidates them and they must be created again from their lines and label points.

The “line_code” and “q_geounit” lookup tables translate the LINE_CODE and GEOUNIT_CODE numbers into line types and geologic units. For example LINE_CODE = 11 translates into “Direct contact” as line type and GEOUNIT_CODE = 58 into Qt as geologic unit.

The original coverage lists its coordinate system as Clarke_1866_UTM_Zone_11N; i.e. using a UTM 11N projection and a Clarke 1866 spheroid. However, it lists no implicit datum. As the Clarke
1866 type spheroid is typically associated with the NAD 1927 datum, the datum was defined explicitly before the conversion using the “Define Projection” tool (“Data Management Tools/Projections and Transformations/ Define Projection,” Fig. 38).

A file geodatabase “Picacho_data_NAD27.gdb” was created with coordinate system NAD 27_UTM 11N (Spheroid Clarke 1866). All parts of the original coverage were first converted into shapefiles and then put into the geodatabase as feature classes, with the exception of the polygons, which needed to be recreated after each correction. The feature class names are “arcs_UM11_NAD27,” “polys_UM11_NAD27,” “labels_UM11_NAD27,” “geo_code_lut,” “line_code_lut.” To export the coverage to the geodatabase, the following procedure was used – “ArcCatalog / Right click on a “line_code.dbf” file/ Export/ To geodatabase (single).” After checking Tian’s (1999) arcs and polygons for internal consistency and with regard to the georeferenced scan of the Mylar sheet, it became clear that many corrections to the geometry and the topology were required. As this meant potentially editing thousands of lines, it was decided to limit the scope of line corrections (adjustments) to a precision that was sufficient for practical use at a scale of 1:24,000. As the width of the original ink lines on the Mylar map correspond to roughly 20 meters, digitized lines that, at a 1:10,000 scale appear to coincide with the inked original from the Mylar map, were considered to be sufficiently precise.

Many of the linear features created by Tian (1999) were adjusted in the ArcMap editing mode to fit the inked lines in the georeferenced version of the Mylar map (Fig. 39). In the “line features” attribute table a new attribute called “Comments” was added, in which “m” denotes a modified line. Many adjustments were made close to the internal margins of the quadrangles to ensure a good fit in this area. After correcting the geometry of the linear feature, the GEOUNIT_CODE “line_code_lut” lookup table was joined to the line feature class attribute table; this makes it possible to label each line by its line type (LINEAR_STR) rather than by its code (Fig. 40).
Figure 37. Examples of how polygons are defined by lines (arcs) and a label point. Unit boundaries are drawn grey, faults in purple. The label points contain numbers denoting the type of the unit. The polygons delineated from lines (arcs) around them are shown via color.

Figure 38. Setup for “Define Projection” tool.
Figure 39. Representative area illustrating differences between corrected lines (in black) and initial lines created by Tian (1999; in red). Scale 1:13,000. Corrected lines are adjusted using georeferenced Mylar map.

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Figure 40. Lookup table for lines that represents codes for different types of lines.
Re-generating polygons from correct lines and label points

After correcting the various problems with the lines (arcs) and points, the polygons were re-created using the “Feature to Polygon” tool (“ArcToolbox/ Data management tools/ Features/ Feature to polygon tool”). “arcs_UTM11_NAD27” was used as an “Input feature,” which creates the polygon’s geometry from the topologically adjacent boundaries and/or fault. The table “labels_UTM11_NAD27” was used as a “Label feature,” which supplies the polygon with its GEOUNIT_CODE value. This GEOUNIT_CODE, a number, was then translated to the geologic unit name of the polygon by performing a data base join operation with the “geo_code_lut” lookup table (Figs. 41–43).

Symbology (appearance) settings

The standard Geology style in ArcGIS was used in order to represent linear features with conventional geologic line types (e.g. continuous for well located contacts, dashed for approximately located contacts, heavy line weight for faults). Not all line types were available, but an attempt was made to closely match the type of lines used for the original Mylar map (Fig. 44).

Color scheme for the geological units

A comparison with related maps of the surrounding areas was performed; however, as the geological units of the study area are not commonly described at the 1:24,000 scale, no readily available comparable color scheme could be found. Ultimately, colors and fill types were chosen that conform to common use in geology (for example – bright yellow for quaternary sediments) while providing a visually effective representation of the units.
Figure 41. Creation of polygons from arcs and labels using “Feature To Polygon” tool.

Figure 42. Joining created polygons to the lookup table with geounits using “Join Data” tool.
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Figure 43. Polygons lookup table.
Figure 44. Symbology used for different line types.

Figure 45. First step for georeferencing of scanned maps using “Fit to Display” with the layer of interest.
Adding the structure symbols

Georeferencing the Mylar map with structural symbols

On the Picacho map, each type of structure symbol was created as a separate layer in the map and stored as a point feature class in the following feature classes: trace of axial surface of an open anticline, trace of axial surface of open syncline, trace of axial surface of overturned syncline, strike and dip of inclined bedding, strike and dip of volcanic layering, strike and dip of metamorphic foliation, bearing and plunge of lineation, vertical foliation, down thrown side of a normal fault, reverse fault, and dip of the fault. In addition, a samples points feature was created. Creation of these features involved scanning a version of Mylar map with those symbols, georeferencing this map based on the previously georeferenced map, creating a separate feature dataset “Structure_symbols” inside “Picacho_data_NAD27” geodatabase for symbols, and creating the symbols on separate layers, with thirteen features total.

Structure symbols associated with the geologic map were not drawn directly on the Mylar basemap described previously, but were rather included on a separate clear overlay sheet. This overlay, which also included some updates to the geologic mapping, had not been included the first time the main Mylar basemap was scanned. Thus, to add the structure symbols to the digital map, and also take into account the updates, it was necessary to scan the Mylar basemap a second time with the clear plastic layer overlaid, creating another scan TIFF file. This TIFF file was again cut into four smaller TIFF files in Adobe Photoshop; each of the four quadrangles was again georeferenced.

Both scans show identical line information, but the new scan also contains the structure symbol points and some new label points. At first, the second scan was manually moved to roughly coincide with the real world location of each quadrangle using the “Fit to Display” tool (Fig. 45). Then, around 20 locations that could be reliably identified visually on both scans were used as match points; for example, bifurcation points or end points of lines (Figs. 46 and 47). The darker part on the left of Figure 46 shows the overlay of both scans, the right part shows only the new scan.
The match points used in each quadrangle were checked and repositioned if they showed large residuals. They were saved in text files: “refpoints_sw_labels.txt,” “refpoints_se_labels.txt,” “refpoints_nw_labels.txt” and “refpoints_ne_labels.txt.” Having these points available for reference is important because as each section is being georeferenced, the previous section is no longer georeferenced. Consequently, instead of having to create a new set of georeference points every time work is begun on the .tif files, they can be loaded from the .txt file (Fig. 48). The final rectification was again performed with the spline method, creating four new rasters: “scan_w_lab_aug19_ne.tif,” “scan_w_lab_aug19_nw.tif,” “scan_w_lab_aug19_se.tif,” and “scan_w_lab_aug19_sw.tif.” The “aug19” segment of the name denotes the second scan of the Mylar map with its transparent overlay. This image was colored brown and its transparency set to 70% (Figs. 49 and 50).

Creating “Structure_symbols” feature dataset in the geodatabase

Based on the second scan, each structure symbol was digitized as a point feature and its data (dip, azimuth, etc.) added to its attribute table. Each type of structure symbol was given its own feature class, all of which were stored in a feature dataset (folder) called “Structure_symbols” within the “Picacho_data_NAD27” geodatabase (Fig. 51):

- trace of axial surface of an open anticline,
- trace of axial surface of open syncline,
- trace of axial surface of overturned syncline,
- strike and dip of inclined bedding,
- strike and dip of volcanic layering,
- strike and dip of metamorphic foliation,
- bearing and plunge of lineation,
- vertical foliation,
- down thrown side of a normal fault,
- reverse fault,
- dip of the fault and
- samples.

**Digitizing the structure features**

The Editing tool was used to create a new feature (location and value) for each structure symbol from the scan (“Edit/ Start editing / Feature Class in the GeoDB”) (Figs. 52 and 53). For some features, such as strike and dip symbols, the angular orientation (compass heading) of the graphic shown on the scan needed to be measured manually. In such cases, the midpoint of the strike line was selected as the insertion point, and the orientation was then measured from the scanned image and entered into the features record for the attributes “strike,” “dip,” and “measured_angle.” The measured angle recorded the initial measurement of a heading (for example strike 14NE = 14 degrees measured angle, strike 47SE = 227 degrees measured angle). This angle was measured by digitizing a temporary helper line that visually matched the scanned structure symbol. ArcMap shows the compass heading of that line at the bottom of the screen as direction (Figs. 54 and 55). This heading was then manually entered into the attribute table.

After creating the features, they were symbolized with the “ESRI Geology” style and properties such as size, color, and offset by x and y axis (Fig. 56) were adjusted in the “Symbol Property Editor.” The “measured_angle” attribute was used to assign rotation in the advanced properties section of the “Layer Properties/ Symbology/ Features.” The rotation style was set to “geographic,” which uses North as 0 (Fig. 57). In “Layer Properties/ Labels Menu” the “Dip” attribute was set to give the label text (Fig. 58). Each type of structure symbol was given a different color (Fig. 59).
Figure 46. Examples of matched features (red plus symbols) in “rect_sw_sp2.img” and “scan_w_lab_aug19_sw.tif” used for georeferencing.

Figure 47. Example of the table with georeference points.
Figure 48. Examples of loading a table with georeference points.

Figure 49. Adjusting colors of the map.
Figure 50. Adjusting transparency of the map.

Figure 51. Content of the “Structure symbols” database.
Figure 52. “Start Editing” tool and choosing the proper layer to edit.

Figure 53. Screenshot of “Create New Feature” task and its target.

Figure 54. Creating the supporting line for strike measurement.
Figure 55. Orientation reading of the supporting line of Fig. 54. This value is used in the “measured_angle” column of the attribute table of strike and dip symbols to represent direction of strike.

Figure 56. Example of the symbology settings for structure symbols.

Figure 57. Setting the rotation for the symbol if needed.
Figure 58. Setting the label field for each symbol.

Figure 59. Example of area of the map with several structure symbols over the Mylar map.
CHAPTER 3. REGIONAL GEOLOGICAL BACKGROUND

Geologic units in the study area

Orocopia Schist

The Orocopia Schist is the structurally deepest unit exposed in the study area. It consists of primarily quartzofeldspathic schist, derived from graywacke. Mafic schist, metachert, marble, and serpentinite make up less than one percent by volume (Jacobson et al., 1988). The schist metagraywacke is compositionally similar to average unmetamorphosed graywacke, which indicates that the Orocopia protolith was derived largely from continental crust (Haxel et al., 2002). In addition, the basalt, ferromanganiferous chert, and peridotite protoliths of the minor rock types in the schist indicate an oceanic depositional environment.

The primary prograde metamorphic minerals in the metagraywacke are quartz, biotite, muscovite, and oligoclase. Minor amounts of garnet, epidote, K-feldspar, opaques, rutile, titanite, zircon, and apatite are also present. Retrograde metamorphism is indicated by replacement of biotite and garnet by chlorite, oligoclase margins by albite, and oligoclase by calcite. The prograde metamorphic assemblage in the metabasalt is characterized by hornblende, oligoclase, and epidote, indicating that the Orocopia Schist belongs to the lower amphibolite facies by the definition of Graham and Powell (1984) (Jacobson et al., 1988). Retrograde metamorphism to the greenschist facies is indicated locally by replacement of hornblende by actinolite and/or chlorite, and oligoclase by albite.

The Orocopia Schist was metamorphosed at relatively high pressure (in the range 6–10 kbar; Graham and Powell, 1984; Jacobson, 1995) corresponding to depths of tectonic burial of approximately 25–35 km (Oyarzabal et al., 1996). Metamorphic temperatures were in the range 400–600 °C.
There are significant structural differences between the lower and the upper parts of the schist. Schist greater than approximately 100 m structurally below the fault typically exhibits a “flaggy” schistosity defined by planar alignment of muscovite, biotite, and, to a lesser degree, ovoids of quartz and feldspar. This schist tends to exhibit fairly little evidence of retrograde metamorphism. In the structurally high schist, the above early foliation tends to be cut by retrograde shear bands. In addition, micas in schist near the fault tend to exhibit a scaly, coarse texture that is also attributed to retrogression.

Oyarzabal (1996) described an early NNE-trending lineation associated with the prograde foliation, defined by elongated grains of biotite, intersections between compositional layering and foliation, and tendency to weather into elongated slabs. In the upper part of the schist, this early lineation is partially preserved, but there is also a late lineation oriented clockwise relative to early lineation (ENE- to EW-trending). In the Gavilan Hills, the early lineation is related to the prograde mineral assemblage and considered to be a stretching lineation, whereas the late lineation is related to extensional reactivation of the Chocolate Mountains fault and indicates the shear direction.

As noted above, prograde foliation in the schist is locally cut by shear zones, which Oyarzabal (1997) divided into two groups. Both groups indicate top-to-the-east-northeast to top-to-the-east sense of transport. The first type of shear zone (“Type I”) is older and occurs throughout the schist, but is most abundant in the upper 100 m of the structural section. Chlorite replaces biotite and garnet, which indicates retrograde metamorphism. Quartz exhibits crystalloblastic texture. Type I shear zones tend to be parallel or slightly oblique to foliation in the surrounding schist. A second type of the shear zone (“Type II”) is younger than the first and present only within a few meters of the Chocolate Mountains faults. Type II shear zones are generally oriented at a moderate angle relative to the foliation of the schist outside the shear zone. Textures within the Type II shear zones range from mylonitic to cataclastic. The earlier mylonitic texture in the Type II shear zones, coarser grained,
represented by mica fish and elongated aggregates of quartz and feldspar, is cut by “late” finer
gained shear bands (Oyarzabal, 1997; Jacobson et al., 2002).

**Gneisses**

As described above, the Orocopia Schist is overlain by amphibolite-facies orthogneisses
derived from the Mesozoic Cordilleran magmatic arc. The gneisses are medium to coarse grained and
layered. They range in composition from hornblendite to leucotonalite and leucogranite (Dillon,
1976). Most abundant are tonalitic gneisses, composed of quartz, plagioclase, K-feldspar, biotite, and
epidote, with minor amounts of titanite, ilmenite, apatite, zircon, and rutile. Also widespread are
amphibolitic gneisses that consist of subequal amounts of plagioclase and hornblende with minor
amounts of epidote, biotite, quartz, titanite, and opaques (Oyarzabal, 1997). Amphibolitic gneisses are
gradational into the tonalitic gneisses. Some granitic gneisses are also present, but less common than
tonalitic gneisses. Based on the prograde assemblages described above, peak metamorphism occurred
in the middle to upper amphibolites facies. Local retrogression to the greenschist facies is indicated
by sericitization of plagioclase; chloritization of garnet, biotite, and hornblende; and actinolite rims
around hornblende grains.

The structure of the gneiss unit is complex and reflects at least two major phases of
deformation, which are presumed to coincide, respectively, with the prograde and retrograde
metamorphism described above. The older, prograde event is defined by gneissic foliation that is also
observed in gneiss along other segments of the Vincent-Chocolate Mountains fault. During the
second phase of deformation, a new foliation was formed that is approximately parallel to the late
foliations in the Orocopia Schist. In the middle of the gneiss unit, away from faults above and below
(Gatuna fault and Chocolate Mountains fault, respectively) the foliation is defined only by
compositional layering. No lineation was found in association with the early, prograde fabrics.
However a late, retrograde lineation trends mostly east-northeast and east-west, coincident with the
trend of the late lineation in the schist, reflecting the shared late deformational history of both units.
Shear zones vary in size up to a few meters and are associated with mylonitization. They are very similar to the Type II shear zones present in the schist near the Chocolate Mountains fault.

**Winterhaven Formation**

The Winterhaven Formation is a very distinct unit of metasedimentary and metavolcanic rocks, named by Haxel (1977), which sits above the gneisses along the Gatuna fault. The Winterhaven Formation was originally considered to be most probably Middle and/or Late Jurassic in age (Haxel et al., 1985), although recent U-Pb dating of detrital zircons indicates that parts of the formation are as young as Cretaceous (A.P. Barth, 2008, personal communication in Reis, 2009). These rocks represent a shallow level of the Mesozoic arc and its supracrustal cover and are thought to be correlated with the lower part of the McCoy Mountains Formation to the north, and with metasedimentary and metavolcanic rocks of Slumgullion in southwestern Arizona (Haxel et al., 1985). The Winterhaven formation is overlain by Oligocene to Holocene volcanic and sedimentary rocks with angular unconformity (Crowe, 1973; Dillon, 1976), although in many locations the original depositional contacts have been cut by steep to low-angle faults.

In the past, some have argued that the Winterhaven Formation and Orocopia Schist were derived from the same protolith. However, this now seems unlikely, as the two units are composed of very different lithologies. The Winterhaven Formation can be divided into two main parts based on composition – a basal volcanic unit and a siliciclastic sedimentary rock unit that consist in turn of a lower quartz arenite member and an upper argillitic siltstone member (Haxel et al., 1985). In addition to the rock units indicated by the member names, the Winterhaven Formation also contains sandy limestone, graywacke, silty argillite, conglomeratic sandstone, and conglomerate.

The thickest (~450 m) and best outcrops of the Winterhaven Formation are present in the set of hills to the east of the Gavilan Hills between Little Picacho Wash and White Wash (Fig. 60). This area is described in detail by Haxel et al. (1985), who proposed a transect on the north side of the hills as the type section. The basal unit of the Winterhaven Formation is a dark-purple-brown strongly
altered dacite including some andesite. Its exposed thickness is in the range of 80 m. The original plagioclase and biotite are altered to chlorite, sericite, and opaque minerals. In a number of places, interlayering with coarse-grained graywacke units is observed. The top of the dacite member is strongly deformed, and breccia is present that consists of fragments of strongly altered porphyritic volcanic rock in a matrix of fine-grained sericitic sandstone. Several dikes and a small, grayish-purple porphyritic body are included in this dacitic flow unit.

The dacitic member is overlain by a 60 m quartz arenite unit. The latter consists of brown, tan, or white quartz arenite and feldspathic quartz arenite. Grain size varies from fine to coarse. The quartz arenite is interbedded with sandy limestone, argillitic siltstone, and calcareous argillite.

The quartz arenite member is overlain in turn by an argillitic siltstone member, about 300 m thick, named by the most common slightly calcareous argillitic siltstone, which is interlayered with silty argillite and slightly calcareous graywacke. Minor amount of argillite, sandy limestone, slightly argillitic sandstone, and conglomerate with graywacke matrix are present as well. Grain size increases gradually toward the top of the member.

Rocks of Slumgullion

In the Castle Dome Mountains of southwestern Arizona there is a sequence of rocks lithologically similar to the Winterhaven Formation that Haxel et al. (1985) named “the sedimentary and volcanic rocks of Slumgullion” (Fig. 61). These rocks are thicker and more diverse than the Winterhaven Formation but occur in the same stratigraphic order, which forms the basis for the correlation of these rocks. The generalized lithostatigraphic columns presented by Haxel et al. (1985) indicate a clear correlation between dacite and quartz arenite members present in both sequences. Correlation of the upper unit of the Winterhaven Formation, the argillitic siltstone member, with the rocks of Slumgullion is less clear. This unit could correspond to either of two subunits of the rocks of Slumgullion — the lower one consists of quartz arenite, argillitic sandstone, silty argillite, minor
Figure 60. Geology of unnamed set of hills due east of the Gavilan Hills (Haxel et al., 1985).

Sample number
Sample number

Figure 61. Geology of the southeast Castle Dome Mountains (Haxel et al., 2002).
conglomerate, and sandy limestone; the upper one contains sandstone, pebble conglomerate, and minor siltstone.

In spite of the likely overall correlation between the Winterhaven Formation and rocks of Slumgullian, there is a significant difference between them. In contrast to the Winterhaven Formation, the rocks of Slumgolian contain large amounts of rhyodacitic volcanic rocks, coarse conglomerate, and sedimentary breccia.

**Geologic characteristics of the areas sampled for (U-Th)/He dating**

**Gavilan Hills**

As described in the Introduction, the Gavilan Hills comprise one of the most important places for understanding the tectonic evolution of the Orocopia-type schist (Haxel, 1977; Dillon et al., 1990; Oyarzabal et al., 1997; Jacobson et al., 2002, 2007) (Fig. 5). Three main geological units are present here. Structurally deepest is the Orocopia Schist, which is overlain by orthogneisses, which are in turn overlain by the Winterhaven Formation. The three units are separated from each other by the lower Chocolate Mountains fault and upper Gatuna fault, respectively (Fig. 6). The Chocolate Mountains fault and the Gatuna fault are low-angle normal faults responsible for the exhumation of the schist. The above rock units and faults are exposed in a doubly-plunging anticline, with the schist in the core and the gneisses and Winterhaven Formation exposed along the north and east flanks. The central schist exposure has a length of approximately 5 km in the east-west direction and 3 km in the north-south direction. The exposed structural thickness of the schist is in range of 300–400 m. The maximum thickness of overlying gneisses is in the range of 120 m, and Winterhaven Formation has an exposed thickness of about 200 m. In general, all three units are present in succession; however, there are several 500-m stretches along the northeastern and eastern sides of the anticline where the gneiss unit and Chocolate Mountains fault are cut out and volcanic rocks of the Winterhaven Formation directly overlie the Orocopia Schist along the Gatuna fault.
Extensive $^{40}$Ar/$^{39}$Ar thermochronological studies of the Orocopia Schist and gneisses in the Gavilan Hills have led to the conclusion that the Chocolate Mountains is an early Cenozoic low-angle normal fault responsible for exhumation of the schist contemporaneously with subduction (Jacobson et al., 2002, 2007). In contrast, there is no direct thermochronological age constraint on the Gatuna fault. This relates to the fine-grained nature of the Winterhaven Formation, which limits the isotopic systems that can be used for dating. The relatively brittle nature of this fault and the fact that the Winterhaven Formation appears to be overlain depositionally by late Oligocene to early Miocene volcanic and sedimentary rocks would seem to imply that this fault is middle Cenozoic in age, analogous to the Orocopia Mountains detachment fault. The purpose of this study was to conduct (U-Th)/He dating of zircon from the Winterhaven Formation and units below the Gatuna fault to test this hypothesis. The Gavilan Hills were chosen as a key area for this analysis because of the large existing thermochronological dataset for the Orocopia Schist and gneiss. Additional samples were also analyzed, however, from two other areas described below.

**Unnamed set of hills due east of Gavilan Hills**

To the east of the Gavilan Hills area, between Little Picacho Wash and White Wash, is another important outcrop of the Orocopia Schist (Fig. 60). As in Gavilan Hills, the schist also forms an elongated dome, approximately 1.5 km in east-west dimension, with upper plate rocks on the flanks. However the spatial distribution of upper plate rocks along the schist is slightly different than in the Gavilan Hills. The Chocolate Mountains fault and overlying gneisses are present only along the south boundary of the schist, with a contact length of ~ 500 m. Elsewhere in this area, the Orocopia Mountains detachment fault and gneisses are cut out and the various units of the Winterhaven Formation are in direct contact with the Orocopia Schist. The fault at the base of the Winterhaven Formation is considered to be a correlative of the Gatuna fault and in this area is known as the Sortan fault (Haxel et al., 1985). In addition, along the south side of this domal structure, the gneiss and Winterhaven Formation are separated by hydrothermally altered granite referred to as the granite of
Marcus Wash by Haxel et al. (1985), but now considered to be correlative with the biotite-bearing leucogranite of the Jurassic Kitt Peak-Trigo Peaks super-unit of Tosdal et al. (1989; Haxel, 2010, personal communication). Haxel et al. (1985) inferred that this granitoid had intruded the Orocopia Schist, gneiss, and Winterhaven Formation along the Gatuna-Sortan fault system. More likely, however, this unit is probably part of the same structural plate as the Winterhaven Formation. The exposed structural thickness of the schist in this area is in the range of 300-400 m, the maximum thickness of the overlying gneisses is in the range of 120 m, and the Winterhaven Formation is about 450 m thick.

**Castle Dome Mountains**

One additional outcrop considered in this study is located to the east of the Gavilan Hills in the southeast Castle Dome Mountains of southwestern Arizona (Fig. 61). Here the Orocopia Schist forms a dome elongated in the north-south direction with the schist in the middle. The exposure of schist is 6 km long and 2.5 km wide. Four plates are present above the schist, divided by low-angle normal faults from each other. The three lower plates are the same is in the Gavilan Hills – the Orocopia Schist, the orthogneiss plate, and the rocks of Slumgullion, separated from each other by the Chocolate Mountains fault and Big Eye fault, respectively. A low-angle middle Cenozoic fault divides the rocks of Slumgullion from an overlying plate of tectonic and sedimentary breccia, which is in turn separated from an upper plate of early Miocene volcanic rocks by a low-angle middle Cenozoic fault.

The Chocolate Mountains fault is preserved in three places along the south and east boundaries of the schist. At these locations, gneisses above the fault, and locally the schist itself, are significantly mylonitized. Along the northwest and west sides of the schist, the contact between the schist and the upper gneiss is debatable. Haxel et al. (2002) described this contact as a segment of the middle Cenozoic Big Eye fault based on observations of strong brecciation along the fault. However
Reis (2009) argued that this fault is the Chocolate Mountains fault analogous to the areas along the south and eastern parts of the schist.

Along the west side of the schist and gneiss dome are exposed the metamorphosed sedimentary and volcanic rocks of Slumgullion. This unit is separated from the underlying gneisses by the Big Eye Fault, which is considered analogous to the Gatuna-Sortan fault.

The above-mentioned breccia plate, which locally overlies the Orocopia Schist, gneiss, and rocks of Slumgullion, is a very distinct unit that consists of both tectonic and sedimentary breccias, feldspathic and quartzofeldspathic in composition. It contains also minor amounts of arkosic conglomerate, pebbly sandstone, sandstone, and siltstone (Haxel et al., 2002).

The early Miocene volcanic and subvolcanic rocks of the structurally highest plate are mostly rhyolitic to dacitic in composition. They are widespread in the southern and southeast parts of the area. The basal fault of this plate cuts all the structurally deeper faults, locally placing the volcanic rocks on the breccia units, granodiorite and leucogranite, rocks of Slumgullion, and Orocopia Schist. Northeast-striking rhyolitic dikes that seem to be genetically related to the volcanic plate intrude the schist and the adjacent rocks.
CHAPTER 4. THERMOCHRONOLOGY OF THE OROCOPIA SCHIST
AND THE UPPER PLATE

The distribution of (U-Th)/He and $^{40}$Ar/$^{39}$Ar ages can be used to analyze rate and extent of motion on faults, and actual timing of the tectonic events that cause rock cooling. In this study, these methods were used to constrain the exhumation history of the Orocopia Schist in southeasternmost California and southwestern Arizona. Previous $^{40}$Ar/$^{39}$Ar dating indicates that the Chocolate Mountains fault in the Gavilan Hills is early Cenozoic in age (Jacobson et al., 2002). The main focus of this study was to constrain the age of the structurally higher Gatuna fault in the Gavilan Hills, as well as the equivalent Sortan fault in the hills directly to the east and the Big Eye fault of the southeast Castle Dome Mountains. To help constrain the age of the Gatuna-type faults, (U-Th)/He thermochronological analyses were performed on single detrital zircons from eight samples collected both above and below the Gatuna-Sortan-Big Eye faults (Table 1). These included (1) four samples from the Gavilan Hills, UG1504 and UG1508 from the Orocopia Schist and UG1509 and UG1510 from the overlying Winterhaven Formation (Fig. 5); (2) two samples from the Little Picacho Wash area, YN16 from the Orocopia Schist and 06-634 for the overlying Winterhaven Formation (Fig. 60), and (3) two samples from the Castle Dome Mountains, KE19 from the gneiss and KE19A from overlying rocks of Slumgullion (Fig. 61).

(U-Th)/He dating of single zircon grains

Thermochronology of a normal fault model

The utility of thermochronological analysis for dating normal faults can be understood from the model of Figure 62. Two samples in the model, indicated by pink and yellow circles, are considered at different depths along the normal fault (Step I). The sample in the footwall is located deeper than the closure temperature for the mineral that has been chosen for analysis (closure temperatures for different minerals are represented in Figure 63). The sample in the hanging wall is
positioned above the isotherm for the closure temperature; its age of 10 Ma is arbitrary and represents the time in the past that the sample was exhumed above the closure temperature by erosion. During faulting (Step II), the sample in the footwall moves toward the Earth’s surface and at some point, for example at 10 Ma, reaches the closure temperature for the analyzed mineral. At this moment, the thermochronological clock for the footwall sample will start recording time (0 Ma). The hanging wall sample age is $10 + 10 = 20$ Ma at this point. Sometime later, for example in 1 m.y., the footwall sample reaches the depth at which it is adjacent to the hanging wall sample (Step III). At this point, the ages of the footwall and hanging wall samples are 1 Ma and 21 Ma, respectively. After some time, for example in 9 m.y., both samples are brought to the Earth’s surface as a result of erosion (Step IV). At this stage, the footwall sample would yield an age of 10 Ma, whereas the hanging wall sample’s age would be 30 Ma. Note that the age of the footwall sample gives a maximum for the time at which the hanging wall and footwall samples were brought together along the fault (i.e., the final phase of movement on the fault). In this case, that juxtaposition occurred at 9 Ma. The older (10 Ma) age of the footwall sample reflects the fact that it passed through the closure temperature during fault movement. The alternative is that the hanging wall and footwall are brought together at a depth below the closure temperature of the mineral system under consideration. In this case, later erosion will cause both samples to be brought through the closure temperature at the same time and yield the same age, which will provide a minimum for the time of movement of the fault. Using multiple mineral systems with different closure temperatures (Fig. 63), it is thus possible to bracket the age of movement on the fault. Such an approach was used here in an attempt to calculate the timing of slip along the Gatuna-type faults and to discuss the structural evolution in this region (see “Results” and “Discussion” chapters for more details).

**Technical aspects of (U-Th)/He chronology**

(U-Th)/He chronology is based on series decay of parent nuclides $^{238}$U, $^{235}$U, and $^{232}$Th to a stable daughter product of $^4$He nuclei ($\alpha$ particles) (Ehlers et al., 2003; Farley, 2002). As explained by
Farley (2002), the equation for ingrowth is defined as: 
\[ ^4\text{He} = 8 \cdot 238\text{U} \cdot (e^{\lambda_{238}t} - 1) + 7 \cdot \left( \frac{238\text{U}}{137.88} \right) \cdot (e^{\lambda_{235}t} - 1) + 6 \cdot 232\text{Th} \cdot (e^{\lambda_{232}t} - 1), \]
where \(^4\text{He}, \text{U}, \text{and Th}\) refer to present-day amounts of the respective elements, \(t\) is the accumulation time (He age), and \(\lambda\) is the decay constant \((\lambda_{238} = 1.551 \times 10^{-10} \text{ yr}^{-1}, \lambda_{235} = 9.849 \times 10^{-10} \text{ yr}^{-1}, \lambda_{232} = 4.948 \times 10^{-10} \text{ yr}^{-1})\). Multiple \(\alpha\) particles are emitted within each of the decay series; this is accounted for in the coefficients preceding the \(\text{U}\) and \(\text{Th}\) abundances (Farley, 2002). The factor of \((1/137.88)\) represents the present-day \(^{235}\text{U}/^{238}\text{U}\) ratio. Measurements of parent and daughter isotopes should be performed to define the time since the source rock reached the closure temperature. The assumption is made that there are no extraneous sources of He.

There are two widely used procedures for He dating. The first one involves in vacuo extraction of He by heating in a furnace (Farley, 2002). The second one, and the one used in this study, utilizes a laser for He extraction (Reiners et al., 2002) followed by purification and analysis by inductively coupled plasma mass spectrometry (ICP-MS). For more information regarding the rationale of the technique and its application to zircon systems see Reiners et al. (2001).

**Zircon preparation methods**

Samples were crushed using a jaw crusher and a disk mill, and sieved with 30, 60, 80, and 100 mesh sieves. The fraction from the 100 mesh sieve was run through a Franz magnetic separator. Then heavy liquids were applied for further separation and a second round of magnetic separation. Finally, hand picking of single zircons grains was performed to choose the best quality grains – euhedral prisms, colorless, with rare inclusions, and with width exceeding 70 microns (Fig. 64). Photographs were made of all picked grains for all three dimension measurements (length and two widths), which are necessary to correct for helium loss due to recoil (Table 1, Appendix C). The final step of the preparation for analysis involved placing each zircon inside a separate niobium (Nb) tube (weight 0.75 mg), and closing the tube with tweezers (Fig. 65). Figure 60. Geology of unnamed set of hills due east of the Gavilan Hills (Haxel et al., 1985).
Figure 62. Thermochronology of a normal fault.

Figure 63. Comparative nominal closure temperatures of various thermochronometers. Ar—$^{40}$Ar/$^{39}$Ar; Ar MDD—$^{40}$Ar/$^{39}$Ar multidiffusion domain; FT—fission track; He—(U-Th)/He (from Farley, 2002).
Figure 64. A picked zircon grain.

Figure 65. Niobium tube closed with tweezers, zircon grain is inside.

Figure 66. Helium extraction line at Stanford University.
Figure 67. Noble gas mass spectrometer.

Figure 68. Schematic diagram of He extraction line and noble gas mass spectrometer.

TP-turbo pump
IP-ion pump
TC - thermocouple
M – manual valves
Figure 69. Close-up of sample chamber.

Figure 70. Sample chamber with laser and optical pyrometer aligned.

Figure 71. Niobium sample packet imaged on computer display. Note increasing sample luminance as the sample is heated.
Figure 72. Parr Instruments Teflon bomb liner.

Figure 73. Pressure vessels and oven set up.

Figure 74. Labeled polypropylene vials ready for measurements for U and Th on quadrupole ICP-MS.
He measurements

He measurements were performed in “The Noble Gas Laboratory” at Stanford University under the supervision of Dr. Marty Grove. The system used to measure He contents consists of two main parts – an extraction line designed at Stanford University, and a noble gas mass spectrometer from Nu Instruments (Nu Instruments, 2010) (Fig. 66–68).

He extraction

Helium is extracted from the samples using a laser for heating the niobium packets containing the zircons. The gas is cleaned in the extraction line and then sent to the mass spectrometer.

The sample packets are held in the sample chamber in a 2.5-cm-diameter tray with 36 wells arranged in a 6 x 6 grid. Each well holds one niobium packet (Figs. 69 and 70). The sample chamber has a transparent, zinc selenide Cleartran™ window, which has excellent transmissivity for the wavelength of the laser used to heat the sample. A double-pumped design is used to counterbalance loss of vacuum around the edges of the window. As a result, blanks in the chamber are extremely low, below detection for $^3\text{He}$ and 50 counts per second for $^4\text{He}$. This is negligible compared to the signal, which is typically billions of counts per second.

Samples are heated through the window using a Synrad CO$_2$ laser. The laser has an output power of 10 watts, wavelength of 10.6 microns, and produces a spot which is 100–130 microns in diameter (Synrad, 2010). The spot diameter can be adjusted with a beam expander.

As a niobium packet is heated by the laser, it begins to glow. This allows the temperature to be determined using a calibrated optical pyrometer. The one used here has a temperature range of 650–1450 °C.

A proportional integral derivative (PID) controller is used to control power to the laser based on the temperature measured by the optical pyrometer (Fig. 71). However, because of imperfect coupling between the laser and packet related to the irregular surface of the packet, some manual
adjustment of the laser power is required by the operator to maintain the correct temperature. Samples are heated for eight minutes at ~1000 °C. The extracted gas is then transferred to the purification part of the line, which contains getters. Getters are made of vanadium, titanium, and other metals that chemically react with the gas and take away all oxygen, nitrogen, carbon monoxide, etc., but don’t react with Noble gases (He and Ar).

In addition to the gas extracted from the sample, a calibrated amount of $^3$He is added to the extraction line from a pipette system. The pipette system consists of a reservoir (four liters volume) and a pipette with a volume of 0.1 cc. Because the volume of $^3$He is known, the amount of $^4$He derived from the unknown is approximated by the relative count rates of $^3$He and $^4$He determined by the mass spectrometer. This value, however, needs to be corrected for fraction of $^3$He and $^4$He in the system. This is done using a relative sensitivity factor determined by standard runs in which a known amount of $^3$He is introduced into the system, as described previously, along with a known amount of pure $^4$He from a second reservoir that is part of the pipette system.

The extraction line is completely metal, except for the window of the laser chamber. Leakage is minimal, and the relative measurements from blanks and samples indicate that 99.9% of He measured is derived from the sample or from the standards.

The extraction process (and mass spectrometer analysis) is performed at least twice on each sample to ensure that most of the He has been outgassed. During the second extraction, the amount of He detected is expected to be 5% or less of the amount measured on the first step. In this project, in several cases, where at the second step a lot of gas was detected, a third extraction was performed.

**Noble Gas Mass Spectrometer**

After He is purified from the sample, it is transferred to the mass spectrometer. A period of 20 seconds is used to equilibrate the gas between the extraction line and mass spectrometer. At the next step, the mass spectrometer is isolated from the extraction line. The analysis is run in static mode.
The mass spectrometer is of the sector type, which consists of a bent flight tube and magnet that causes the dispersion of the ion beams such that they can be resolved and measured individually. It has sufficient dispersion that is also able to resolve some of the residual gas interferences. For example, the interference between hydrogen-deuterium molecules and $^3$He is resolved by 90%. Interference for $^4$He blanks is about 40–50 counts per second, which is typical for other laboratories (M. Grove, personal communication), although the source of the interference is not known. All the valves of the mass spectrometer are fully automated.

The mass spectrometer uses a Nier-type electron-bombardment source to ionize the gas to be analyzed. Potential of the mass spectrometer half-plates is adjusted so that the relative sensitivity of $^3$He and $^4$He is close to 1.0.

$^4$He is typically counted on a Faraday detector during the first extraction for each zircon, when count rates are relatively high. For young samples, or those with low U and Th, however, $^4$He may be measured on an ion counter, even for the first extraction. An ion counter is always used for $^4$He for the second extraction and for $^3$He, which is introduced in known amounts from the pipette system, for both extractions. The ion counter is fitted with an electrostatic filter that excludes extraneous ions, so base line noise is very low, typically 0–5 counts per second. Extraneous counts are considered to be a residual of radioactive material previously run through the system.

Mass discrimination is typically measured 10 times over a 24-hour period. The results of these measurements are averaged to calculate the $^3$He/$^4$He relative sensitivity factor to be used for the unknowns. The relative sensitivity factor is typically stable over the course of a given analysis session to 3–5‰ for measurements made using a combination of the Faraday detector and ion counter and 2–3‰ when $^3$He and $^4$He are both measured on the ion counter.

**U-Th measurements**

After the measurements for He were finished, another set of isotope dilutions was performed to measure U and Th concentrations. The zircons, in their Nb tubes, were transferred to labeled clean
Ludwig style micro-vials (200 µl) (Fosdick, 2010). One to two drops of spike of $^{233}$U/$^{229}$Th were gravimetrically added to each micro-vial. In addition to the spike, 175µl of Optima HF and 25µl of Optima HNO$_3$ were added to each micro-vial. Each vial was capped and transferred to a Parr Instruments Teflon bomb liner (Fig. 72). Each bomb liner holds 15 micro-capsules. Typically 13 of the capsules contain unknowns. Usually, one additional capsule will include an empty Nb capsule without a spike, for a spike blank, and one capsule will include a Fish Canyon standard zircon, which has a known (U-Th)/He age of 28.02 ± 0.28 Ma (Renne et al., 1998). Water blanks were also added periodically.

In addition, 9650 µl of TMG HF and 400 µl of TMG HNO$_3$ were added to the bottom of the liner. The construction of the micro-vials allows vapor exchange between the micro-vials and liner during the heating stage. This prevents the build-up of pressure within the micro-vials, which can cause the caps to pop off and allow mixing of the fluids between the vials and liner. Measurements indicate that, although this system is open to vapor, there is very little exchange of U and Th between the vials and external solutions. For the hydrothermal digestion phase, the liners were sealed and placed in a pressure vessel. The pressure vessel was heated up to the 225 °C during 72 hours (Fig. 73). At this temperature, internal pressure is expected to be 10–15 bars.

After the heating stage, the pressure vessels were disassembled and micro-vials were opened and dried on a hotplate at 115 °C for 8–12 hours. When each vial’s content was dried down to a salt, 25 µl of TMG HF and 200 µl of TMG HNO$_3$ was added to each vial. Vials were placed on the hotplate for 60 minutes to cause final dissolution of the salt. Then the contents of the vials were transferred to polypropylene vials (Fig.74). Two hundred microliters of Milli-Q water was added to each emptied micro-vial and poured into the corresponding polypropylene vial to ensure complete transfer of the solutions from the micro-vials. At this stage, 2700 µl of Milli-Q water was added to each polypropylene vial to create a final volume of approximately 3125 ml.
Samples in polypropylene vials were transferred to the University of Santa Cruz lab to make measurements for U and Th on a quadrupole ICP-MS. This instrument is equipped with a special gas inlet to perform measurements of highly concentrated Nb solutions. Results of analyses were exported to Excel spreadsheets for the further age calculations.
CHAPTER 5. RESULTS

In order to constrain the age of slip along the Gatuna-type faults, (U-Th)/He thermochronological dating was performed on single zircons from rocks above and below the faults in three areas – the Gavilan Hills, the unnamed hills east of the Gavilan Hills, and the southeast Castle Dome Mountains. Eight samples were analyzed total in this study, four each from above and below the Gatuna-type faults (Table 4). Monotonic cooling and a closure temperature for zircon 180 ± 50 °C (McDougall and Harrison, 1999) were assumed for interpreting the results. Detailed results of (U-Th)/He dating are provided in the Table 1, Appendix C.

Unfortunately, not all the analyses were completed within the time frame of this study. Helium data were obtained for 112 zircon grains total, not including standards, but only 63 dissolutions and ICP-MS U-Th analyses were finished. Therefore, final (U-Th)/He ages are available for only part of the dataset.

For one sample, only one zircon age has been determined so far, and for another sample only two ages are available. These limited results are not considered significant and are removed from further discussion. For the remaining samples, all age results were averaged by sample and sample standard deviations were calculated. Ages deviating from the mean by more than two standard deviations were eliminated from the data set and new averages calculated. Errors reported below for the final average ages represent one standard deviation of the mean (i.e., the standard error).

Technical aspects of age calculations

As mentioned above, radioactive decay of U and Th produces alpha-particles (He nuclei). The alpha particles have such a high kinetic energy that they may be ejected from the host crystal. In order to account for this loss of He atoms, it is necessary to calculate an alpha-ejection correction factor \( F_T \), which is defined as the fraction of radiogenic \(^4\text{He}\) retained in the host grain (Farley et al., 1996; Farley, 2002; Hourigan 2005; Reiners, 2005). The He age is corrected for ejection loss of
alpha-particles by $t = t' / F_T$, where $t'$ is the raw uncorrected He age, and $t$ is the corrected age (Hourigan 2005). In order to calculate $F_T$, grains are divided into two principal groups based on morphology: prolate spheroid and prismatic grains with bipyramidal terminations (or with broken ends perpendicular to the c-axis). Surface area and volume of the grains are calculated based on measurements of zircons along the crystallographic axis using the equations from Table 2.

**Table 2.** Surface areas and volumes of zircons for assumed geometries of zircon crystals (Reiners, 2005).

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Volume</th>
<th>Surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetragonal prism with pyramidal terminations</td>
<td>$V_z = 4 r_1 r_2 \left[ (l - h_1 - h_2) + \frac{1}{3} (h_1 + h_2) \right]$</td>
<td>$SA_z = 4 (l - h_1 - h_2) (r_1 + r_2) + 2 r_1 a + 2 r_2 b$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$a = \sqrt{h_1^2 + r_1^2} + \sqrt{h_2^2 + r_2^2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$b = \sqrt{h_1^2 + r_1^2} + \sqrt{h_2^2 + r_2^2}$</td>
</tr>
<tr>
<td>Prolate Spheroid</td>
<td>$V_{ps} = \frac{2}{3} \pi r^2 l$</td>
<td>$SA_{ps} = 2 \pi r^2 \left[ \frac{2 \pi r \left( \frac{l}{2} \right)^2}{\sqrt{\left( \frac{l}{2} \right)^2 - r^2}} \right] \sin^{-1} \left[ \frac{\sqrt{\left( \frac{l}{2} \right)^2 - r^2}}{\left( \frac{l}{2} \right)} \right]$</td>
</tr>
</tbody>
</table>

**Note:** $l$ – c-axis parallel length; $h_1$, $h_2$ – pyramidal termination lengths; $r_1$, $r_2$ – mutually-perpendicular prism half-widths or average equatorial radius. Prolate spheroid geometry was not modeled for independent polynomial factors, and is assumed to have the same $A$’s as the tetragonal prism with pyramidal terminations.

At the next step, the surface-area-to-volume ratio ($\beta = SA/V$) is calculated. This parameter is used to determine the alpha-ejection factor, $F_T$:

$$F_T = 1 + A_1 \beta + A_2 \beta,$$
where \(A_1\) and \(A_2\) are factors for different morphologies. Values for \(^{238}\text{U}\) and \(^{232}\text{Th}\) are given in Table 3, and those for \(^{235}\text{U}\) are similar to the ones for \(^{232}\text{Th}\). The \(F_T\) factor is used to calculate the corrected age as described above.

**Table 3.** Factors \(A_1\) and \(A_2\) for calculating fraction of He retained in crystals from the \(^{238}\text{U}\) and \(^{232}\text{Th}\) decay series in zircon, for different assumed crystal geometries (Hourigan et al., 2005).

<table>
<thead>
<tr>
<th>Parent Nuclide</th>
<th>Tetrahedral prism with pinacoidal terminations</th>
<th>Tetrahedral prism with pyramidal terminations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238}\text{U})</td>
<td>(A_1) -4.31 \hspace{1cm} (A_2) 4.92</td>
<td>(A_1) -4.35 \hspace{1cm} (A_2) 5.47</td>
</tr>
<tr>
<td>(^{232}\text{Th})</td>
<td>(A_1) -5.00 \hspace{1cm} (A_2) 6.80</td>
<td>(A_1) -4.94 \hspace{1cm} (A_2) 6.88</td>
</tr>
</tbody>
</table>

**FCT standards**

Ten Fish Canyon Tuff zircons (FCTs) were added as standards to the sequence. Ages have so far been obtained for seven of these grains, and range from 25.8 to 31.0 Ma, with an average of 28.5 ± 0.5 Ma (Table 4). The generally accepted \((\text{U-Th})/\text{He}\) age for Fish Canyon Tuff zircon is 28.02 ± 0.28 Ma (Renne et al., 1998).

**Gavilan Hills**

Zircon \((\text{U-Th})/\text{He}\) ages were determined for the same schist samples (UG1504 and UG1508) from the Gavilan Hills that were analyzed before with the \(^{40}\text{Ar}/^{39}\text{Ar}\) MDD method on K-feldspar (Jacobson et al., 2007). For sample UG1504, nine single zircons were analyzed and the ages are in the range 21.4–27.7 Ma (Fig. 5; Table 4; Table 1, Appendix C), with an average of 24.3 ± 0.7 Ma. For sample UG1508, 15 grains were analyzed. Two of the ages were eliminated from consideration
based on the statistical criterion discussed above. The remaining 13 ages have a range of 10.7–34.8 Ma. The average age is 22.4 ± 1.6 Ma.

In addition to the two samples from the schist, two samples, UG1509 and UG1510, were processed from the overlaying Winterhaven Formation. Only two zircons ages were obtained so far from UG1509, and consideration of this sample is deferred until the remaining results are available. In contrast, for UG1510, twelve grain ages were completed. Ten of these yielded acceptable ages, with a range of 27.9–46.6 Ma and an average age of 39.7 ± 1.8 Ma (Table 4; Table 1, Appendix C).

**Unnamed hills due east of the Gavilan Hills**

In the unnamed hills east of the Gavilan Hills, two samples were selected: YN16 from the Orocopia schist and 06-634 from the Winterhaven Formation (Fig. 60; Table 4; Table 1, Appendix C). Nine ages completed so far for YN16 show a spread from 17.0 to 25.1 Ma and an average of 22.6 ± 0.8 Ma, which is within the range of ages for the schist from the Gavilan Hills. Only five ages were completed for sample 06-634, of which one has been eliminated from the average as a statistical outlier. The remaining four ages range from 11.2 to 97.3 Ma, with an average of 38.0 ± 20.0. This is quite similar to the age determined from the Winterhaven Formation in the Gavilan Hills, although the high error and limited number of ages suggest that little weight should be placed on this result until the remaining 8 grains (Table 4) are analyzed.

**Castle Dome Mountains**

Two samples were analyzed from the Castle Dome Mountains, one of gneiss (KE19) and one from the rocks of Slumgullion (KE19A), which is analogous to the Winterhaven Formation (Fig. 61). Ten single-grain ages from KE19 vary from 17.3 to 30.0 Ma, with an average of 24.8 ± 1.3 Ma. For KE19A, only one result (26.6 Ma) has been obtained so far; more data are needed for a meaningful interpretation.
Table 4. Summary of (U-Th)/He ages.

<table>
<thead>
<tr>
<th>Fish Canyon Tuff standards</th>
<th>Sample</th>
<th>Grains prepared(^1)</th>
<th>Grains analyzed(^2)</th>
<th>Grains used(^3)</th>
<th>Range(^4) (Ma)</th>
<th>Age ± 1σ(^5) (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCT</td>
<td>10</td>
<td>7</td>
<td>7</td>
<td>25.8 - 31.0</td>
<td>28.5 ± 0.7</td>
</tr>
<tr>
<td><strong>Gavilan Hills</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oroccopia schist</td>
<td>UG1504</td>
<td>13</td>
<td>9</td>
<td>9</td>
<td>21.4 - 27.7</td>
<td>24.3 ± 0.7</td>
</tr>
<tr>
<td>Oroccopia schist</td>
<td>UG1508</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>10.7 - 34.8</td>
<td>22.4 ± 1.6</td>
</tr>
<tr>
<td>Winterhaven Formation</td>
<td>UG1509</td>
<td>14</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winterhaven Formation</td>
<td>UG1510</td>
<td>16</td>
<td>12</td>
<td>10</td>
<td>27.9 - 46.6</td>
<td>39.7 ± 1.8</td>
</tr>
<tr>
<td><strong>Unnamed hills east of the Gavilan Hills</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oroccopia schist</td>
<td>YN16</td>
<td>13</td>
<td>9</td>
<td>9</td>
<td>17.0 - 25.1</td>
<td>22.6 ± 0.8</td>
</tr>
<tr>
<td>Winterhaven Formation</td>
<td>06-634</td>
<td>13</td>
<td>5</td>
<td>4</td>
<td>11.2 - 97.3</td>
<td>38.0 ± 20.0</td>
</tr>
<tr>
<td><strong>Castle Dome Mountains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gneiss</td>
<td>KE19</td>
<td>14</td>
<td>10</td>
<td>10</td>
<td>17.3 - 30.0</td>
<td>24.8 ± 1.3</td>
</tr>
<tr>
<td>Shungullion Formation</td>
<td>KE19A</td>
<td>14</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**

\(^1\) Grains prepared – number of zircon grains prepared for (U-Th)/He analyses.

\(^2\) Grains analyzed – number of zircon grains for which analysis has been completed.

\(^3\) Grains used – number of zircon grains used to calculate sample age. Grains with ages more than two standard deviations above or below mean age were not used.

\(^4\) Range – range of calculated ages for each sample.

\(^5\) Age ± 1σ – mean calculated age of the sample ± one standard deviation of the mean age. Typical analytical error for individual ages is ± 2–3%.
CHAPTER 6. DISCUSSION

Throughout southeasternmost California and southwesternmost Arizona, the low-angle Chocolate Mountains fault separates the Orocopia Schist, at the structurally deepest level, from overlying orthogneisses derived from relatively deep levels of the Mesozoic Cordilleran magmatic arc. The gneisses, in turn, are separated from overlying low-grade metavolcanic and metasedimentary rocks of the Jurassic to Cretaceous Winterhaven Formation and rocks of Slumgullion and relatively shallow Jurassic plutonic rocks by the Gatuna-Sortan-Buckeye fault system. Determining the age and tectonic significance of the Chocolate Mountains and Gatuna-Sortan-Buckeye fault system is critical for understanding the geology of the region.

Previous $^{40}\text{Ar}/^{39}\text{Ar}$ and related thermochronological analyses of the Orocopia Schist and gneiss from the Gavilan Hills area provide important, but incomplete, constraints on the ages of these fault systems (Fig. 7; Jacobson et al., 2002, 2007). In particular, both the schist and gneiss exhibit two phases of rapid cooling, one in the early Cenozoic (ca. 55–48 Ma) and another in the middle Cenozoic (ca. 28–24 Ma). The data further indicate that the early Cenozoic cooling event occurred in association with slip on the Chocolate Mountains fault. This is inferred from the fact that hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ total gas ages from the Orocopia schist are younger than those from the gneiss. This implies that juxtaposition of the two units occurred at temperatures below those for the closure of argon diffusion in hornblende ($525 \pm 50 ^\circ\text{C}$). In contrast, muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the schist and gneiss overlap, as do the ages for all isotopic systems with lower closure temperatures. Thus, the two plates must have been joined along the Chocolate Mountains fault above the closure temperature for muscovite ($400 \pm 50 ^\circ\text{C}$) and prior to cooling below that temperature; i.e., at ca. 50–48 Ma. The overlapping temperature-time paths for the schist and gneiss following 50–48 Ma indicate that from this point on the schist and the gneiss moved toward the Earth’s surface as a single unit. This in turn indicates that there was no significant slip on the Chocolate Mountains fault after 50–48 Ma.
The early Cenozoic phase of slip along the Chocolate Mountains fault is correlated with retrograde green-schist facies metamorphism of the schist. This event brought the schist from depths of 30–35 km to 10–15 km below the Earth’s surface (Jacobson et al., 2002).

The second cooling event in the region at ca. 28–24 Ma is particularly well highlighted in both the schist and gneiss by MDD K-feldspar data, but is also evident from the youngest biotite ages and apatite fission track ages (Fig. 7). As noted, this cooling event could not be due to slip on the Chocolate Mountains fault. Consequently, it has been suggested that the Gatuna-Sortan-Buckeye fault is the principal structure related to middle Cenozoic exhumation of the Orocopia Schist and gneiss (Jacobson et al., 2002, 2007). However, this has not been confirmed directly through comparison of temperature-time paths of rocks above and below the fault. The (U-Th)/He analyses of this study were conducted to provide such information.

As described above samples for (U-Th)/He analysis were analyzed from three areas of southeasternmost California-southwesternmost Arizona. In each area, samples were selected from either the Orocopia Schist or gneiss from below the Gatuna-Sortan-Buckeye fault system and from the Winterhaven Formation or rocks of Slumgullion above the fault. At this time, complete or nearly complete results are available for only five of the samples: two from the Orocopia Schist of the Gavilan Hills (Fig. 5), one from the Winterhaven Formation of this same area (Fig. 5), one from the schist in the hills to the east of the Gavilan Hills (Fig. 60), and one from the gneiss of the southeast Castle Dome Mountains (Fig. 61).

The three ages from the schist and one from the gneiss are all remarkably similar, ranging from 24.8 ± 1.3 to 22.4 ± 1.6 Ma (Table 4). These dates are entirely consistent with the preexisting thermochronology (Fig. 75) and the view that the schist and gneiss belonged to a single regional structural plate subsequent to being juxtaposed by slip on the Chocolate Mountains fault.

Considering that only one nearly complete (U-Th)/He age is available for the units above the Gatuna-Sortan-Buckeye fault (from the Winterhaven Formation of the Gavilan Hills), interpretation
Figure 75. Generalized temperature-time paths for Orocopia schist (dark grey) and, gneiss (grey) of the Gavilan Hills based on the results of Jacobson et al. (2002, 2007). Colored symbols show the (U-\text{Th})/He results. Light grey band shows the T-t path inferred in this study for the Winterhaven Formation and rocks of Slumgullion based on one analysis of the former unit in the Gavilan Hills area.
of this result must be considered preliminary. Nonetheless, this age is $39.7 \pm 1.8$ Ma, which is significantly older than the schist and gneiss ages. Following the same reasoning described above for using thermochronology to date slip on faults, the implication is that the Gatuna-Sortan-Buckeye fault system has a maximum age of ca. 24–22 Ma. It is interesting to note that a second sample of Winterhaven Formation, from the hills east of the Gavilan Hills, has so far yielded four useable single-grain ages with an average age of $38.0 \pm 20$ Ma. This is nearly identical to the age of the Winterhaven sample from the Gavilan Hills, although it was excluded from the plot of Figure 75 due to the relatively few grains involved and the large error. In any case, the results are consistent with previous interpretation of the Gatuna-Sortan-Buckeye fault as a middle Cenozoic detachment fault.

Slip along the Gatuna-Sortan-Buckeye fault is considered responsible for bringing the schist up from depths of 10–15 km to just below the earth surface. This event is also thought to be correlated with the Cordilleran regional extensional event.

The thermochronological results from the Gavilan Hills can be compared to similar analyses conducted on the Orocopia Schist and related rocks in the Orocopia Mountains to the northwest (Jacobson et al., 2007). Orocopia schist in Orocopia Mountains is overlain by multiple tectonic slices of upper plate rocks that are significantly different from those in the Gavilan Hills area. The deeper upper-plate rocks are predominantly felsic and mafic gneisses and leucogranite, and the shallow rocks are composed of anorthosite-syenite.

Results for the schist in the Orocopia Mountains show a two-stage cooling history very similar to that of the Gavilan Hills area (Fig. 8). Upper-plate rocks in the Orocopia Mountains exhibit a range of cooling histories depending on structural depths. However, none of these slices appears to be equivalent to the gneiss unit of the Gavilan Hills in terms of sharing a similar high-temperature cooling history with the schist. For example, biotite ages in the upper plate of the Orocopia Mountains tend to be at least 30 m.y. older than those in schist, compared to the situation in the Gavilan Hills, where muscovite and biotite ages overlap in the schist and upper plate. Thus, all upper
plate rocks in the Orocopia Mountains must have already been at mid- to shallow-crustal levels when the schist underwent its first phase of exhumation in the early Cenozoic. At that time, the schist was presumably juxtaposed against relatively deep levels of the upper plate along a fault equivalent to the Chocolate Mountains fault, but those rocks were apparently cut out by the present fault separating schist from upper-plate rocks. The thermochronological data imply a middle Cenozoic age for this younger fault event. Consequently, the upper plate in Orocopia Mountains appears to correlate structurally, although not lithologically, with the Winterhaven Formation and rocks of Slumgullion in the Gavilan Hills and related areas considered in this study. In the same sense, the Gatuna-Sortan-Buckeye fault system can be correlated with the Orocopia Mountains detachment fault. Thus, despite the fact that the (U-Th)/He results from this study are preliminary, they confirm other evidence for the presence of a regional middle Cenozoic event responsible for the latest major phase of exhumation of the Orocopia Schist.

The above conclusion has implications for the age of the Chocolate Mountains anticlinorium, which is defined by the folding of the Orocopia Mountains and Gatuna-Sortan-Buckeye detachment faults. The anticlinorium must be younger than the detachment faults and thus younger than 28–22 Ma. This contradicts the theory of Yin (2002) that exhumation of the schist was caused primarily by erosion of an early Cenozoic anticlinorium. Although some role for erosion cannot be excluded, a substantial amount of exhumation of the schists appears to be tectonic, related to early Cenozoic slip on the Chocolate Mountains fault and middle Cenozoic slip on the Orocopia Mountains and Gatuna-Sortan-Buckeye detachment faults.
CHAPTER 7. CONCLUSIONS

1. (U-Th)/He analyses described here comprise the first data set of such analyses performed at the Stanford thermochronological facility. The age of 28.5 ± 0.5 Ma obtained for zircon from Fish Canyon Tuff, which is used as the laboratory standard, correlates well with the generally accepted age of 28.02 ± 0.28 Ma (Renne et al., 1998) and indicates that the He extraction and subsequent U-Th dissolution and ICP-MS analysis should provide correct ages for zircons of unknown ages.

2. (U-Th)/He analysis of zircons and ⁴⁰Ar/³⁹Ar analysis of hornblende, muscovite, biotite, and K-feldspar, combined with previous apatite fission track measurements from the Gavilan Hills of southeastern California, indicate two major cooling events during the early and middle Cenozoic, respectively. The first rapid cooling event occurred from 55 Ma to 48 Ma and is thought to be related to slip on the Chocolate Mountains fault. The interpretation is that this fault brought the schist from maximum depths of underthrusting of 30–35 km to 10–15 km. The preliminary ages obtained in this study from the Gavilan Hills area provide the first direct thermochronological evidence that the main mechanism responsible for younger, middle Cenozoic exhumation is slip along the Gatuna fault. This second rapid cooling event occurred from 28 to 24 Ma and brought the schist from depths of 10–15 km to just below the Earth’s surface. The Orocopia Schist and the Winterhaven Formation overlying the Gatuna fault are thought to have had similar cooling paths following cooling below the zircon closure temperature (180 ± 50 °C). These results are analogous to those for the Orocopia schist and the upper plates in the Orocopia Mountains 100 km to the northwest of the Gavilan Hills and provide additional evidence for a major middle Cenozoic extensional event throughout the region.
3. The publication-quality digital geologic map of the Picacho, Picacho NW, Picacho SW, and Hidden Valley 7.5' Quadrangles in Arizona and California was created based on unpublished mapping of D.R. Sherrod, R.M.Tosdal, and G.B. Haxel conducted for the U.S. Geological Survey, supplemented by the work of Parker (1966), Haxel (1977), Pietenpol (1983), and Oyarzabal et al. (1997). The map includes parts of the exposures of the Orocopia Schist in the Gavilan Hills and unnamed hills east of the Gavilan Hills that were studied here, along with outcrops of the schists in the Trigo Mountains. The map therefore provides information for understanding the tectonic evolution of the area that complements the (U-Th)/He results reported here.
Appendix A

DESCRIPTION OF MAP UNITS

Younger alluvium (Holocene) – Unconsolidated angular to subrounded sand and gravel. Forms wash-bed deposits composed chiefly of locally derived detritus and lacking desert varnish on surfaces.

Flood plain deposits (Holocene) – Unconsolidated sand, silt, and mud. Unit forms broad flood plain of Colorado River and includes stream, over bank, and oxbow-lake deposits. Geomorphic features of Colorado River flood plain have been obscured by agricultural practices.

Younger fluvial deposits (Holocene and Pleistocene) – Chiefly fine- to coarse-grained, rounded to well-rounded unconsolidated sand and gravel deposited by Colorado River. Forms hills less than 12 m high adjacent to river.

Talus (Holocene and Pleistocene) – Slope-mantling deposits of angular to subangular cobbles and boulders. Found chiefly downslope of capping basalt lava flows (unit Tob).

Older alluvium (Pleistocene and Pliocene) – Poorly indurated sandstone and sedimentary breccia. Forms terraces, high-standing alluvial fans, and pediment-veneering deposits that contain mostly locally derived, angular to subrounded clasts of volcanic or crystalline rocks. Veneers pediments, ranging from 2 to 12 m above modern wash floors, cut chiefly in fanglomerate (Tf). Desert varnish is moderately to well-developed on most pediment surfaces.

Older fluvial deposits (Pleistocene and Pliocene) – Unconsolidated to lithified pale-gray to pale-brown arkosic silt, sand, and minor gravel. Commonly weathers pale grayish orange. Unit is interbedded with and overlain by older alluvium (QTa) but
distinguished from it by the presence of predominantly rounded to well-rounded grains, including clasts such as quartzite, quartzose sandstone, and rarely limestone that are foreign to the bedrock of the Picacho quadrangle. Originated mainly as channel deposits, with lesser slackwater deposition. Locally includes:

**Mudstone and siltstone (Pleistocene and Pliocene)** – Unconsolidated to consolidated pale-gray to pale-brown mud and silt. Originated mainly as slackwater deposits (overbank, oxbow lakes)

**Bouse Formation (Pliocene and Miocene)** – White calcareous mudstone, greenish-gray to orange-brown siltstone, and fine-grained sandstone and pebbly sandstone. Locally includes minor barnacle coquina and tufa. Forms gently northwest-dipping strata that cap fanglomerate (Tf) at north-central edge of map. Equivalent to "interbedded member" of Bouse Formation as defined by Metzger (1968); whereas the basal limestone member is lacking in map area. Age is late Miocene and Pliocene

**Fanglomerate (Miocene)** – Sandstone, fanglomerate, sedimentary breccia, and rare beds of air-fall tuff and gypsiferous siltstone. Beds are poorly defined and as much as 80 cm thick. Clasts are subangular to subrounded, heterolithic, and usually no more than 50 cm across but locally as large as 3 m. Clast composition generally changes upsection from Cenozoic volcanic clasts to mixtures of Cenozoic volcanic and pre-Cenozoic crystalline clasts including Orocopia Schist (TKo). Contains numerous internal angular unconformities that record syndepositional extension. In Cibola Valley, strata dip 3°–30° basinward. In Hidden Valley, unit forms 15°–25°-east-dipping homoclinal of well-bedded blocky sandstone and siltstone, with minor gritstone, pebbly sandstone, and breccia. In Bear Canyon, strata dip 2°–40° north to northeast, with several internal unconformities and decreasing dips upsection. Includes rocks previously assigned to conglomerate of Bear Canyon of Crowe (1978)
Landslide or glide-block breccia (Miocene) – Sheet-forming breccia of hornblende dacite interpreted as a shattered gravity glide block. Discordantly overlies tuff of Ferguson Wash (Tfw). Underlies fanglomerate (Tf) in a small area about 1 km north of Hoge Ranch site near mouth of Red Cloud Wash.

Conglomerate and sandstone (Miocene) – Pebby sandstone, conglomerate, arkosic sandstone, and gritstone. Pale brownish gray, light gray, grayish red to yellow gray. Color darkens with increasing grain size. Generally consists of parallel graded beds, 5–30 cm thick; locally displays planar and trough cross bedding. Clasts are well rounded, as much as 60 cm but usually less than 5 cm in diameter, and principally volcanic with rarer quartzite or milky vein quartz. Clasts are commonly imbricated.

Andesite (Miocene) – Lavas of limited outcrop are in Red Cloud Wash and southeast of Gavilan Wash.

Rhyolite (Miocene) – Dikes, plugs, and sills(?) of black, glassy biotite rhyolite. Biotite phenocrysts are ≤ 1 mm across and feldspar phenocrysts ~1 mm across.

Andesitic intrusive rocks (Miocene) – Sills, dikes, and plugs of glassy clinopyroxene-bearing andesite exposed near Vinagre Wash and Clip Wash.

Microdiorite (early Miocene or Oligocene) – Dark greenish-gray microdiorite or microgabbro dikes that intrude Orocopia Schist (TKo) north of the Colorado River.

Granite (latest Oligocene) – Fine-grained, leucocratic biotite granite, and aplogranite that forms dikes and sills intruding Orocopia Schist (TKo) north of the Colorado River. Petrographically resembles other Cenozoic granites that also intrude Orocopia Schist as far west as Mt. Barrow (~38 km to the west) (Dillon, 1976; Smith and others, 1987). Those at Mt. Barrow and Peter Kane Mountains have yielded U-Pb zircon ages of 24.2 ± 0.2 and 24.3 ± 0.9 Ma, respectively (Needy et al., 2007). Early Miocene K-Ar ages (20.5–22 Ma recalculated using the critical tables of Dalrymple.
(1979); Miller and Morton (1977) and Armstrong and Suppe (1973)) and an unpublished late Oligocene U-Pb age of about 25 Ma (Frost and others, 1989) have also been reported for these granites

**Tuff of Felipe Pass (lower Miocene or Oligocene)** – Densely welded, orange-brown weathering rhyodacitic ash-flow tuff. Consists of two cooling units, each with vitrophyric base in most places. Lower cooling unit is biotite-rich; upper cooling unit is biotite-poor. Contains sanidine phenocrysts. Thickness and degree of welding increase to east. Unit is discontinuously exposed eastward to Kofa and Castle Dome Mountains and probably was erupted from caldera source in Kofa Mountains. A U-Pb zircon age of 24.1 ± 0.3 has been reported for this unit from Mule Mountains immediately north of the map area (Needy et al., 2007). K-Ar and ⁴⁰Ar/³⁹Ar ages are interpreted to indicate eruption at about 24 Ma but could be as young as 22 Ma. Forms uppermost, regionally extensive ash-flow sheet in region

**Olivine basalt (lower Miocene or Oligocene)** – Lava flows and interbedded breccia. Exposed in northeastern part of map, where it underlies tuff of Felipe Pass (Tfp)

**Dacite of Vinagre Wash (lower Miocene or Oligocene)** – Domes, lava flows, and volcaniclastic rocks of porphyritic hornblende-bearing dacite or rhyodacite. Commonly contains as much as 15 percent blocky plagioclase phenocrystals, 1–3 mm across; and 5–10 percent hornblende phenocrystals, 1–2 mm long. Weathers grayish red to grayish purple owing to oxidation of groundmass and phenocrysts. Divided into:

**Tuff breccia** – Chiefly coarse-grained, poorly sorted volcaniclastic strata and highly fragmented lava flows. Clasts range from 5 to 50 cm across, deposits range from matrix- to clast-supported. Unit typically shows incipient cavernous weathering. Includes minor tuff and pumiceous lapilli tuff, which is rarely welded
Domes and lava flows – Flow-banded to massive dacite with local vitrophyric margins near contacts with volcaniclastic strata

Tuff and tuffaceous sedimentary rocks (lower Miocene or Oligocene) – Interbedded partially welded ash-flow tuff, tuff, and tuffaceous sandstone. South of Draper Lake, consists of pumiceous sandstone and lapilli tuff, moderately bedded near-vent fallout tuff, and sheet-wash deposits. Probably includes distal parts of major sheet-forming pyroclastic flows such as tuffs of Crazy Woman Wash and Ferguson Wash (Tcw and Tfw), as well as other less extensive deposits

Welded tuff (lower Miocene or Oligocene) – Gray to pink, unwelded to densely welded, slightly porphyritic ash-flow tuff. Includes minor tuff, lapilli tuff, and tuffaceous sandstone

Tuff of Crazy Woman Wash (lower Miocene or Oligocene) – Partially to moderately welded rhyolitic ash-flow tuff. Consists of multiple flows and cooling units in northeast corner of map. Thickness and degree of welding increase north of map area. Unit has K-Ar age on biotite of 24.6 ± 0.7 Ma from the Trigo Mountains, immediately north of quadrangle. Laterally equivalent to 24.1 ± 0.1 Ma lithic tuff in the northern Chocolate Mountains in Arizona to the east (Spencer and others, 1995)

Ignimbrite of Ferguson Wash of Crowe (1978) (lower Miocene and Oligocene) – Partially welded rhyolitic ash-flow tuff forming multiple-flow, single-cooling unit. Phenocrysts are plagioclase (1–3 percent), sanidine-anorthoclase (1–2 percent), oxidized biotite (1–2 percent), iron-titanium oxides, and trace amounts of hornblende, quartz, hypersthene, zircon, and monazite. A sample from along the Colorado River in the south-central part of the map area has yielded a U-Pb zircon age of 23.2 ± 0.2 Ma (Needy et al., 2007). Probably laterally equivalent to rhyolite welded tuff to the immediate south of the map area that has an age of 23.6 ± 0.2 Ma (S.R. Richard,
written commun., 1996). Tentatively correlated with the middle volcanic horizons of
the ignimbrite of Ferguson Wash in the Ferguson Wash area (Crowe, 1978; Richard,
1993a), ~8 km southeast of the map area

**Rhyolite of Red Cloud Wash (Oligocene)** – Grayish-pink to pale-greenish-yellow
porphyritic rhyolite lava, tuff, and epiclastic sandstone and gritstone; grayish yellow
where devitrified. North of Julian Wash and around lower Arrastra Wash, included
dikes of rhyolite porphyry. Pale-greenish-yellow extrusive rhyolite is zeolitized,
generally massive, and forms low topography, whereas grayish pink rhyolite is
strongly flow-banded and forms higher peaks. Unit is widespread from lower Red
Cloud Wash to Julian Wash. Generally overlies andesite (Ta) and underlies tuff of
Ferguson Wash (Tfw)

**Volcanic rocks of Yuma Wash (early Miocene or Oligocene)** – Divided into:

**Rhyolite** – Pale-gray to bluish-gray or pale-pink, finely porphyritic, flow-laminated
rhyolite lava flows. Biotite phenocrysts, ≤1 mm across, compose less than 1 percent
of rock; blocky plagioclase, 1–3 mm in long dimension, locally compose as much as
10 percent of rock. Includes local zones of greenish-black perlitized obsidian and
minor lapilli tuff containing clasts of subjacent basaltic lava (Tywb)

**Tuff and lapilli tuff** – Pinkish to grayish-pink unwelded pumiceous ash-flow, tuff
and lithic lapilli tuff. Contains biotite phenocrysts. East of Yuma Wash, includes
interbedded pale yellowish-green andesitic lithic-lapilli tuff and reddish-brown
arkosic sandstone and pebbly sandstone about 2 m thick. Clasts include diorite and
granite

**Basalt and basaltic andesite** – Reddish- to grayish-brown, massive or very thick and
poorly layered lava flows. Consists of 5–10 percent plagioclase laths, 1–2 mm in long
dimension, and 1–3 percent altered orthopyroxene(?), clinopyroxene, and trace amounts of olivine

Quechan volcanic rocks of Crowe (1978) (Oligocene) – Divided into:

**Andesite or dacite with minor interbedded tuff, lapilli tuff, tuff breccia, and breccia** – Thick flows and domes of olive-brown to reddish-brown, slightly porphyritic rocks. Olivine-bearing basaltic andesite locally present near base of unit. Lavas are typically fractured and altered; liesegang bands common. Phenocrysts, except for clinopyroxene, are altered to saussurite, smectite, clay minerals, and iron oxides.

**Intrusive rocks** – Fine-grained, aphyric to porphyritic dikes, sill, and plugs of gray to reddish- or brownish-gray dacite or rhyodacite. Phenocrysts are plagioclase about 1–3 mm long (<20 percent), pyroxene <1 mm long (<1 percent), and biotite ≤1 mm across (≤2 percent). Multiple, coalescing form cliffs in western part of map area.

**Rhyolite** – Domes, flows, and shallow intrusions of medium-gray to grayish-red, slightly porphyritic rhyolite and thin-bedded rhyolite tuff, breccia, and ash-flow tuff. Phenocrysts consist of plagioclase 1–5 mm long (10–15 percent), biotite ≤1 mm across (1–2 percent), and hornblende 1–3 mm long (1–2 percent).

**Rhyolitic tuff** – Lithic and pumiceous lapilli tuff, chiefly as partially welded to unwelded pyroclastic-flow deposits spatially associated with rhyolite (Tqr).

**Tuff** – Andesitic and dacitic(?) pyroclastic-flow, laharc and hot-avalanche debris-flow deposits (lithic lapilli tuff), breccia, and volcaniclastic sandstone. Contains minor granitic and metamorphic clasts in sedimentary breccias near base of section. Lapilli tuff is bedded 2–5 m thick, with partings defined by 5–10 cm thick sandstone layers, and contains 10–20 percent fragments 1–2 cm across of aphanitic volcanic rock and locally, crystalline clasts. Generally unwelded to partially welded with only
local densely welded tuff. Phenocrysts consist of biotite ≤1 mm across, plagioclase 1–2 mm long, and quartz 1-2 mm across. Biotite from tuff near Velian Wash has a K-Ar age of 26.2 ± 0.8 Ma

**Tuffaceous sandstone (Oligocene)** – Thinly bedded flaggy white sandstone and tuffaceous sandstone. Locally contains thick beds of lapilli tuff similar to tuff of Quechan Formation (Tqt), suggesting that tuffaceous sandstone represents reworked ashy material from early, explosive Quechan eruptions. Also contains few brownish-grayish-red andesitic lava flows. Devitrification and zeolitization have destroyed most sedimentary structures. Includes as much as 40 m of underlying thin-bedded algal limestone south of Velian Wash. Base of unit locally includes arkosic breccia and sandstone equivalent to underlying sedimentary rocks (Ts)

**Sedimentary rocks (Oligocene and Eocene(?))** – Reddish brown breccia, conglomerate, fine- to coarse-grained sandstone, with tuffaceous sandstone locally present at the base. Contains subangular to subrounded clasts derived locally from Jurassic granitic rocks (Jtd, Jtm, Jtd, Jpg, Jtg) or the Winterhaven Formation (Jw). In Black Rock Wash area, rare quartzite clasts suggest input from relatively distant sources

**UPPER PLATE OF CHOCOLATE MOUNTAINS FAULT**

**Granite of Black Rock Wash (Early Cretaceous)** – Hornblende-biotite monzogranite and granite intruded by gray to purplish-gray, fine-grained granite dikes and dark green, fine-grained monzodiorite dikes. Contains pendants of Jurassic diorite (Jtd) and monzodiorite (Jtm). Converted to protomylonite along southern contact near Black Rock and Julian Washes. Has U-Pb age of 100 ± 2 Ma

**Granite** – Leucocratic, medium-grained biotite granite, granite gneiss, pegmatite, and aplite. Petrologically similar to biotite granite locally dated at 158 ± 2 Ma in Trigo Peaks area, located ~40 km to the north-northeast (Tosdal, 1988), and near the
Picacho Mine about 7 km to south. Locally, rocks are strongly altered along low- to moderate-angle faults separating it from the subjacent Orocopia Schist

**Porphyritic granodiorite** – Medium- to coarse-grained, hornblende-bearing biotite porphyritic granodiorite and derivative mylonitic augen gneiss. Characterized by K-feldspar phenocrysts or augen as long as 5 cm and mafic inclusions. Locally intruded by microdiorite dikes. Converted to mylonitic augen gneiss southeast of Black Rock Mine. Petrologically similar to porphyritic granodiorite in the Trigo Mountains and the adjacent Dome Rock Mountains to the north that are 164-165 Ma (U-Pb on zircons) (Tosdal, 1988; Tosdal and others, 1989; R.M. Tosdal, unpublished data 1988-1995)

**Granodiorite** – Fine-grained, leucocratic biotite granodiorite that occurs as dikes intruding the diorite (Jtd) and gneiss (Mzg and pCg) in the vicinity of Lighthouse Rock. Intrudes all older fabrics in the country rocks

**Monzodiorite** – Medium- to coarse grained, mesocratic biotite-bearing hornblende porphyritic monzodiorite characterized by pink K-feldspar phenocrysts as much as 3 cm in length

**Diorite** – Fine- to medium-grained mesocratic to melanocratic hornblende diorite and hornblende leucodiorite, and less abundant biotite-hornblende diorite, biotite quartz diorite, and hornblendite; includes small unmapped bodies of granodiorite (Jtdg), monzodiorite (Jtm), and granite (Jtg). Plagioclase in fresh diorite has dark purplish tint. Locally converted to orthogneiss

**Winterhaven Formation (Jurassic and Cretaceous)** – Divided into:

**Argillitic siltstone and quartz arenite members, undivided** – Brown, purple, tan, and light-gray argillite, phyllite, metasandstone, metaconglomerate, and minor
siliceous marble. Metamorphic minerals include quartz, albite, muscovite, chlorite, calcite, and locally porphyroblastic pyrite and biotite

**Dacite member** – Weakly to moderately foliated purple and dark-brown lava and tuff(?) of dacitic composition. Converted to greenstone and locally actinolitic schist near contact with Middle Jurassic granite (Jtg) in Arrastra Wash. Contains a few dikes and irregular intrusions of grayish-purple porphyry, rare beds of coarse-grained volcaniclastic graywacke, and near top of unit, dark-gray, very poorly bedded volcanic breccia

**Quartz porphyry (Jurassic)** – Light-gray and greenish-gray, metamorphosed rhyodacitic and rhyolitic ash-flow tuffs, now composed of white mica and white mica-chlorite phyllite and schist. West of Arrastra Wash, schist is interlayered with base of overlying dacite member of the Winterhaven Formation. Intruded by Jurassic granite (Jtg) and porphyritic granodiorite (Jtpg). Includes metaporphry phase of the granite of Marcus Wash of Haxel and others (1985). In Marcus Wash, unit has a minimum age of 148 ± 9 Ma (U-Pb on zircon)

**Aplit and pegmatite (Mesozoic)** – Biotite-bearing granitic aplite and pegmatite that intrude gneiss (Mzg). Only larger bodies or dense concentrations of dikes are mapped separately

**Gneiss (Mesozoic)** – Amphibole gneiss, amphibolite, biotite-hornblende quartzofeldspathic gneiss, and layered hornblende diorite, hornblendite, and monzodiorite. Intruded by aplite and pegmatite (Mza). Forms sole of upper plate of the Chocolate Mountains fault south of Gavilan Wash. At the mouth of Clip Wash, the rocks are less metamorphosed and locally resemble Triassic(?) hornblende dioritic and gabbroic rocks in the Mule Mountains (Tosdal, 1988; Barth and others, 1990). Includes unmapped dikes of Cenozoic andesite (Tq) and Jurassic monzodiorite
and granodiorite (Jtm and Jtgd). May include small bodies of Proterozoic gneiss (pCg) and augen gneiss (pCa). Assigned Mesozoic age because of petrologic resemblance to Triassic (?) plutonic rocks and to Jurassic hornblende diorite and monzodiorite where metamorphosed

**Augen gneiss (Proterozoic)** – Strongly foliated, biotite-K-feldspar augen gneiss and layered quartzofeldspathic and biotite gneiss and schist that occurs as irregular layers, masses, and rarely mappable bodies within Mesozoic gneiss (Mzg) and Proterozoic gneiss (pCg).

**Gneiss (Proterozoic)** – Layered biotite and biotite-hornblende quartzofeldspathic gneiss, augen gneiss, and granite gneiss

### LOWER PLATE OF CHOCOLATE MOUNTAINS FAULT

**Orocopia Schist (latest Cretaceous-early Cenozoic)** – Divided into:

**Quartzofeldspathic schist and interlayered mica schist** – Light-gray to dark-gray, flaggy micaceous schist, includes minor metamorphosed basalt, chert, siliceous marble, and serpentinite. Quartzofeldspathic schist is characterized by black albite porphyroblasts and aggregates of bright green fuchsite (chrome muscovite). Peak metamorphic lower amphibolite facies mineral assemblages are present near Chocolate Mountains fault (Haxel and Dillon, 1978; Oyarzabal and others, 1997; Jacobson and others, 2002). Unit underwent retrograde metamorphism and hydrothermal alteration during tectonic unroofing along the low-angle Chocolate Mountains and Gatuna-Sortan faults (Haxel and others, 1985; Jacobson and others, 1996, 2002; Oyarzabal and others, 1997). Cut by brittle shear zones that are generally less resistant than undeformed schist; in some places rocks adjacent to the shear zones, especially in their hanging walls, are more resistant owing to moderate
silicification. In other places, shear zones contain pods or blocks of coarse-grained actinolite-(or tremolite)-talc rock, variably altered to orangish, reddish, or brownish carbonate-rich rocks with relict coarsely fibrous textures. Though widely and sparsely scattered throughout the Orocopia Schist, pods of actinolite-talc rock are most abundant within the shear zones. Locally, the shear zones contain fibrous, talc-rich veins as much as several centimeters wide. The shear zones locally contain epithermal veins of coarsely crystalline calcite, and in the Eureka Mining District bear galena. Only the larger and more prominent shear zones are mapped. Protoliths of the quartzofeldspathic to schistose units are Maastrichtian to Paleocene or early Eocene in age (Grove and others, 2003; Jacobson and others, 2011); the unit is diachronous on a regional scale and the same may be true even within the map area. Peak metamorphic age is not constrained directly, but the oldest cooling ages (hornblende $^{40}\text{Ar}/^{39}\text{Ar}$) are 57–56 Ma (Jacobson et al. 2002). Muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ within the map area range from 49 to 43 Ma and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 42–22 Ma (Jacobson et al., 2002, 2007, 2011; Grove et al. 2003). Locally includes:

**Metabasalt** – Dark green layers consisting of albite/oligoclase-hornblende amphibolites interlayered with micaceous quartzofeldspathic schist

**Serpentinite** – Magnetite- and ferroan carbonate-bearing antigorite rock that occurs as a premetamorphic protusion into the quartzofeldspathic schist

**Metadiorite (Jurassic(?))**– Massive greenstone derived from microdiorite. Occurs as pods and lenses within Orocopia schist (TKo). Locally surrounded by a selvage of tremolite. At one time interpreted as fragments of dikes intruded into the protolith of the schist (Mukasa and others, 1984). More recent work indicates that the intrusive age of the metadiorite predates the deposition of the schist protolith, which implies that the metadiorite bodies are olistoliths or tectonic inclusions. Petrologically similar
to a 163 ± 2 Ma metadiorite intruding Orocopia Schist in western Chocolate Mountains
Appendix B

CORRELATION OF MAP UNITS
Appendix C. ANALYTICAL RESULTS

Table 1. Analytical results of (U-Th)/He dating samples from Gavilan Hills, unnamed set of hills to the east of Gavilan Hills and the Castle Dome Mountains and FCT standards for each grain.

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