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Neotectonic evolution of the Avawatz Mountains, Southern Death Valley, California

Jennifer A. Mendonça
San Jose State University

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NEOTECTONIC EVOLUTION OF THE AVAWATZ MOUNTAINS,
SOUTHERN DEATH VALLEY, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology
San Jose State University

In Partial Fulfillment

Of the requirements for the Degree
Master of Science

by

Jennifer A. Mendonça

August 2006

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APPROVED FOR THE DEPARTMENT OF GEOLOGY

Dr. Paula Messina

Dr. Matthew McMackin

Dr. Richard Sedlock

APPROVED FOR THE UNIVERSITY

ABSTRACT

NEOTECTONIC EVOLUTION OF THE AVAWATZ MOUNTAINS, SOUTHERN DEATH VALLEY, CALIFORNIA

by Jennifer A. Mendonça

Field mapping of geologic and surficial deposits within the northeastern Avawatz piedmont was conducted to investigate the interaction of the southern Death Valley fault zone with the Garlock/Mule Spring fault zone south of the Salt Spring Hills and to assess the style, timing and kinematics of Quaternary deformation.

Interaction with the Mule Spring fault zone has resulted in the formation of dextral reverse motion along the southern Death Valley fault zone, forcing the zone to behave as a critical wedge. Longitudinal and topographic profiles document the progressive influence of the southern Death Valley fault zone, and suggest an increase in magnitude and decrease in age of deformation from north to south along the range front. Variations in kinematics of the Mule Spring fault zone along the range front suggest the presence of a fault asperity between the Avawatz and the Salt Spring Hills.

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INTRODUCTION

The Avawatz Mountains, located in southern Death Valley, California, lie at the structural boundary between the eastern California Basin and Range province to the north and the Mojave geologic province to the south. Its northern and eastern boundaries are formed by two major fault systems (Fig. 1). The southern Death Valley fault zone is a northwest-striking dextral fault system that lies along the northeastern margin of the Avawatz Mountains. The Garlock fault zone is an east-striking, sinistral oblique slip fault system that extends from the San Andreas fault eastward along the northern margin of the Avawatz Mountains. Near the intersection of these fault systems, extensive contraction, transpression, and uplift have formed north- and northeast-vergent thrust faults and folds within Quaternary fan sediments (Brady, 1986a).

The kinematics of and relation between the Garlock and southern Death Valley fault zones to the south and east of this intersection are controversial. While eastward continuation of the Garlock past the southern Death Valley fault zone was suggested by Davis and Burchfiel (1973) and Plescia and Henyey (1982), Brady and Verosub (1983) suggested that the Garlock fault terminates in the northeastern Avawatz, with the Mule Spring fault accommodating the lateral slip of the Garlock with east-vergent thrusting. Geologic mapping by Troxel and Butler (1998) and Brady (1986b) suggested that the older branches of the southern Death Valley fault zone are truncated by the Mule Spring fault while the younger branches continue past the intersection as a series of reverse faults that are responsible for Quaternary deformation in the piedmont. Spencer (1981)

Figure 1. A simplified fault map of the northeastern Avawatz Mountains. Only major faults are shown.

suggested that all branches of the southern Death Valley fault zone die out against the Mule Spring fault and that all Quaternary deformation is associated with branches and splays of the Mule Springs fault zone.

Understanding the interaction of these two fault systems is critical for understanding the formation of the modern landscape of the southern Death Valley region. While there are Quaternary examples of basin and range extension to the north of this intersection, there are no such examples to the east and south. The current hypothesis suggests that this region has changed tectonically from an extensional regime to a contractional regime in the latest Tertiary and early Quaternary (Miller et al., 2005). The landscape still exhibits a “basin and range” topography, but the “basins” are believed to be downwarped synclines formed in response to loading by thrust block “ranges” (Miller et al., 2005). Research currently being conducted by the USGS has taken a surficial mapping approach to address this issue.

PURPOSE AND SCOPE

The purpose of this study was to investigate the interaction of the southern Death Valley fault zone with the Garlock and Mule Spring fault zones along the Avawatz range front and within the piedmont south of the southern Salt Spring Hills. This area was selected because the Quaternary stratigraphy and structure of the range front and piedmont had not been mapped in detail. The scope of this study was restricted to Quaternary stratigraphy and structure of the piedmont to:

1. Define the stratigraphy and morphology of the surficial deposits to gain better understanding of the tectonic development of the piedmont and the neotectonic development of the Avawatz Mountains.
2. Determine what factors control the kinematics, style, and timing of deformation within the northeastern Avawatz Mountains
3. Gain new insights into the tectonics of the intersection of the southern Death Valley and Garlock fault zones and the relative role of faults and tectonic blocks they subdivide.

RESEARCH METHODS

A combination of field methods and geographic information system (GIS) applications were selected to address the questions proposed by this study. A compilation geologic map is included, highlighting the main structural features of the study area (Plate 1).

The GIS database files were constructed using ArcGIS 9.1, Student Edition (Environmental Systems Research Institute, Inc., 2005). The spatial, three-dimensional, and analytical capabilities of this software were employed for all structural and geomorphic analyses conducted for this study. Longitudinal and transverse profiles across the piedmont and apron structure were constructed using 10-meter Digital Elevation Model (DEM) data and the script EZ Profiler for ArcMap 9.X (Multi-layers & profile lines version. Huang, 2004). Graphical representation was accomplished using Microsoft Excel 2003.

Field-based mapping of geologic and surficial deposits was conducted on 1:12,000 USGS 7.5 minute Sheep Creek Spring and Silurian Lake topographic map quadrangles and digital orthophoto quadrangles (DOQ). Geologic mapping along the range front incorporates previous work done by Spencer (1981) and Troxel and Butler (1979). Mapping of surficial deposits was performed using criteria outlined by Menges (2003; personal communication, 2003) and described in Miller and Menges (2005). GPS coordinates of all field stations were recorded using a Garmin eTrex Venture, with real-

time WAAS correction, and projected using the Universal Transverse Mercator (UTM) coordinate system and North American Datum 1983 (NAD83).

STUDY AREA

The Avawatz Mountains are located about 30 miles north of Baker, California. They form a prominent transverse range at the southern end of Death Valley that is arcuate in shape, with gentle concave slopes in the southwest and steep escarpments incised by deep canyons in the east (Brady, 1986a) (Fig. 2). Elevations range from near sea level at the base of the piedmont to over 1800 m at Avawatz Peak (Brady, 1986a).

Figure 2. Aerial view of the Avawatz Mountains, looking south-southwest. US Air Force photograph, circa 1945 (modified from Gregory and Baldwin, 1988).

The study area is bound to the north by the southern Salt Spring Hills, to the south by the Old Mormon Spring road, to the east by Highway 127, and to the west by the Mule Spring fault, covering approximately 40-km² (Fig. 3). Two roads run through the southern portion of the area: the Old Mormon Spring road, located close to the 20 mile marker on Highway 127, and the Renoville road, located close to the 22 mile marker on Highway 127. Both roads are poor, and access requires high clearance vehicles; four-wheel-drive is recommended. Many portions of the study area are accessible only on foot from the highway.

The bedrock of the Avawatz Mountains are comprised of a diverse complex of rock types. They consist chiefly of a heterogeneous assemblage of Mesozoic plutonic rocks, mainly quartz monzodiorite, and limited exposures of Tertiary sedimentary rocks and volcanics (Brady, 1986b). The range front within the study area is defined by a 6 km² section of extensively dissected bedrock and fan deposits that forms an apron-like structure in the proximal region of the piedmont. This apron extends from the range front eastward 2 km into the piedmont. Three large canyons dissect the piedmont near the range front. Mormon Canyon forms the southwestern boundary of the study area. Avawatz Canyon, about 1 km north of Mormon Canyon, is the largest canyon within the study area. Ventania Ridge Canyon divides the apron structure and is the largest canyon in the northern half of the study area.

Figure 3. Map of the study area, showing the locations of access roads and major features.

PREVIOUS WORK

The earliest studies of the Avawatz Mountains focused on mineral resources and deposits. Phalen (1914) briefly discussed salt, gypsum, and celestite deposits within Tertiary sedimentary strata. Noble (1922) studied nitrates in the southern Death Valley region and examined specific sedimentary deposits in the northeastern Avawatz Mountains. Durrell (1953) studied celestite in the Avawatz as part of a regional study and Ver Planck (1952, 1957) investigated gypsum and halite deposits.

The first geologic mapping of the area was published by Noble and Wright (1954), who studied the northern part of the Avawatz Mountains. Jahns and Wright (1960) identified the intersection of the Garlock and southern Death Valley fault zones and Troxel and Butler (1979, 1998) compiled the first detailed map of this intersection. Additional mapping was completed by Stamm (1981); Spencer (1981), who studied Precambrian, Paleozoic, and Cenozoic stratigraphy and Mesozoic magmatism, deformation and geochronology in the southern Avawatz Mountains; and Brady (1986b), who investigated the Cenozoic evolution of the Avawatz and intersection for his dissertation.

Quaternary and geomorphic studies in the Avawatz are limited. Anderson (1999) described the soils and stratigraphy for an area of fan deposits on the piedmont just north of the southern Salt Spring Hills as part of his dissertation on vesicular horizon development and desert pavement formation. Clayton (1989) described the stratigraphy of fan deposits near Sheep Creek to investigate Quaternary deformation within the

piedmont. Lackey and others (2005) described fan soils and stratigraphy south of Mormon Canyon to investigate late Quaternary deformation within the piedmont.

DESCRIPTION OF BEDROCK UNITS

Since surficial deposits were mapped in detail as part of this study, all non-surficial units are considered to be bedrock. These units are restricted to the range front and comprise the northwestern portion of the apron structure (Fig. 4). They include igneous, metamorphic, and sedimentary rocks that range in age from the Precambrian to the Tertiary. Many of the units described here correlate with units mapped by Spencer (1981), Brady (1986b), and Troxel and Butler (1979).

The bedrock units can be structurally subdivided into two groups; the Avawatz block and the southern Death Valley fault block. Some units within the southern Death Valley fault block have not been observed elsewhere in the range and are described here for the first time. These units are found between faults, and the absence of materials suited for radiometric dating permits only relative stratigraphic placement.

Avawatz Block

Avawatz Quartz Monzodiorite Complex (Kqmd)

The Avawatz quartz monzodiorite complex makes up the bedrock core of the Avawatz Mountains. It is exposed at the range front in the hanging wall of the Mule Spring fault zone and as an inselberg within the piedmont below Mormon Spring. The complex encompasses a wide range of compositions, varying from diorite to quartz monzodiorite, granodiorite, granite, and quartz monzonite (Spencer, 1981). The mineral assemblage consists primarily of biotite and hornblende of varying proportions.

Figure 4. Location map of bedrock units.

plagioclase, potassium feldspar, and minor amounts of quartz. Pegmatitic veins and mafic dikes cut the unit in several locations. Exposures are usually medium- to coarse-grained, possess a color index between 30 and 50%, and often display a brownish black varnish (5YR2/1) (Munsell Color Co., 1975). The unit forms resistant bouldery outcrops and steep slopes and is often highly fractured.

Age

The complex was dated using K-Ar on biotite extracted from a sample collected in upper Sheep Creek by Troxel in 1963, yielding an age of 126 ± 7 million years (Troxel and Butler, 1998). Spencer (1981) collected samples along lower Sheep Creek and obtained an age of 200 ± 20 million years applying a Rb-Sr isochron, K-Ar on hornblende and biotite grains, and cross-cutting relations.

Southern Death Valley Fault Block

Precambrian Gneiss (pg)

A complex of gneiss is exposed in a northwest-trending fault block in the northwestern portion of the apron structure. It is a medium- to coarse-grained quartzofeldspathic rock with gneissic layering. Foliation planes, defined by hornblende and biotite, are closely spaced and wavy. It is in contact with a grayish white (5Y6/1) crystalline quartzite body that contains biotite and garnet; it contains slightly-preserved sedimentary structures, and a porphyritic granite body with abundant pink potassium feldspar phenocrysts. The quartzite is most likely a subunit of the Crystal Spring

Formation and the granite is part of the Teutonia batholith, both of which appear within the same fault block. The gneiss is also in fault contact with the tan member of the Tertiary sedimentary rocks, forming a breccia zone approximately 0.5 m thick. Exposures are highly fractured, form talus slopes, and display grayish black (N2) varnish.

Age

The gneiss is believed to part of the crystalline metamorphic complex found in the greater Death Valley region (Brady, 1986b). An age of 1.4 to 1.8 billion years was obtained by Lanphere (1964) for gneissic basement rocks of the Death Valley area. Spencer (1981) analyzed a leucosome-melanosome pair collected in the southeastern portion of the range for rubidium and strontium content and obtained an isochron of 1.387 billion years.

Pahrump Group, Crystal Spring Formation (pcc)

The Pahrump group consists of the Crystal Spring Formation and Kingston Peak Formation. Crystal Spring Formation is interleaved with Teutonia batholith and Precambrian gneiss in a northwest-trending fault block in the northwestern portion of the study area. It contains a variety of metamorphosed sedimentary rocks. Coarse-grained, crystalline black (N4) and white (10YR7/2) quartzite appear as isolated ledges throughout the fault slice. Depositional bedding is preserved in both units. Thin- to thick-bedded chloritized (5G5/2) quartzite forms resistant ledges in a small exposure in the northeastern half of the fault slice. Many layers have been tightly folded, with some

layers displaying pygmatic folds. Coarse-grained, massive greywacke (N4) also forms resistant ledges in a small exposure in the northeastern half of the fault slice.

A dense, black (N2) crystalline unit with pink (10R5/4) patches, possibly stretched relict clasts, forms cliffs in a small exposure in the northeastern half of the fault slice. This unit may actually be part of the southern facies of the Kingston Peak Formation, which appears in the Avawatz Mountains (Brady, 1986b).

Age

Two diabase sills, one from the southern Black Mountains, and the other from the northwest part of the Kingston Range, were dated by Heaman and Grotzinger (1992), yielding U-Pb baddeleyite ages of 1.087 ± 3 billion years and 1.069 ± 3 billion years.

Teutonia Batholith (Ktb)

The Teutonia batholith forms one of the larger intrusive complexes in the eastern Mojave desert, occupying over 3000 km² (Beckerman et al., 1982). It is comprised of seven Jurassic to Cretaceous metaluminous to weakly peraluminous granite plutons (Beckerman et al., 1982).

Teutonia plutonic rocks are interleaved with Crystal Spring Formation and Precambrian gneiss in a northwest-trending fault block in the northwestern portion of the study area. The majority of the exposure consists of porphyritic granitic rocks with 15% to 20% euhedral pink potassium feldspar phenocrysts, 15 to 20% mafics (biotite and hornblende), and 60 to 70% plagioclase, white potassium feldspar, and quartz. The

phenocrysts range in size between 0.5 cm and 2 cm. Light gray aphanitic granitic rocks, abundant in plagioclase and white potassium feldspars, occur with the porphyritic granitic rocks. Mafic minerals (biotite, hornblende) make up only 5% of the total composition, and garnet and quartz are minor constituents. Contacts are generally sharp and exposures are highly fractured and brecciated, forming talus slopes and weakly resistant ledges.

Age

Rocks of the Teutonia batholith mapped within the study area most closely resemble the Kessler Springs Adamellite, which contains hornblende that yielded a minimum K-Ar age of 92.1 Ma (Beckerman et al., 1982).

Tertiary Volcanics (Tv)

Two volcanic andesites are exposed within a northwest-trending fault block in the west-central portion of the study area. The largest exposure is a brownish black (5YR2/1) andesite with abundant phenocrysts of feldspars and pyroxenes (Fig. 5a). Plutonic clasts are present in the matrix, suggesting that this unit represents some kind of lahar or flow deposit. Southern exposures within the fault block are highly indurated with little chemical weathering while northern exposures have been more hydrothermally altered. Clasts in the northern exposures are pale reddish brown (10R4/6) and less indurated; almost all feldspar phenocrysts have weathered to kaolinite. Exposures throughout the block are highly fractured and form gentle slopes abundant in talus and limited in outcrop.

Figure 5. Photographs of the Tertiary volcanics. a: Hand sample of the brownish black andesite. Note the kaolinite that represents weathered feldspars. Scale in photograph is in centimeters. b: Hand sample of the purple andesite. Note vesicular texture. Scale in photograph is in centimeters. c: Outcrop of the lithic ash flow tuff.

A second andesite unit appears as small isolated, highly fractured bodies adjacent to the brownish black andesite unit. It is purple (SRP4/2) and contains abundant biotite

and hornblende phenocrysts that have been hydrothermally altered (Fig. 5b). The unit is moderately indurated and slightly vesicular.

A small isolated exposure of a lithic ash flow tuff is exposed as a resistant knob within a northwest-trending fault block in the northwestern portion of the study area (Fig. 5c). It is comprised of 40-50% volcanic cobble-sized lithics in a light gray (N8, 5YR8/1), friable matrix.

Age

These units are unique to this portion of the Avawatz and have not been observed in the north (B. W. Troxel, personal communication, 2005). The andesites may be correlative in age to an andesite that forms the base of the central belt of the Noble Hills Assemblage (Brady, 1986b; Troxel and Butler, 1998), which has a concordant K-Ar age from hornblende and biotite of 11.3 ± 0.6 Ma (Brady, 1986b).

Tertiary Sedimentary Rocks (Ts)

Sandstones, breccias, and conglomerates are exposed within a northwest-trending fault slice that extends along the western margin of the study area adjacent to the range front. They are in fault contact with the Avawatz quartz monzodiorite complex to the west and fan deposits to the east, and in some locations are unconformably capped by fan deposits.

The sedimentary rocks consist of four members: red, pink, tan, and gray (Fig. 6). The members are all poorly sorted and contain subangular to angular clasts derived from

a variety of rock types. This unit is slightly resistant and friable, forming gentle rolling slopes with abundant talus.

The red (10R4/6) member is a thin to thick interbedded pebble conglomerate and arkosic sandstone (Fig. 7). Clasts are angular to subrounded and poorly sorted, with no visible sedimentary structures. Clast composition is dominated by Precambrian gneiss and plutonic clasts. Other rock types include carbonates, brownish black andesite, chunks of quartz and potassium feldspar, and minor amounts of a dark purple quartzite breccia. No Teutonia granite clasts are present. The red member is thickest, with a maximum exposed thickness of 500 m.

The pink (10R5/4) member is a thick interbedded pebble and cobble conglomerate that contains beds and lenses of coarse arkosic sandstone, shale, and mudstone (Fig. 8). Clasts are subangular to subrounded and poorly sorted, with no visible sedimentary structures. Clast composition is dominated by pink granite of unknown association, Teutonia granite, and roof pendant dolomites and quartzites. Other rock types include brownish black andesite, purple andesite, and minor amounts of plutonic clasts and dark purple quartzite breccia. No gneiss clasts are present. Thickness of this member varies from 80 m to 150 m.

Figure 6. Photographs of the Tertiary sedimentary rocks. Top photo: view to northeast, with Salt Spring Hills in the distance. All four members of the Tertiary unit dip steeply to the east. Bottom photo: view to west-southwest with Silurian Hills in the distance. Gray member in the foreground. Talus slopes dominate exposures. Overlying fan deposits are absent.

Figure 7. Photograph of the red member.

Figure 8. Photograph of the pink member.

The tan (5YR7/2) member is a weakly interbedded, massive cobble, boulder, and pebble conglomerate and sandstone (Fig. 9). Clasts are angular to subrounded and poorly sorted, with no visible sedimentary structures. Clast provenance varies between northern and southern exposures of this member. In the south, clasts are dominated by plutonic rocks, and include pink granite of unknown association, Precambrian gneiss, roof pendant quartzite and dolomite, and tabular fine grain sandstone clasts from the pink member. In the north, clasts are dominated by brownish black and purple andesite, chloritized Crystal Spring Formation, possible Kingston Peak Formation, and Teutonia granite, with minor amounts of roof pendant dolomites and quartzites. Plutonic and gneiss clasts are absent in the northern deposits while Crystal Spring and Kingston Peak clasts are absent in the southern deposits. Thickness of this member varies from 80 m to 180 m.

The gray (10YR8/2) member consists of thick and thin crude interbeds of pebble conglomerate and sandstone, with some boulder conglomerate layers near the top of the member (Fig. 10). Clasts are dominated by Teutonia granite and pink granite of unknown association, and include modest amounts of roof pendant quartzites and dolomites, gneiss, plutonic clasts, and minor amounts of purple andesite. Crystal Spring Formation and possible Kingston Peak Formation clasts may also be present. This member appears only in the southern half of the fault slice and has an average thickness of 25 m.

Figure 9. Photograph of the tan member. Note that the cobble patches are fluvial deposits that sit atop the outcrop, and are not part of the outcrop.

Figure 10. Photograph of the gray member. Note pencil for scale.

A very small exposure of possible evaporite material is located near the southern exposure of the Mule Spring fault. It is a yellowish gray (5Y7/2) to dusky yellow (5Y6/4) layered deposit, with beds between 1 to 2 cm thick. It is fine-grained, slightly indurated, and very porous, forming gentle slopes.

Age

Similar sedimentary deposits have been described and mapped by Troxel and Butler (1998) slightly north of the study area, but are not associated with other Tertiary basin deposits (e.g. Noble Hills Assemblage, Military Canyon Formation, Avawatz Formation) mapped in the Avawatz Mountains (B.W. Troxel, personal communication, 2005). An age of 13 Ma was obtained by Jim Calzia from a basalt layer slightly east of Sheep Creek that forms the base of these sedimentary deposits in the north (B.W. Troxel, personal communication, 2005).

DESCRIPTION OF SURFICIAL DEPOSITS

Surficial deposits of the Avawatz piedmont are composed of alluvial fans comprised chiefly of debris flow deposits with a few interbedded fluvial flow deposits in some of the more deeply incised channels. Clasts are angular to subrounded; and moderately to poorly sorted, ranging from coarse sand to boulders up to four meters, in a silt- to fine-sand matrix. Fluvial deposits are better sorted and, in many cases, appear to be reworked from different deposits on the piedmont.

The fan deposits are derived from rocks of the Avawatz Mountains and consist chiefly of Avawatz quartz monzodiorite, with minor amounts of pink and red granites exposed in the southern half of the study area. Various Proterozoic and Precambrian rocks also make up a sizeable portion of the clasts, primarily in the southern half of the study area. These clasts are derived from roof pendants exposed in the higher elevations of the range and include the Proterozoic Noonday Dolomite, Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite; the Cambrian Carrara, Bonanza King and Nopah Formations; Devonian Sultan Limestone; Mississippian Monte Cristo Limestone; and the Pennsylvanian or Permian Bird Spring Formation (Brady, 1986b).

Three classes of fans and nine generations of fan deposits have been recognized using relative age criteria (Menges, 2003; Miller and Menges, 2005). These criteria include general physiography, stratigraphy and sedimentology, geomorphic surface characteristics (pavement, bar and swale topography, varnish), pedogenesis and

weathering, eolian processes, vegetation, and deformation. Grain size classification in the field was described as outlined in Compton (1985). Colors of varnish, soils, and clast rubification were classified using the Munsell soil color chart (Munsell Color Co., Inc., Baltimore). Stages of carbonate morphology were identified in the field as described in Birkeland (1999).

Fan class and generation are labeled using the system described in Miller and Menges (2005). Geologic age is specified first, followed sequentially by fan class, depositional environment, and a relative age rank. Fan class is denoted by “o,” “i,” or “y,” representing old, intermediate, and young, respectively. Depositional environment in this area is denoted by “df,” representing debris flow. Age rank is denoted by the numbers one through four, with one designating the youngest deposit of that class and four representing the oldest.

Fan deposits included in the “young” class possess the geomorphic characteristics of an actively forming surface. Bar and swale topography is the diagnostic feature of fan deposits within this class. The younger deposits possess high-relief bar and swale topography while the older deposits display eroded remnants of such topography. Desert pavement is poorly developed, clasts are not heavily varnished, and soils display Stage I to II+ carbonate development. Surfaces of this class are heavily incised and have high drainage densities. Fan deposits of this class are interpreted to be Holocene in age (C. M. Menges, personal communication, 2003).

Fan deposits included in the “intermediate” class possess the geomorphic characteristics of a mature surface. Desert pavement is the diagnostic feature of fan

deposits within this class. Pavement is smooth and interlocking, with no evidence of bar and swale topography. Clasts are heavily varnished and display rubification of the undersides. Soils of this class display Stage II+ to III carbonate development, with the oldest deposits displaying up to Stage IV. Fan deposits of this class are interpreted to be Pleistocene in age (C. M. Menges, personal communication, 2003).

Fan deposits included in the “old” class possess the geomorphic characteristics of an actively eroding surface. Carbonate stage is the diagnostic feature of fan deposits within this class. Soils of this class display Stage IV and V carbonate development and surfaces contain abundant carbonate chips. Fan deposits of this class are heavily eroded and dissected, forming knife-edge interfluvies. Desert pavement is also weaker than in the intermediate class and clasts are not heavily varnished. Fan deposits of this class are interpreted to be earliest Pleistocene and/or Pliocene in age (C. M. Menges, personal communication, 2003).

The geographic distribution of the three fan classes is determined by age (Fig. 11). Old class fan deposits are located at the range front and are the topographically highest topographic surfaces on the piedmont. Intermediate class fan deposits are primarily located in the medial part of the piedmont, and young class fan deposits are located in the distal portions of the piedmont, merging with active channels to form braid plains. Some of the intermediate and young fan deposits also display evidence of a reworked origin, containing anomalously varnished clasts and carbonate stage development. These deposits are isolated, small in scale, and found mostly in the distal portions of the piedmont.

Figure 11. Location map of surficial deposits.

Old Class Fan Deposits

Qoa

This unit is exposed at the range front near Old Mormon Spring (Fig. 12). Clasts are mostly subangular to subrounded, with angular clasts in some locations. Clasts are poorly sorted and range in size from very coarse sand to boulder, with a range in modes from fine to medium pebble gravel. Surfaces of this unit are extremely dissected and degraded, characterized by carbonate chips and knife-edge interfluves. Pavement is mostly absent; varnish and rubification of clast undersides occurs on 20% of clasts. Varnish color is dark gray (N3) and clast undersides are red (2.5YR5/8). Surfaces of this unit display in situ clast fracturing, ghost clasts, and granular weathering (Fig. 13a-c). Soils in this unit possess a light yellowish brown (10YR6/4) vesicular A horizon that is approximately 0.5-1 cm thick, and a pink (7.5YR7/4) Btk horizon. Stage IV carbonate development is observed, with an average depth of 20 cm to the calcic horizon and 3-mm-thick carbonate coats on most clasts.

Figure 12. Fan deposits in the "old" class. Note the degraded pavement surface.

Figure 13. Weathering and geomorphic surface characteristics. a: In situ clast fracturing. b: Ghost clast. c: Granular or disaggregation weathering. d: "Zebra stripes."

Intermediate Class Fan Deposits

Qidf4

This unit makes up the surface of the apron structure and is also found in small patches near Old Mormon Spring (Fig. 14a). Surfaces of this unit are defined by narrow lobes due to the onset of erosion. Pavement development varies from moderate to strong, with interlocking clasts and slightly rough to slightly smooth surfaces. Most clasts display strong varnish development and rubification of clast undersides. Varnish is dark gray (N3) and clast undersides are red (2.5YR5/8). Surfaces of this unit display in situ clast fracturing, ghost clasts, granular weathering, and “zebra stripe” sheet flood remnants in some locations (Fig. 13d). Soils in this unit possess a light yellowish brown (10YR6/4) vesicular A horizon that is approximately 3-4 cm thick, a yellowish brown (10YR5/4) Btk horizon, and Stage IV carbonate development.

Figure 14. Photographs of fan deposits in the "intermediate" class. a: Qidf4. b: Qidf3. c: Qidf2. d: Qidf1.

Qidf3

This unit is exposed primarily in the northern half of the study area, bordering the eastern margin of the apron structure (Fig. 14b). Pavement development is strong, very smooth and compact, with interlocking clasts. There is strong varnish development on 95% of clasts and rubification of clast undersides that encompasses the entire underside of the clast. Varnish is black (5YR2.5/1) and clast undersides are red (2.5YR5/8, 10R4/6) or dusky red (10R3/4). Surfaces of this unit display in situ clast fracturing to the pavement surface, granular weathering, and ghost clasts. Soils in this unit possess a light yellowish brown (10YR6/4) Av horizon that is approximately 3 cm thick, a yellowish brown (10YR5/4) Btk horizon and Stage III+ carbonate development.

Qidf2

This unit is exposed primarily in the southwestern portion of the study area on the surface of terraces within Avawatz Canyon (Fig. 14c). Pavement is slightly smooth and firm, and moderately to strongly developed with interlocking clasts. There is moderate to strong varnish development and rubification of undersides on approximately 50% of clasts. Varnish is grayish black (N2) and clast undersides are light red (2.5YR6/8). Surfaces of this unit display in situ clast fracturing, granular weathering and ghost clasts. Soils in this unit possess very pale brown (10YR7/4) vesicular A horizon that is approximately 1.5 cm thick, a very pale brown (10YR7/4) Btk horizon, and Stage II+ carbonate development.

Qidf1

This unit is poorly preserved, with scattered remnants on the medial and distal portions of the piedmont in the southern half of the study area (Fig. 14d). Pavement is firm, slightly smooth, and moderately to strongly developed with interlocking clasts. Relicts of the larger bar clasts are retained on some surfaces. There is moderate to strong varnish development on at least 50% of clasts and rubification of undersides on approximately 50% of clasts. Varnish is moderate brown (5YR4/4) and clast undersides are yellowish red (5YR4/6) or reddish yellow (7.5YR6/6). Crude “zebra stripes,” ghost clasts, granular weathering, and in situ clast fracturing to the pavement surface are present on some surfaces. Soils in this unit possess a very pale brown (10YR8/3) vesicular A horizon that is approximately 1-3 cm thick, a very pale brown (10YR7/4) Btk horizon, and Stage II to II+ carbonate development. This unit bears a striking resemblance to Qydf4 and can be best differentiated by the absence of bar and swale topography.

Young Class Fan Deposits

Qydf4

This unit is found mainly in the southern half of the study area as scattered patches in the medial portion of the piedmont east of Avawatz and Mormon Canyons (Fig. 15a). Pavement is firm, slightly smooth, and strongly developed with interlocking clasts and very sparse vegetation. Bar and swale topography is weak and boundaries are indistinct. Relief ranges from 5 cm to 30 cm, with an average relief between 5 cm and 10 cm. There is moderate to strong varnish development on at least 60% of clasts and rubification of undersides on approximately 50% of clasts. Varnish is black (N1) and clast undersides are yellowish red (5YR5/6, 5YR5/8) or red (2.5YR4/6). Evidence of sheet flood deposits, resembling “zebra stripes,” are common and appear on the smoothest surfaces. In situ clast fracturing to the pavement surface, granular weathering, and ghost clasts are also present. Soils in this unit possess a light yellowish brown (10YR6/4) to very pale brown (10YR7/4) vesicular A horizon that is approximately 4 cm thick, a very pale brown (10YR7/3) Btk horizon, and Stage II to II+ carbonate development, with an average depth of 55 cm to the calcic horizon.

Figure 15. Fan deposits in the "young" class. a: Qydf4. b: Qydf3. Note the bar and swale morphology. c: Qydf2. d: Qydf1.

Qydf3

This unit is found in the more distal reaches of the piedmont and, along with Qydf1 and Qydf2, comprises approximately one-third of the study area (Fig. 15b). Pavement is moderately to (locally) weakly developed. Pavement is slightly firm to firm, slightly rough to rough, and weakly to strongly interlocking. Bar and swale development is strong, with relief ranging from 15 cm to 40 cm and averaging between 25 and 30 cm. There is moderate to strong varnish development on approximately 30% of clasts and rubification of undersides on approximately 50% of clasts. Varnish is moderate brown (5YR4/4) and clast undersides are red (2.5YR5/8), reddish yellow (5YR6/6), or yellowish red (5YR5/8). Soils in this unit possess a pale brown (10YR6/3) vesicular A horizon that is approximately 2 cm thick, a light yellowish brown (10YR6/4) platy Btk horizon, and Stage I+ to II carbonate development. Buried Av horizons were also observed.

Some surfaces within this unit are reworked remnants of older surfaces. They often possess an eroding pavement surface, sparse vegetation, and display in situ clast fracturing to the pavement surface on a few clasts, granular weathering, and ghost clasts.

Qydf2

This unit comprises the more distal reaches of the piedmont and the non-active channels (Fig. 15c). It possesses gradational contacts with Qydf3 and Qydf1 deposits. Pavement is developed in only some areas. Where present, it is weak, slightly soft to slightly firm, slightly rough to rough, lacks interlocking clasts and rubification of clast undersides. There is no varnish development, but varnished clasts are often present. These clasts are interpreted to be recycled from older fan deposits. Soils in this unit

possess a very pale brown (10YR8/3) vesicular A horizon that is approximately 1 cm thick, a very weak to mostly absent Bt horizon, and Stage I carbonate development.

A diagnostic feature of this unit is its strong bar and swale development, with relief ranging from 2 cm to 120 cm and averaging between 40 and 60 cm. A smooth, single-clast relief surface comprised of coarse sand to coarse pebble clasts forms the swales, while a fine pebble gravel to boulder surface with 2-3 clast relief forms the bars.

Qydf1

This unit comprises the active channel deposits (Fig. 15d). Contacts with older surfaces are sharper in the proximal portions of the piedmont, and become diffuse and gradational in the distal portions. They are loose, unconsolidated, and moderately to well sorted, with no soil development. Pavement development is absent and clasts display no varnish or rubification of clast undersides. Bar and swale topography is weak, with relief ranging from 5 cm to 30 cm. Vegetation is sparse, with average creosote distances of 5 m between individual plants.

STRUCTURE

Structures associated with the Mule Spring and southern Death Valley fault zones were mapped in the study area. Field relations suggest that the Mule Spring fault zone truncates and overrides the southern Death Valley fault zone, supporting interpretations made by Troxel and Butler (1998) and Brady (1986b). The relation of the Garlock fault zone to these structures is uncertain based on this study.

Mule Spring Fault Zone

The Mule Spring fault zone is a northwest-striking set of thrust faults exposed along the range front that forms the western margin of the study area. Exposures extend along the western margin of the apron structure, disappear under the alluvium within Avawatz Canyon, reappear in the southern wall of Avawatz Canyon, and continue south through Mormon Canyon (Fig. 16). The segment of the fault zone between Avawatz and Mormon Canyons was mapped as the Mormon Spring fault by Spencer (1981) and interpreted to be a minor splay of the Mule Spring fault. However, field observations and kinematic data suggest that the Mule Spring and Mormon Spring faults are too similar to be considered separate systems. Observations for this project support a segmented Mule Spring fault zone. Thus, the name “Mormon Spring fault” will be abandoned hereafter, and all faults within this portion of the range front will be considered part of the Mule Spring fault zone.

Figure 16. Mule Spring fault map. Numbers represent dip in degrees.

Exposures in the northern half of the study area place Avawatz quartz monzodiorite over rocks of the southern Death Valley fault zone, which include the Tertiary sedimentary rocks and rocks of the Teutonia batholith (Fig. 17). Between Ventania Ridge Canyon and Avawatz Canyon, Avawatz quartz monzodiorite overlies Qidf4 fan deposits except along a 1-km-long stretch where a thin slice of extensively brecciated andesites and leucocratic granite is pulled up in the footwall of the Mule Spring fault (Fig. 16). These breccias are interpreted here as rocks of the southern Death Valley fault zone. Clasts in the breccias are poorly sorted, angular medium sands to coarse pebble gravels. Abundant carbonate cement makes these breccias moderately indurated, but they are also highly fractured, making them slope-formers with limited outcrop. The breccia sliver averages about 150 m in thickness measured normal to the range front.

South of Avawatz Canyon, rocks of the southern Death Valley fault zone are absent and the fault places Avawatz quartz monzodiorite atop fan deposits. An exposure in the southern channel wall of Avawatz Canyon places Avawatz quartz monzodiorite atop Qidf3 and Qidf2 fan deposits (Fig. 18). The vertical separation between the Qidf3 and Qidf2 fan deposits and quartz monzodiorite in this exposure is approximately 10 m.

Figure 17. Exposure of the Mule Spring fault zone north of Ventania Ridge Canyon, looking west-northwest. The footwall at this location is comprised of rocks of the southern Death Valley fault zone, primarily Teutonia batholith. Tertiary sedimentary rocks are seen in the foreground.

Figure 18. Exposure of the Mule Spring fault zone in the southern wall of Avawatz Canyon, looking south. Several slip surfaces involving fan deposits and Avawatz quartz monzodiorite are visible within this exposure. The major surfaces are outlined.

Fault kinematics along the Mule Spring fault zone vary from north to south within the study area. North of Avawatz Canyon, exposures of the fault zone strike to the northwest and possess shallow dips. A well-exposed section of the fault north of Ventania Ridge Canyon displays dips between 30° - 35° to the southwest. South of Avawatz Canyon, exposures of the fault zone strike to the northwest and possess steeper dips. In Avawatz Canyon, several slip surfaces within the quartz monzodiorite are lined with brown clay gouge that range in thickness from a few millimeters to a few centimeters, and dip 35° to 70° to the southwest (Fig. 18). Grooves and mullions present on one of these slip surfaces plunge 45° to the southeast, indicating dextral oblique slip.

Deformation in the footwall varies from north to south along the fault zone. North of Avawatz Canyon, brecciation and cataclasis extend a minimum of 20 m into the footwall. South of Avawatz Canyon, minimal deformation is seen within the footwall, and the fault surface is lined with breccia. A well-exposed section of the fault approximately 0.5 km north of Mormon Canyon is lined with a pale brown fault breccia approximately 1 m thick (Fig. 19a). In Mormon Canyon, the fault is lined by a pale red (5R6/2) breccia that is approximately 1.5 m thick (Fig. 19b). Both breccias are well indurated and poorly sorted, with angular clasts ranging in size from medium sand to coarse pebble gravel. Clast compositions include Avawatz quartz monzodiorite, monomineralic monzodiorite detritus (quartz, potassium feldspar, biotite) and roof pendant carbonates. Carbonate veins and cement, and gypsum are also present.

Figure 19. Breccia along the Mule Spring fault zone. a: Breccia along the fault exposure approximately 0.5 km north of Mormon Canyon. Note the extent of deformation seen in the hanging wall. Length of fault surface is approximately 5 m. b: Breccia along the fault exposure in Mormon Canyon. Note the cellular phone for scale.

Southern Death Valley Fault Zone

The southern Death Valley fault zone is exposed as a wide zone of faulted and brecciated rocks in the footwall of the Mule Spring fault zone (Fig. 20). The zone is exposed along the range front in the northern half of the study area and is similar to exposures mapped in the north (Brady, 1986b).

The fault zone is mostly composed of Tertiary sedimentary rocks that are juxtaposed against and overly fault-bounded slices of Teutonia batholith, and Precambrian gneiss and Crystal Spring Formation. The largest of these exposures, approximately 1.2 km north of Ventania Ridge Canyon, is approximately 100 m thick and extensively brecciated. It is comprised of pink, leucocratic granite, thinly banded gneiss (possibly associated with the formation of the pluton), and mafic dikes.

An elongate, northwest-trending fault-bounded slice of Crystal Spring Formation, gneiss, and Teutonia batholith, is juxtaposed against the Tertiary sedimentary rocks in the northeastern portion of the exposure. The slice is approximately 420 m thick and is extensively brecciated. Some portions of the fault-bounded slice have also undergone cataclasis.

Figure 20. Faults of the southern Death Valley fault zone. Numbers represent dip in degrees.

Bedding attitudes of the Tertiary sedimentary rocks suggest that these rocks were deposited over the southern Death Valley fault zone and then subsequently uplifted by interaction with the overriding Mule Spring fault zone. This interaction resulted in the emplacement of both the Teutonia and Precambrian/Teutonia fault slices along out-of-sequence thrust faults. Bedding near the Teutonia exposures dips away from the slice and bedding adjacent to the Precambrian/Teutonia slice displays an antiformal structure. Away from the fault slices, beds generally dip steeply to the east-northeast (Fig. 21).

The western margin of the zone is defined by the Mule Spring fault zone, and the eastern margin of the zone is characterized as a west-northwest dipping thrust fault that places the fault zone rocks over fan deposits. In the northernmost portion of the zone, this fault is blind and is expressed at the surface as a fault propagation fold within the red member of the Tertiary sedimentary rocks. The maximum dip within the forelimb of this fold is 53° to the east. Farther south along the margin, the fault plane is visible and displays dips between 15° and 30°. Vertical separation of the Tertiary sedimentary rocks and the fan deposits is less than a meter.

A large, open fold was measured within the red member of the Tertiary sedimentary rocks that appears to have formed in response to stress associated with this fault. The fold is present only within a hanging-wall promontory just north of Ventania Ridge Canyon (Fig. 22). The axis of the fold strikes northwest and dips 8° to the northeast.

Figure 21. Bedding measurements in Ts and their relation with the Precambrian/Teutonia fault block. Photos a and b show the antiformal structure created around the fault block. Photo c shows chaotic bedding at the termination of the fault block. All photos were taken looking north-northwest.

The fault zone was not observed south of Ventania Ridge Canyon, but may return 0.5 km farther south as a thin slice of extensively brecciated andesites and leucocratic granites that extends for about a kilometer before it pinches out into the Qidf4 fan deposits that form the northern wall of Avawatz Canyon. Deformation is minimal along the eastern margin of the zone and fault exposures are poor, but a few locations display dips around 40°.

Quaternary Deformation

Faults that involve only Quaternary fan deposits are found east of the Mule Spring and southern Death Valley fault zones (Fig. 23). Exposures are generally difficult to recognize and limited to the northeastern portion of the apron structure, but surficial expressions of faulting are seen within the medial portion of the piedmont close to the northern boundary of the study area and are not continuous over large distances. Intermediate class fan deposits, mainly Qidf4, cap the zone along the fault exposure and display evidence for surface rupture, suggesting that activity along these fault systems occurred during the early Pleistocene.

Figure 23. Quaternary faults map. Numbers represent dip in degrees.

The dominant style of Quaternary faulting is blind thrusting expressed as fault propagation folds. Two fault propagation fold sequences were identified in the northeastern portion of the apron structure with northwest-striking fold axes and forelimb dips that exceed 15° to the east. The easternmost sequence forms the fold scarps of the eastern margin of the apron structure. The fold scarp in the northernmost reach of the study area is formed within the red member of the Tertiary sedimentary rocks and is considered part of the southern Death Valley fault zone. A second fault propagation fold sequence exposed further west piggybacks the eastern fold. A large antithetic normal fault is exposed in the backlimb of this fold. While separation is visible along this fault, its magnitude could not be determined due to the absence of marker beds. The fold axis of this second sequence is aligned with the eastern margin of the Precambrian/Teutonia fault slice, suggesting they may be kinematically related.

Farther east, in the medial portion of the piedmont, a potential fault is exposed within Qid₃ deposits. However, the fault surface could not be identified with certainty. This exposure may represent the tip of a growing thrust fault or a hinge of a growing fold within the fan deposits, indicating the presence of a blind thrust fault below the active channel alluvium.

The only exposure of a Quaternary fault plane exhibiting reverse motion at the surface is seen within the northern wall of Ventania Ridge Canyon (Fig. 24). Unlike the fault propagation folds, this fault has a northeast strike. It dips 25° to the northwest and shows vertical separation of 1-2 m. This fault also displays evidence for surface rupture, suggesting that it was active in the early Pleistocene.

Figure 24. Quaternary fault in the northern wall of Ventania Ridge Canyon.

GEOMORPHOLOGY

The geomorphology of the northeastern Avawatz piedmont is defined by a proximal piedmont region that has been tectonically uplifted and incised. Active fan formation is confined to the southern half of the study area within the medial and distal piedmont, with Avawatz and Mormon Canyons serving as the main feeder channels, and resulting in younger deposits in the medial and distal regions of the piedmont and higher fan surfaces in the southern half of the piedmont. The gradient of the piedmont is unusually steep, ranging between 6% and 6.5%, with steeper slopes near the range front. In addition, a variety of elevated and deformed fan surfaces exist within the medial portions of the piedmont (Fig. 25).

A series of transverse and longitudinal profiles were used to characterize the morphology and development of the piedmont. Transverse profiles were constructed within the apron structure, medial, and distal piedmont to look at overall piedmont morphology. Longitudinal profiles were constructed within the interfluvial surfaces of the apron structure, major fan surfaces within the medial and distal piedmont, and within the major channels to identify growing structures and analyze the tectonic development of the piedmont.

Morphology of the Apron Structure

The apron structure is the largest of the elevated and deformed fan surfaces within the study area. The surface of the structure is extensively dissected, resulting in well-

Figure 25. Photographs showing deformed fan surfaces within the piedmont. Top photo shows relief within study area: fan surfaces in foreground are at elevations of 200-300 m; tallest peak in the range is 1875.8 m. Bottom photo (courtesy David Miller, USGS) shows scarps in apron structure and Qidf3 fan lobe that formed within it.

defined channels and narrow fan lobes. The deepest channels and narrowest lobes occur within the northern half of the structure. The eastern margin of the structure is defined by east-dipping fold scarps formed by fault propagation folds. The scarps are best defined in the northern half of the structure, with heights between 40 and 60 m and slopes between 20° and 30°. The scarps become less defined toward the south, with heights of 30 m or less, and slopes under 20°.

Fan surfaces within the structure are composed of the same unit (Qidf4), but span a wide range of elevations (Fig. 26). Elevations of the fan surfaces drop from 570-610 m at its northern end to 540-570 m in the north-central section, and rise to 565-590 m in the southern half of the structure, suggesting a loading coincident with uplift along the Mule Spring fault zone. A few isolated fan surfaces in the southern quarter of the structure are 10-25 m lower than surrounding surfaces. This is interpreted as an erosional feature due to channel deflection by a Quaternary fault.

Nine profiles constructed perpendicular to the margin of the structure along the fan surfaces display perturbations in locations where fault structures were mapped in the field (Fig. 27). Due to the 10-meter resolution of the DEMs, the profiles have a jagged appearance and may not entirely represent the extent of deformation within the fan surfaces.

The fold scarps that define the eastern margin of the structure appear in all profiles, but are most pronounced in the northern profiles. Profile 2, constructed on a lobe where the eastern fault propagation fold is exposed at the channel level, displays the steepest scarp. The western fault propagation fold is also most pronounced in the

Figure 26. Transverse profile across the apron structure. All distances expressed in meters. Vertical exaggeration = 14x.

Figure 27. Longitudinal profiles of apron structure. Perturbations in profiles associated with mapped structures are labeled. All lengths are in meters; all profiles are oriented with west on the left.

northern profiles. It is expressed as a knickpoint behind the growing forelimb of the eastern fault propagation fold. Profile 2, constructed slightly north of the mapped exposure, displays the most distinct signature. Profiles around Ventania Ridge Canyon display perturbations associated with the Quaternary reverse fault mapped within the canyon. It is expressed mainly as a knickpoint behind a growing bulge, but in Profile 4 it is expressed as a scarp-like structure. Profile 9, located slightly east of the brecciated southern Death Valley fault zone slice, displays small perturbations near the contact with this structure.

Morphology of the Medial and Distal Piedmont

The medial and distal piedmont show similar ranges in elevations as seen in the apron structure (Fig. 28). Elevation differences between fan surfaces in the northern and southern portions of the piedmont range from 40 to 60 m. This is interpreted to be loading associated with the interaction of the Avawatz block with the southern Salt Spring Hills.

The morphology of the piedmont east of the apron structure displays the typical signature of alluvial fan surfaces. Longitudinal profiles constructed along fan surfaces in the southern half of the piedmont are convex in shape, displaying no evidence of deformation (Fig. 29 a-f). However, Profiles 1 and 2, constructed along Qidf3 fan surfaces in the northern half of the piedmont, show uplifts that coincide with a surficial lineament and possible fault. About 1.5 km east of the lineament, Profile 2 displays another minor uplift in the fan surface. Although perturbations are also present in Profile

Figure 28. Topographic profile displaying the decline in elevation from south to north within the study area. The convex shape of the profile in the southern half of the area represents active fan formation. All distances expressed in meters. Vertical exaggeration is 34x.

Figure 29a. Medial Profile 1. All distances expressed in meters. Vertical exaggeration = 33x.

Figure 29b. Medial Profile 2. All distances expressed in meters. Vertical exaggeration = 18x.

Figure 29c. Medial Profile 3. All distances expressed in meters. Vertical exaggeration = 7.5x.

Figure 29d. Medial Profile 4. All distances expressed in meters. Vertical exaggeration = 11x.

Figure 29e. Medial Profile 5. All distances expressed in meters. Vertical exaggeration = 18x.

Figure 29f. Medial Profile 6. All distances expressed in meters. Vertical exaggeration = 16x.

4, they correspond to the deformation associated with the apron structure. East of the apron margin, the profile is convex with no abnormalities.

The ages of the fan surfaces may control the preservation of active deformation within the medial and distal portions of the piedmont. Profiles 1 and 2 transect the oldest fan surface profiled. The other, younger fan surfaces may not have the soil development (in particular, a well developed carbonate content/calclac layer), needed to record the small perturbations in Profiles 1 and 2. In addition, active deformation in the piedmont may not have generated sufficient relief to be distinguished with the 10-meter resolution of the DEMs.

Channel Morphology

Profiles constructed within the four largest channels of the study area show significant changes in gradient, suggesting active deformation associated with mapped fault structures (Fig. 30a-d). The greatest deformation is associated with the youngest structures and concentrated in the southern half of the study area.

The Quaternary fault mapped within the northern wall of Ventania Ridge Canyon displays the greatest degree of deformation. Measurements suggest an uplift range between 0.5 m and 2.3 m. This fault exposure also marks the deflection of the channel slightly southward, suggesting oblique dextral motion along this fault system.

Faults associated with the southern Death Valley fault zone show evidence of active deformation. In Ventania Ridge Canyon (Profile 3), the area associated with the junction of the southern Death Valley and Mule Spring fault zones suggests uplift ranging from 0.9 to 1.1 m.

Figure 30a. Channel Profile 1. All distances expressed in meters. Vertical exaggeration = 9.5x.

Figure 30b. Channel Profile 2. All distances expressed in meters. Vertical exaggeration = 7.6x.

Figure 30c. Channel Profile 3. All distances expressed in meters. Vertical exaggeration = 5.6x.

In Avawatz Canyon (Profile 4), uplift associated with the Mule Spring fault zone ranges from 0.2 m to 0.4 m within the quartz monzodiorite (Profile 4, zone 1), and 0.2 m to 0.8 m within the fan deposits (Profile 4, zone 2). Slightly east of this exposure (Profile 4, zone 3), perturbations in the channel profile in addition to vertical fractures observed within the Qidf1 and Qydf4 fan deposits, suggest the presence of a growing structure. Channel uplift ranges between 0.1 m and 0.3 m.

Perturbations associated with both the eastern and western fault propagation folds are seen within all channels north of Ventania Ridge Canyon and display relatively constant magnitudes of deformation. Uplift associated with the eastern fault propagation fold ranges from 0.4 m to 0.5 m (in Profile 1) and from 0.3 m to 0.5 m (in Profile 2). Uplift associated with this structure is not seen within Ventania Ridge Canyon (Profile 3). Uplift associated with the western fault propagation fold is absent in Profile 1, but ranges from 0.3 m to 0.5 m in Profile 2; and from 0.3 m to 0.7 m in Profile 3. Overall, the magnitudes of uplift associated with the western fault propagation fold are slightly higher than those associated with the eastern fault propagation fold, and show a slight increase in magnitude from north to south. These trends in the western fault propagation fold signature may be attributed to its position on the backlimb of the eastern fault propagation fold.

East of the apron structure, Profiles 1 and 2 display perturbations that coincide with the surficial lineament and potential fault locality observed with the medial and distal fan profiles. Uplift ranges from 0.4 m to 0.5 m in Profile 1; and from 0.1 m to 0.4 m in Profile 2, showing a slight decrease in magnitude of uplift from north to south.

DISCUSSION

The structural and geomorphic results obtained from this study provide new insights into the Neogene evolution of the eastern range front of the Avawatz Mountains, and clarifies questions raised by previous workers.

Structural Evolution of the Northeastern Avawatz Mountains

The range front is defined by the juxtaposition of two different lithologic domains. The low-strain intact Avawatz Mountain block, composed of Avawatz quartz monzodiorite, is in sharp contact with the highly-strained, heavily brecciated and sheared southern Death Valley fault zone, composed of Tertiary sedimentary rocks, Mesozoic Teutonia batholith, and Proterozoic sedimentary and metamorphic rocks. The presence of the southern Death Valley fault zone east of its intersection with the Garlock/Mule Spring fault zone is consistent with observations made by Troxel and Butler (1998) and Brady (1986b). Large offset along the southern Death Valley fault zone is suggested by the presence of rocks of the Teutonia batholith, which have been mapped only in the Owlshhead Mountains to the north and Halloran Hills to the southeast (Hewett, 1956).

The occurrence of the southern Death Valley fault zone in this area predates the uplift of the Avawatz Mountains, which is believed to have initiated 4-7 million years ago along the Mule Spring fault zone (Brady and Troxel, 1981; Reinert et al., 2003). The southern Death Valley fault zone is overlain by the Tertiary sedimentary rocks, interpreted to be syntectonic basin deposits similar to the Military Canyon and Avawatz Formations in the northern and southern portions of the range, respectively (Brady,

1986b). The absence of quartz monzodiorite in the fault zone and as clasts in the Tertiary sedimentary rocks suggests that the initiation of motion along the Mule Spring fault zone began in the Quaternary.

The initiation of eastward-vergent motion along the Mule Spring fault zone has forced the southern Death Valley fault zone to tilt eastward and behave as a critical wedge, resulting in the formation of dextral reverse motion along the fault zone and eastward propagation of reverse faults into the piedmont. This style of deformation dominates Quaternary deformation in the piedmont.

Evidence for critical wedge behavior can be seen in the bedding attitudes within the Tertiary sedimentary rocks. Beds dip mostly to the east within the zone, except around the Precambrian and Teutonia fault slices, where beds dip away from the slices. These fault slices can be interpreted as imbricate slices of deeper levels of the southern Death Valley fault zone brought to the surface along out-of-sequence thrust faults.

Several Quaternary structures within the apron structure share similar kinematics to structures of the southern Death Valley fault zone, and are interpreted to be extensions of those structures. The eastern and western fault propagation fold axes are extensions of the fault propagation fold axis in the red member of the Tertiary sedimentary rocks, near the northern boundary of the study area, and the eastern margin of the Precambrian/Teutonia fault slice, respectively. Other Quaternary faults appear to be divergent splays from the zone, some of which display dextral oblique kinematics, such as the Ventania Ridge Canyon fault. These kinematics also extend eastward beyond the apron structure with the presence of a potential blind fault in the Qidf3 fan deposits.

Geomorphic evidence for critical wedge behavior can be seen in the fan surface elevations within the apron structure. The lower elevations seen in the northern portion of the apron structure can be attributed to thrust loading by the advancing Mule Spring fault zone. The presence of a large, northwest-striking, east-dipping normal fault supports this idea. In addition, this low region is correlative with the northwest-striking eastern margin of the southern Death Valley fault zone, where the zone is thickest. Farther south, where the strike changes from northwest to northeast, the zone becomes buried under fan deposits and fan surface elevations become higher.

Geomorphic Evolution of the Northeastern Avawatz Mountains

The geomorphic evolution of the piedmont documents the progressive influence of the interaction between the Mule Spring and southern Death Valley fault zones in this area. This is best seen in Ventania Ridge Canyon where east of the mapped fault exposure in the northern canyon wall, channel flow is deflected south. This channel was the likely feeder channel of the Qidf3 fan whose apex is entrenched in the apron structure. If the channel path west of the Ventania Ridge Canyon fault is projected into the piedmont, it lines up perfectly with the distal tip of the fan, suggesting this deflection occurred sometime after the early Pleistocene (Fig. 31). Southward deflection of the channel led to the cessation of fan formation in the northern half of the piedmont and subsequent down-cutting and erosion of the Qidf4 surfaces in the southern half of the apron structure. Erosion of the Qidf3 deposits at the southeastern margin of the apron structure can also be attributed to this deflection.

Figure 31. Map of southward deflection of channel flow within Ventania Ridge Canyon in response to the southern Death Valley fault zone.

Geomorphic evidence also suggests a decrease in age and an increase in the degree of deformation from north to south along the range front. This is most clearly seen in the mid-Pleistocene Qidf3 fan deposits that border the eastern margin of the apron structure. The northernmost Qidf3 surface appears to have been cut off from its apex by the fault propagation fold that forms the eastern margin of the apron structure. Farther south, a Qidf3-equivalent fan formed syntectonic with the uplift and formation of the apron structure. The apex is visible and preserved; medial Profile 3 (Fig. 29) displays the typical convex shape of an alluvial fan, suggesting that the surface is undeformed.

The channel longitudinal profiles show similar trends. The greatest degrees of deformation are seen within the southern profiles and are associated with Quaternary structures. The northern profiles do not display the same degree of deformation because they involve older structures. This pattern suggests that active fan formation may be restricted to the south because pre-Quaternary structures may have cut off potential feeder channels needed for active fan formation in the north.

Evidence for a Fault Asperity Between the Avawatz Mountains and Salt Spring Hills

Structural and geomorphic analyses conducted for this study, along with ongoing research in the area (Miller et al., 2005), have recognized a potential fault asperity between the Avawatz Mountains and the southern Salt Spring Hills. The presence of a fault asperity in this region may be an explanation for the absence of an eastward continuation of the Garlock fault, and it challenges previously suggested hypotheses suggesting its direct termination in the Avawatz Mountains.

The Mule Spring fault zone displays variations in kinematics and fault processes along its exposure in the Avawatz Mountains. It is a high-angle, north-vergent reverse fault system that changes to a shallow, east-vergent thrust system south of the Salt Spring Hills (Brady, 1986b; Troxel and Butler, 1998; Miller et al., 2005). Within the study area, northern segments of the fault zone have shallow dips, and display fine-grained breccia and gouge in the footwall while southern segments of the fault zone have steep dips and display a cohesive fault breccia that lines the footwall.

The shallow fault plane in the northeastern corner of the Avawatz suggests that the fault zone in this region is experiencing increased frictional resistance, resulting in impeded lateral motion; increased vertical motion; and loading of the fault plane. Evidence for this is seen in the extreme relief of the northeastern Avawatz Mountains and in the presence of gouge and incohesive fault breccia within the footwall of the northern segments.

Increased loading of the fault plane also leads to the formation of shallow stress planes and increased eastward vergence along the fault segments. The location of the southern Death Valley fault zone, situated between the Avawatz and the Salt Spring Hills, is responsible for the eastward vergence of the Mule Spring fault zone, causing the southern Death Valley fault zone to overturn and behave as a critical wedge. Evidence for Quaternary deformation along the southern Death Valley fault zone in concert with localized seismicity in the Salt Spring Hills and Quaternary deformation to the north (Miller et al., 2005) suggests that the interaction between these two structural blocks is ongoing and has a profound effect of the local tectonics of the region.

CONCLUSIONS

The principal conclusions of this study define the relationship between and the Neogene evolution of the southern Death Valley and Garlock/Mule Spring fault zones in the northeastern Avawatz piedmont.

1) The southern Death Valley fault zone continues past its intersection with the Garlock fault zone south of the southern Salt Spring Hills. It is expressed as a sequence of faults encompassed in a northeast-trending triangular wedge of Tertiary sedimentary rocks, Precambrian units, and Teutonia batholith.

2) The southern Death Valley fault zone is being overridden and truncated by the Mule Spring fault zone. This interaction has caused the southern Death Valley fault zone to overturn and display dextral oblique kinematics.

3) Uplift and loading on the Mule Spring fault zone has forced the southern Death Valley fault zone to behave as a critical wedge, resulting in an eastward propagation of faulting. This kinematic signature is expressed within the Quaternary faults of the apron structure, indicating that Quaternary deformation in the piedmont is controlled by the southern Death Valley fault zone.

4) Profile and structural data, along with morphologic evidence, show a decrease in age and an increase in the magnitude of piedmont deformation from north to south within the study area.

5) Faults within the study area are capped by or occur within intermediate-age fan deposits, suggesting rupture occurred within the early to middle Pleistocene.

6) The Mule Spring fault zone is comprised of several fault segments that are kinematically related. Strikes are aligned along north-trending axes and dips along this fault zone steepen from north to south, suggesting the presence of a crustal asperity in the northeastern Avawatz region. The Salt Spring Hills may be the location for this asperity.

Regional Implications and Suggestions for Future Studies

The presence of a crustal asperity between the Avawatz Mountains and the Salt Spring Hills greatly affects the structural and geomorphic evolution of the southern Death Valley region. A more detailed kinematic study of the northeastern Avawatz region involving the bedrock core of the range is needed to better understand the nature of this potential asperity.

The Mule Spring fault zone around Avawatz and Mormon Canyons involves faults predominantly within the quartz monzidiorite. However these faults are often difficult to identify since visible differences within the unit are minor in this region. Furthermore, no detailed geologic mapping has been undertaken south of Mormon Canyon to study this fault zone in detail. Detailed geologic and surficial mapping of this region can be used to further investigate the nature of the southern Death Valley fault zone and its involvement with Quaternary deformation in this portion of the piedmont.

The presence of growing structures within the medial and distal portions of the piedmont serves not only as further support of active deformation, but can also lead to a better understanding of the contractional regime of the southern Death Valley region. A more detailed geomorphic study involving field generated profiles and fracture measurements may help identify smaller structures beyond the scope of this study.

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Map Location

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THE NORTHEASTERN AVAWATZ MOUNTAINS

By

Jennifer Mendonça

2006

MOUNTAINS, CALIFORNIA