Cenozoic extension in the River Mountains and Frenchman Mountain, Southern Nevada

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CENOZOIC EXTENSION IN THE RIVER MOUNTAINS AND FRENCHMAN MOUNTAIN, SOUTHERN NEVADA

by

William Michael Rittase

Bachelor of Science
University of North Carolina at Chapel Hill
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A thesis submitted in partial fulfillment of the requirements for

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ABSTRACT

Cenozoic Extension in the River Mountains and Frenchman Mountain, Southern Nevada

by

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Dr. Wanda J. Taylor, Examination Committee Chair
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The River Mountains are the eroded remnants of a mid-Miocene stratovolcano complex located between Henderson, Nevada and western Lake Mead. This study addresses the tectonic and societal significance of (1) a 13.5-9 Ma initial stage and (2) a late-Pliocene(?)-present stage of extension. Multiple slip histories were recorded on NW-, N-, NE-, and E-striking conjugate fault sets, in addition to numerous orthorhombic faults. Multiple corrugations on the Saddle Island detachment (SID) during 13.5-9 Ma extension are interpreted to have produced localized zones of triaxial strain and orthorhombic faulting. Conjugate faults occurred where the SID was planar. The multiple kinematics suggest that 13.5-9 Ma tectonism in the River Mountains was controlled by transient slip gradients on the Las Vegas Valley shear zone and the Lake Mead fault system. Active faults of the second period of extension may impact present day Las Vegas. An earthquake rupturing the combined 38 km length of the Ithaca Avenue Fault-Frenchman Mountain Fault could produce a $M_w 6.9 \pm 0.3$ earthquake.
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CHAPTER 1

INTRODUCTION

This thesis investigates and describes the Cenozoic tectonic history of the River Mountains and westernmost Frenchman Mountain. The resolved temporal and spatial strain patterns in the River Mountains are tested against new and existing concepts to better understand the Cenozoic tectonic framework of the Las Vegas-Lake Mead region in the southwestern United States (Fig. 1).

The two study areas in the River Mountains and Frenchman Mountain lie between Las Vegas and Lake Mead in southern Nevada (Fig. 1). The River Mountains study area is 50 km$^2$ (19.5 mi$^2$) and is bounded by the Las Vegas Wash to the north and the edge of the Henderson 7.5' U.S. Geological Survey topographic quadrangle boundary to the south (Plate 1). The Frenchman Mountain study area is 2.3 km$^2$ (0.9 mi$^2$) and is located between $36^\circ$ 10' 0.00" N and $36^\circ$ 08' 30.00" N, and $115^\circ$ 00' 0.00" W and $115^\circ$ 01' 0.00" W (Plate 2).

Two central objectives of this thesis are (1) to document, characterize, and evaluate the evolution of strain and stress during upper plate extension on a Miocene low-angle normal fault (LANF), and (2) to address the seismic hazards in Las Vegas posed by documented Quaternary faults near Frenchman Mountain and the River Mountains (Fig. 2; Plates 1 and 2). The two hypotheses to be tested here are: (1) the 13.5-9 Ma record of strain in the western River Mountains is a consequence of both
induced NW-directed shear on the Las Vegas Valley shear zone from the proto-San Andreas plate margin as first proposed by (Stewart, 1985) and WSW-directed strike-slip faulting on the Lake Mead fault system, and (2) the Frenchman Mountain Fault and the Ithaca Avenue Fault are linked (Fig. 2) and may rupture together in the future producing a larger earthquake than if they were separate faults. The dual objectives of this thesis will prove beneficial to advancing geologic knowledge and society’s understanding of the seismic risk alike. Understanding the temporal and spatial evolution of stress and strain (e.g., faults, folds) in the River Mountains will offer valuable insight into Central Basin and Range (CBR) tectonism and other extensional regimes. Refining our understanding of the seismic hazards posed by active faults on the east side of the Las Vegas Valley will afford residents, visitors, and local government officials an improved awareness of the seismic risks.

Methods

The major data-collection technique in this project was standard geologic mapping (e.g., Compton, 1985). Tephra samples collected from mid-Miocene sedimentary rocks were sent to Janet Slate’s USGS microprobe laboratory in Menlo Park, CA for correlation to known samples dated previously by others (Appendix A) (Nash, 1992; Perkins et al., 1995, 1998). Slate’s analytical data of the five tephra samples (Appendix A) were additionally analyzed by Mike Perkins (University of Utah) for possible correlations with his tephra database. These two methods, plus (1) generating paleo-stress and strain reconstructions of Miocene faults and (2) constructing geologic cross sections (Chapter 3) were necessary to address the first
objective of this thesis outlined above. The second objective of this study is addressed through fault scarp profiling of the Ithaca Avenue fault and the Frenchman Mountain fault, and trenching a strand of the Frenchman Mountain fault (Chapter 3).
CHAPTER 2

REGIONAL GEOLOGY

The tectonic history of western North America near the latitude of southern Nevada (Figs. 1 and 3) includes a contractional stage in the Mesozoic followed by Cenozoic extension and bimodal volcanism (Wernicke et al., 1988; Wernicke, 1992; Burchfiel et al., 1992; Sonder and Jones, 1999). Though Mesozoic rocks are not exposed in the two study areas, a general understanding of this preceding tectonism is important to understanding Cenozoic extension.

Mesozoic Contraction

During the Late Triassic to Early Cretaceous, subduction of the Farallon plate under western North America generated arc volcanism above the Sierran block and imparted significant contractional strain across the Cordillera at this latitude (Sonder and Jones, 1999). Crustal thickening through thin-skinned thrusting, including ramping and duplexing of Sevier thrust sheets, and thick-skinned block uplifts of the Laramide in the Sevier foreland, was facilitated by large contractional stresses during the Mesozoic (Burchfiel et al., 1992; DeCelles and Coogan, 2006). Prior to the initiation of Miocene extension, the River Mountains and Frenchman Mountain lay east of the Sevier fold and thrust belt and west of the Laramide basement uplifts (Fig. 3).
Cenozoic Extension, Volcanism, and Sedimentation

The CBR is a highly extended, tectonically complex sub-province of the greater Basin and Range (Fig. 3). Previous tectonic studies indicate as much as 250 km of east-west extension during Cenozoic time based on the restorations of offset Mesozoic thrust faults, Paleozoic stratigraphy, and synextensional deposits (Longwell, 1974; Bohannon, 1984; Parolini, 1986; Wernicke et al., 1988; Fryxell and Duebendorfer, 1990; Rowland et al., 1990; Beard, 1996; Duebendorfer et al., 1998; Wernicke and Snow, 1998; Snow and Wernicke, 2000; Fryxell and Duebendorfer, 2005).

In addition to the large-magnitude extension, the initiation of both extension and magmatism in the CBR are significantly younger (late Oligocene-Miocene) than in the Northern Basin and Range (NBR) and Southern Basin and Range (SBR) (Eocene and Oligocene) (Fig. 3) (Glazner and Bartley, 1984; Burchfiel et al., 1992; Beard, 1996; Sonder and Jones, 1999; Dickinson, 2002). Several hypotheses attempt to explain the late arrival of extension and magmatism in the CBR. One idea suggests the presence of a more competent lithosphere under the CBR resisted extension until the early Miocene (Sonder and Jones, 1999). A second explanation is that the foundering Farallon slab beneath western North America generated the southward sweep of volcanism and extension throughout the NBR (Humphries, 1995). Models for the northwest sweep in volcanism and extension in the SBR invoke the development of the Mendocino triple junction and its subsequent migration to the northwest (Glazner and Supplee, 1992; Glazner and Bartley, 1984; Glazner et al., 2002). The passage of the triple junction and the subsequent slab window (Atwater,
1970; Severinghaus and Atwater, 1990; Atwater and Stock, 1998) has the effect of flexing the North American lithosphere and imparting tensional stresses adjacent to the triple junction (Glazner and Supplee, 1992; Glazner and Bartley, 1984; Glazner et al., 2002).

Extension in the CBR initiated at 16-14 Ma, as indicated by the development of sharp facies changes in the Thumb Member of the Oligo-Miocene Horse Spring basin in the Lake Mead region (Bohannon, 1984; Fryxell and Duebendorfer, 2005). Mega-breccia deposits of Proterozoic gneisses and granites within the Thumb Member indicate the development of significant topographic relief and extension during this time (Longwell, 1974, Bohannon, 1984; Wernicke et al., 1984; Parolini, 1986; Fryxell and Duebendorfer, 1990; Rowland et al., 1990; Beard, 1996; Duebendorfer et al., 1998; Fryxell and Duebendorfer, 2005). Large-magnitude extension in the CBR east of the Spring Mountains (Fig. 4) continued until around 9 Ma (see Chapter 6).

Temporally and spatially coeval with this extension was widespread 15-10 Ma volcanism and sedimentation (Anderson et al., 1972; Bell and Smith, 1980; Smith, 1982, 1984; Bohannon, 1984; Thompson, 1985; Larsen and Smith, 1990; Feuerbach et al., 1991; Anderson et al., 1994; Beard, 1996; Harlan et al., 1998). A more detailed description of mid-Miocene igneous rocks and their localities around western Lake Mead is in Appendix B.

Many of these syntectonic igneous and sedimentary rocks have been subsequently truncated and displaced on strike-slip faults and low-angle detachment faults that are overprinted by high-angle normal faults (e.g., River Mountains, Bell and Smith, 1980) (Burchfiel et al., 1992; Wernicke, 1992; Dickinson, 2002). Temporal changes
in faulting style may be attributed to a decrease in CBR extension rates and the
development of the Eastern California shear zone (ECSZ) and Walker Lane Belt
(WLB) (Fig. 3) post-10 Ma (Wernicke, 1988; Wernicke and Snow, 1998; Snow and
Wernicke, 2000).

North American-Pacific Plate Margin During Late Cenozoic Time

By ~28 Ma, the entrainment of the eastern half of the spreading center between
the Farallon and Pacific plates into the subduction zone off the coast of southern
California resulted in the change from convergence to translation along the North
American plate margin (Atwater, 1970; Severinghaus and Atwater, 1990; Atwater
and Stock, 1998). It appears that this change into a transform system showed little
effect in the way of major induced inboard strain and is speculated by Atwater (1970)
to indicate that translational strain between the Mendocino and Rivera triple junctions
was either (1) broadly diffused through the Cordillera and/or (2) localized outboard in
relatively young, hot, and weak oceanic lithosphere. An inboard jump of the proto-
San Andreas system into a continental setting with the abandonment of this earlier
oceanic transform system was proposed by Atwater (1970).

Today, a significant component (~25%) of the strain occurs inboard along the
Eastern California shear zone (ECSZ) and Walker Lane belt (Fig. 3) (Savage et al.,
1990; Dixon et al., 1995; Gan et al., 2000). Following the opening of the Gulf of
California and the inception of the ECSZ-WLB system during the late-Miocene, the
CBR was effectively partitioned into a zone of rapid NNW-directed strike-slip
faulting west of the Spring Mountains and slow E-W extension to the east (Wernicke et al., 1988; Wernicke and Snow, 1998; Snow and Wernicke, 2000).

**Major Las Vegas-Lake Mead Regional Structures**

Four tectonic structures that have significantly shaped, or are presently shaping, southern Nevada geology are: (1) the Las Vegas Valley shear zone, (2) Lake Mead fault system, (3) the Saddle Island Detachment fault (Figs. 1 and 4), and (4) Quaternary faults in the Las Vegas Valley and nearby regions (Fig. 2).

**Las Vegas Valley Shear Zone**

The Las Vegas Valley shear zone (LVVSZ) lies immediately north of Frenchman Mountain near Hamblin Mountain and continues northwest for 140 km to near Mercury, Nevada (Fig. 4) (Longwell, 1960). Offset Mesozoic thrust faults exposed in the Spring Mountains and Sheep Range, on the western and northern flanks of the Las Vegas Valley, respectively, indicate 48 ± 7 km of dextral slip (Longwell, 1960, 1974; Burchfiel, 1965; Fleck 1970; Wernicke et al., 1988). Motion along the LVVSZ is believed to have initiated at around 15 Ma (Fleck, 1970) and is responsible for a dramatic increase in Miocene basin-fill thickness under northeast and north Las Vegas Valley (Duebendorfer and Black, 1992; Campagna and Aydin, 1994; Langenheim et al., 2001). Strands of the LVVSZ cut rocks as young as the 12-10.6 Ma Red Sandstone Unit (Duebendorfer and Wallin, 1991) and are covered by Quaternary sediments and possibly the 10(?)-6 Ma Muddy Creek Formation (Longwell, 1974).
Lake Mead Fault System

The Lake Mead fault system (LMFS) is a zone of NE-SW striking left-lateral strike-slip faults that cut rocks from the Virgin Mountains through Bitter Spring Valley to the River Mountains (Figs. 1 and 4) (Campagna and Aydin, 1994; Beard, 1996; Fryxell and Duebendorfer, 2005). At least two known detachment structures that were active synchronously with strike-slip faulting in the LMFS are the Saddle Island detachment (SID) and Lakeside Mine detachment fault (Figs. 1 and 4) (Weber and Smith, 1987; Fryxell and Duebendorfer, 2005). Paleo-reconstructions of the location of Frenchman Mountain, based on the correlation of breccia deposits contained in the Thumb Member of the Horse Spring Formation to Gold Butte, reveal 50-60 km of west-southwest directed extension (Longwell, 1974; Parolini, 1986; Rowland et al., 1990; Duebendorfer et al., 1998; Fryxell and Duebendorfer, 2005). All but one strand of the LMFS, the Mead Slope fault (see below), are inactive (Fig. 2).

Low-angle Normal Faults

Saddle Island Detachment

The SID daylights as a 450 m long, LANF on Saddle Island in Lake Mead (Fig. 1) (Smith, 1982, 1984; Sewall, 1988). Here, a metamorphic core of amphibolite-grade Precambrian rocks containing mylonites is overprinted with chlorite schist and fault breccia related to denudation of the footwall rocks (Smith, 1982, 1984; Weber and Smith, 1987; Sewall, 1988; Duebendorfer et al., 1990).
Its location between the River Mountains and the Wilson Ridge Pluton (Fig. 1) suggests that the SID is responsible for the detachment and 20 km of westward transport of the River Mountains volcanic suite from its plutonic counterpart, the Wilson Ridge Pluton (Weber and Smith, 1987). Frenchman Mountain (Fig. 1) is also considered to be undercut by the SID (Weber and Smith, 1987; Duebendorfer and Wallin, 1991). The relationship between the SID and the Las Vegas Valley (LVV) is less clear but will be discussed in Chapter 6.

Las Vegas Valley Quaternary Faults

Approximately four named faults cut Quaternary sediments in the Las Vegas Valley and strike roughly north-south (Fig. 2). From east to west, these faults include: (1) the Frenchman Mountain fault (FMF)-Ithaca Avenue fault (IAF) system (this study), (2) the Cashman-Whitney Mesa fault system, (3) the Valley View fault, and (4) the Eglington-Decatur fault system (Slemmons et al., 2001). Together, the Cashman, Whitney Mesa, Valley View, Decatur, and Eglington faults are called the Las Vegas Valley fault system. The FMF and IAF (this study) dip 60-80° W and are antithetic to other active valley faults. Quaternary faults in the central valley (e.g., Eglington-Decatur fault, Valley View fault, and Cashman-Whitney Mesa fault) dip east and are curved with strikes changing from N to NE toward the north (Fig. 2) (Slemmons et al., 2001). Although earthquakes of $M_w < 4$ occur in the valley (USGS Earthquake Hazards Program), none of these faults had historical surface ruptures on them (Slemmons et al., 2001). Based on exposed surface rupture lengths, the four
valley faults have maximum earthquake potentials ranging from $M_w$ 6.4 to $M_w$ 6.9 (Slemmons et al., 2001).

**Nearby Quaternary Faults**

In addition to the Las Vegas Valley Quaternary faults, other active faults within 80 km (50 miles) of Las Vegas include the: (1) Mead Slope fault, (2) Black Hills fault, (3) California Wash fault, (4) Pahrump Valley faults, (5) Arrow Canyon Range fault, (6) Dry Lake fault, (7) Wildcat Wash fault, and (8) State Line fault (Fig. 2). All of these are high-angle normal faults, except the Mead Slope fault and the State Line fault, which are high-angle strike-slip faults. Earthquake magnitude estimates have been published for two faults: $M_w$ 6.4-6.9 for the Black Hills fault (Fossett, 2005) and $M_w$ 5.9-7.2 on the California Wash fault (Zaragoza et al., 2005).

**Oligocene-Quaternary Western Lake Mead Stratigraphy**

The pertinent formations and rock units pertinent to this thesis are briefly outlined here but are more thoroughly discussed in Appendix B. The Horse Spring Formation is a 26(?)–12 Ma sedimentary unit composed of the Rainbow Gardens Member, the Bitter Ridge Limestone Member, and the Lovell Wash Member, from oldest to youngest (Fig. 5) (Bohannon, 1984). Mid-Miocene igneous rocks of felsic to mafic composition intrude and interbed with the Horse Spring Formation. Resting unconformably on top of the Horse Spring Formation is the informally named Red Sandstone Unit and the younger Muddy Creek Formation (Bohannon, 1984). Late Miocene basalts (e.g., Fortification Hill basalt) locally intrude and overlie the Muddy
Creek Formation. Pleistocene gypsiferous lacustrine deposits are commonly exposed in the valleys and capped by fanglomerates.
CHAPTER 3

METHODS

Geologic Mapping

Geologic mapping of the River Mountains and Frenchman Mountain study areas was performed at a 1:12,000 scale using standard geologic mapping techniques (Figs. 6 and 7; Plates 1 and 2 (e.g., Compton, 1985).

The area mapped in the River Mountains consisted of approximately 50 km² located in the Henderson U.S.G.S. geologic quadrangle (Bell and Smith, 1980). The mapped Frenchman Mountain study area consisted of approximately 2.3 km² located on the Las Vegas NE (Matti et al., 1993) and Frenchman (Castor et al., 2000) U.S.G.S. geologic quadrangles.

Aerial photographs were used as an aid in locating young fault scarps prior to actual field mapping. In the field, faults were recognized by the presence of fault breccia, gouge, exposed fault planes or scarps, and the omission or repetition of stratigraphy.

A Brunton compass was used to measure bedding attitudes and the strike and dip of fault planes and striations. Measuring kinematic indicators (i.e., slickenlines and grooves and mullions) was done by either (1) getting the trend of the lineation across the exposed plane and its dip or (2) by recording the angle formed between a horizontal plane across the fault’s face and the striation (rake).
Fault Scarp Profiling & Degradation Modeling

Quantitative age estimates and fault rupture correlations among Frenchman Mountain and River Mountains Quaternary fault scarps were performed. The first step was to measure a topographic profile (Figs. 8 and 9) for selected fault scarps using the TopCon GPT-8203A auto tracking pulse total station, a laser-guided, surveying apparatus. The data were then downloaded onto a PC where the angles of the hanging wall surface, footwall surface and eroded scarp were determined in Excel. Using the diffusion equation of Coleman and Watson (1983):

\[
\kappa t = \frac{d^2}{4\Pi} \frac{1}{(\tan \theta - \tan \alpha)}
\]

where \(\kappa\) is the calculated diffusivity, \(d\) is the vertical distance between upper and lower slope, \(\theta\) is the maximum scarp angle, and \(\alpha\) is the average slope of the upper and lower non-fault surfaces; time \(t\) of the most recent rupturing event (MRE) can be estimated.

Paleo-Stress/Strain Techniques

Stereonet plots of the conjugate faults’ principal strain axes (Figs. 10 and 11) and the orthorhombic faults’ principal strain axes (Table 6.1) were generated using FaultKinWin v.1.2 (Allmendinger, R.W., 2002a and b). All plots are an equal area, lower hemisphere projection of the data.

For conjugate faults, strain analysis plots were made from both the individual fault-plane measurements as they were recorded in the field and from the 3-point method and structure contour orientations calculated off the geologic map (Fig. 6a, Plate 1). This redundancy allows for a more robust comparison of the strain field that
may be affected by neighboring fault block and faulting patterns causing multiple slickenline orientations on fault sets. Principal stress and strain axes for orthorhombic faults are determined from field-based, fault plane measurements and are not 3-point calculations because (1) the odd-axis model technique (Chapter 4) averages fault plane measurements, (2) the fault sets have low sinuosity, and (3) of the underlying assumption that orthorhombic faults and the 3-D strain field permit multiple slip senses per fault.

Cross Section Techniques

Four geologic cross sections were constructed throughout the River Mountains study area. Because of a lack of laterally-continuous stratigraphy in the volcanic rocks, limited exposures of sedimentary rock formations (e.g., Horse Spring Formation), and kinematic indicators that document movement in and out of the plane of the section, neither line-length or equal-area balanced cross sections were possible. The presence of three-dimensional strain in the western River Mountains violates the conditions necessary for balancing cross sections.

Apparent dips of faults and rock units were determined from real and contoured measurements on the geologic map (Fig. 6a, Plate 1) using the conversion equation:

\[
\tan \alpha = \tan \theta \sin \beta
\]  

where \( \theta \) is the true dip of the object, \( \beta \) is the angle between an object's strike and the cross section plane, and \( \alpha \) is apparent dip in the plane of the cross section.

Because stratigraphic constraints are poor in most places, determination of absolute offsets of faults in the cross sections was not possible. Instead, an
approximate offset magnitude was calculated to be $1/5^{th}$ of a fault's trace length where a fault's real offset was unknown. This principle was applied universally.

Where outcrop patterns are sufficient (i.e., the top and bottom of a unit is exposed and not faulted), calculations of stratigraphic thickness were made using the same 3-point method and structure contouring techniques as used for faults (Fig. 12). The length of a horizontal line (perpendicular to strike) from the top to the bottom of a unit is measured on the map. The geometric identity

$$z \sin \theta = y$$

(3.3)
gives the bedding thickness $y$, where $z$ is the horizontal distance (hypotenuse of triangle) and $\theta$ is the dip angle.

**Tephrochronology**

The five tephra samples were submitted to Janet Slate's U.S.G.S. microprobe laboratory in Menlo Park, CA for elemental and oxide ratios analysis. The geochemistry of the submitted samples were then compared with a large suite of dated ash deposits by Janet Slate's lab and subsequently by Mike Perkins at the University of Utah (Appendix A).

Sample preparation prior to submission involved only crushing. Sieving was not required as tephra samples were loose and crumbly.
CHAPTER 4

CONJUGATE AND ORTHORHOMBIC FAULT THEORIES

Conjugate and orthorhombic faults are found in the western River Mountains study area, indicating the existence of both triaxial and plane strain. Because the techniques of analyzing strain on these faults and the mechanisms responsible for their formation are different, it is necessary to discuss the theory behind each fault set before going on to the data and interpretations chapters.

Conjugate Faults

Conjugate faults, genetically related faults with the same strike but opposite dip directions and differently oriented shear senses, form under plane-strain (2-D strain) conditions. In plane strain, strain is focused along the $\varepsilon_1$ (maximum) and $\varepsilon_3$ (minimum) principal strain axes and no strain occurs along the $\varepsilon_2$ (intermediate) strain axis (Fig. 13.1–3) (Anderson, 1951). Experiments replicating conjugate faults in the lab typically involve a cubic specimen of rock being subjected to a maximum compressive load ($\sigma_1$) and a lesser lateral pressure of equal magnitudes in the $\sigma_2$ and $\sigma_3$ direction (Anderson, 1951; Brace, 1964; Friedman and Logan, 1973).

Rupturing of first-generation faults, under these conditions, is explained by the Mohr-Coulomb failure criterion (equation 3.1) where $\tau_{\text{crit}}$ is the shear stress required
for rupture, $\tau_o$ is the rock’s intrinsic shear strength, $\mu$ is the coefficient of friction, and $\sigma_n$ is the normal force on a plane.

$$\tau_{crit} = \tau_o + \mu\sigma_n$$  \hspace{1cm} (4.1)

Ideally, a conjugate set of fault planes would be inclined 45° to the maximum compressive stress ($\sigma_1$) if the rock body were frictionless ($\mu = 0$) because this is the orientation of the plane with maximum shear stress (equations 3.2 and 3.3) (Anderson, 1951).

$$\tan 2\theta = -\frac{1}{\mu}$$  \hspace{1cm} (4.2)

$$\left| \lim_{\mu \to 0} \frac{1}{2} \tan^{-1}\left(-\frac{1}{\mu}\right) \right| = 45^\circ$$  \hspace{1cm} (4.3)

However, a rock’s internal friction (static friction) is not zero; the force of friction ($\mu\sigma_n$) inhibits slip along the maximum shear stress plane. A common coefficient of internal friction for rock is ~0.6, and consequently conjugate fault sets are inclined ~30° to $\sigma_1$ (Anderson, 1951).

Because the principal stress axes are orthogonal, $\sigma_1$ bisects the acute angle between faults; $\sigma_3$ is the obtuse-angle bisector for a conjugate fault set. The intermediate stress axis ($\sigma_2$) is defined as parallel to the intersection of the two conjugate fault planes. Anderson’s theory of faulting, which is derived from Mohr-Coulomb failure criterion (equations 3.1-3.3), is intrinsically limited to plane stress systems because the orientation of conjugate fault sets is a product of $\sigma_1$ and $\sigma_3$ only.

Graphical stereonet programs, such as Allmendinger’s FaultKin for Windows v. 1.2.2 (2002a & b), use the fault plane orientation, the slip direction, and the sense-of-slip to backward model hypothetical paleo-stress and -strain tensors (Marrett and
Allmendinger, 1990, 1991). The diagonal values in these stress and strain tensors represent the magnitudes, or vector lengths, of the principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$) and the principal strains ($\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$), respectively. Strain ellipsoids are graphical representations of the relative magnitudes of the principal strains. The elongation and shortening axes of the instantaneous strain ellipsoid for a fault or shear zone are oriented 45° to the shear plane. These two axes lie in an orthogonal plane defined by the fault pole and the kinematic rake (Fig. 13C).

**Orthorhombic Faults**

Some tectonic faults violate the assumptions of conjugate (plane strain) faulting in that strain along $\varepsilon_3$ is not negligible and actually approaches $\varepsilon_1$ or $\varepsilon_3$ strain values (e.g., Reches, 1983; Reches and Dieterich, 1983; Krantz, 1988 & 1989; Langrock, 1995; this study). Under such triaxial strain conditions orthorhombic faults (Fig. 13B1-B3) may form (Reches and Dieterich, 1983).

Early works of Reches and Dieterich (1983) and Reches (1983) attempt to both experimentally and theoretically model orthorhombic faulting in sandstone, limestone, and granite. To mimic a variable triaxial strain field in the lab, these authors loaded rock cubes into a hydraulic press where six steel anvils applied specified forces. The vertical anvils applied the maximum compressive stress (load force) in the z-direction and were held constant for the duration of each run. Four anvils compressed the sides of the cube at variable strain rates in the x- and y-directions. They concluded that a minimum of four fault sets should form (one in each stereonet quadrant, if plotted) and that none of the poles lie in a principal plane.
If a fault’s pole occurs on a principal plane, it is presumed that the fault set is conjugate and oriented preferentially such that all strain on it occurs in the plane defined by $\sigma_1$ and $\sigma_3$ (Reches, 1978, 1983; Reches and Dieterich, 1983).

Expanding upon the earlier faulting theory of Jaeger and Cook’s (1969) Griffith model, and Oertel’s (1965) experimentation with homogeneous (constant) stress and triaxial strain in clay, Reches (1983) proposed his “slip model”, wherein four or more orthorhombic fault sets slip synchronously under triaxial (3-D) stress. The “slip model” requires that: (1) many randomly oriented fractures exist prior to deformation, (2) slip occurs along a few preferentially oriented fracture sets with similar “efficiencies,” (3) fault densities of each set are sufficient enough that synchronous deformation of faults is homogeneous, and (4) resistance to slip along faults includes both cohesive and frictional forces and thus obeys Coulomb’s friction law (Reches, 1983). Cumulative strain on an orthorhombic set is broken down into a hierarchy of different strain components that, summed together, are indicative of three-dimensional strain conditions. The triaxial strain tensor for an orthorhombic group is a function of the averaged simple-shears among all fault sets. At the smallest hierarchical level, the averaged simple-shear for an individual fault set is the collective average for all individual simple shears of that set.

An important aspect of the slip model is that the principal stress axes coincide with the principal strain axes, in agreement with Oertel’s (1965) findings. Because all faults in the orthorhombic set have the same efficiencies and same orientation with respect to the stress field, and because each set contains a conjugate, the eigenvectors of the summed strain tensor are identical to the stress tensor (Reches, 1983).
A more evolved model for analyzing triaxial strain is the odd-axis model of Krantz (1988, 1989). This model, which is a partial adaptation of the slip-model of Reches (1978, 1983), uses the orientation of faults and their kinematics to determine the principal strain axes and their relative magnitudes (Krantz, 1988, 1989). More specifically, the odd-axis model works by first calculating the average fault plane and slip vector for each orthorhombic set. According to the orthorhombic rule (Reches and Dieterich, 1983), all fault poles falling outside of the NE-quadrant are to be rotated 90° or 180°, including the corresponding slip vectors, until those poles lie within the first quadrant (Krantz, 1988, 1989). The planes passing through the rotated fault plane poles and slip vectors are then determined using a graphical plotting program (e.g., Allmendinger’s FaultKinWin v. 1.2.2 (2002b)) (Krantz, 1988, 1989).

The odd-axis (e_odd) is defined as the common intersection point for the great circles, which defines a line in 3-D space, and has an opposite sense of strain from the other two principal axes (e_intermediate and e_similar) (Fig. 13b) (Krantz, 1988, 1989). For normal fault systems (e.g., this study), the odd-axis is compressional and vertical (Krantz, 1988, 1989).

The odd-axis for an orthorhombic fault population can be found by performing a Linked Bingham Distribution using Allmendinger’s FaultKinWin v. 1.2.2 (2002b), which determines an unweighted moment (strain) tensor summation for all of the orthorhombic fault sets. If the odd-axis is oriented vertically, dip-slip motion is predicted on the orthorhombic fault sets (Krantz, 1988, 1989). Conversely, if the odd-axis is horizontal, oblique-slip motion is required (Krantz, 1988, 1989). Without
knowledge of slip magnitudes, the relative strain magnitudes between the three principle strain axes may not be determined (Krantz, 1988, 1989).
CHAPTER 5

STRUCTURAL AND KINEMATIC DESCRIPTIONS

The following sub-sections describe structural field data and its relationship to the tectonic history of the River Mountains and Frenchman Mountain. All reported uncertainties are one standard deviation ($\sigma$).

High-angle Faults

This study documented 240 Miocene-Quaternary age faults, with dip magnitudes in excess of 45° in the River Mountains study area through field mapping and cross section construction techniques (Fig. 6a; Plates 1 and 3). Faults were recognized in the field by the presence of (1) breccia, fault gouge, and/or fault surfaces, which may contain calcite and/or jasperoid; (2) topographic scarps; and (3) the repetition or omission of strata. Of the 240 high-angle faults documented, three were not exposed (they lie under alluvium), but were geometrically required to restore bedding attitudes and correlative lithofacies in cross-sections (Plate 3).

All faults display strike-slip to normal-slip motion. Of these faults whose slip orientation is determined primarily by slickenline rakes, the criteria used to distinguish normal, oblique, and strike-slip motion are rakes of 90-60°, 60-30°, and 30-0°, respectively.
Geometric and cross-cutting relationships indicate two groups of high-angle extensional faults: conjugate and orthorhombic faults (see subsequent discussion). Conjugate faults are categorized into four sets based on their three-point calculated (Figs. 11 and 12) strike orientations (Plate 5; Appendix C) but are analyzed by individual fault plane measurements. Orthorhombic faults are grouped into zones based on their geometric and cross-cutting relations (Plate 5). The scatter in strike measurements of individual conjugate and orthorhombic fault segments is a result of the sinuosity of faults (see below) (Appendix C).

Cross-cutting relations among faults in the River Mountains and Frenchman Mountain map areas (Figs. 6a and 7; Plates 1 and 2) demonstrate the occurrence of two post-13.5 Ma extensional events in the western Lake Mead tectonic domain. Most mapped faults cut the 13.5 Ma volcanic rocks of the River Mountains (Damon et al., 1978; Bell and Smith, 1980) and the 12-10.6 Ma Red Sandstone Unit (Bell and Smith, 1980; Bohannon, 1984; Duebendorfer and Wallin, 1991; J. Slate, 2006 personal communication; M. Perkins, 2006 personal communication; S. Beard, 2006 personal communication), but not Pleistocene and Quaternary-age sediments. Two faults however, the IAF and the FMF do cut these younger sedimentary deposits, demonstrating a second extensional phase. Consequently, these two extensional events are loosely bracketed into: (1) a 13.5-9 Ma and (2) a late Pliocene(?) to Quaternary faulting stage. The 9 Ma bracket for the cessation of Miocene extension is based on (1) regional outcrops of largely unfaulted 10(?)-6 Ma Muddy Creek Formation (Appendix B) (Damon et al., 1978; Bohannon, 1984), (2) the documentation of waning extension in the northern Death Valley region at this time.
(Snow and Wernicke, 2000) and (3) the possibility that some faulted and folded sediments in the western Lake Mead area that were mapped as Muddy Creek may actually be the Red Sandstone Unit (S. Beard, personal communication 2006). Further discussion and interpretation of these extensional events follow in the subsequent sections of Chapters 5 and 6.

Conjugate Faults

One-hundred and twenty-one conjugate high-angle faults, documented here as cutting rocks as young as the 12-10.6 Ma Red Sandstone Unit (Bohannon, 1984) and covered by late Pliocene(?) - early Quaternary fanglomerates (Fig. 6a; Plate 1), are described in this section based on the calculated data measurements contained in Appendix C. For consistency in measuring and describing these faults, a conjugate fault is counted as a single fault if it is continuously exposed or is intermittently exposed with identical outcrop geometries between alluvial coverings. Conjugate faults in the River Mountains map area are evenly distributed with no significant spatial clustering. Descriptions of faults cutting late Pliocene(?) to Quaternary sediments in the River Mountains and Frenchman Mountain study areas are reserved for the “Pliocene(?) - Quaternary Faults” section below.

Based on their strike orientations, conjugate faults are grouped into four sets. These include: (I) NW-, (II) NE-, (III) N-, and (IV) E-W-striking sets. Set I contains 54 faults, set II contains 32 faults, set III contains 32 faults, and set IV has 3 faults (Appendix C). Spread in the strike populations of the first three conjugate sets is given by a standard deviation value (σ). When σ ≤ 10°, the fault population is
considered to be tightly clustered. When $30^\circ > \sigma > 10^\circ$, the fault population is considered to be moderately clustered.

Sinuosity of the mapped River Mountain faults (Fig. 6a; Plate 1; Appendix C) reflects the structural integrity and the strain heterogeneities of the faulted rocks. In addition the processes of fault growth via propagation and linkage can be understood (Chapter 6). Its value is the ratio of the measured fault trace length to that of the shortest path from endpoint A to endpoint B (fault length) and can be expressed by the equation

$$\text{Sinuosity} = \frac{\text{Fault Trace Length}}{\text{Fault Length}}.$$ (5.1)

The mapped traces of most conjugate faults are linear to slightly sinuous with a median sinuosity value of 1.0 to 1.03 (Appendix C). Rarely do the high-angle faults have sinuosity values greater than 1.11. A fault’s sinuosity may reflect strain-field variations and is discussed further in Chapter 6.

**Set I: NW-striking Faults**

The 54 faults composing set I strike between 267° and 348° and are moderately clustered about a mean of 320 ± 20° (Appendix C). One fault (fault I-107; Plate 5; Appendix C) has a strike differing from the mean by more than 2σ and is considered an outlier. Fault trace lengths vary between 78 m (fault I-94; Plate 5; Appendix C) and 4560 m (fault I-116; Plate 5; Appendix C) about a mean of 1000 ± 1000 m (Fig. 14; Appendix C). Fault trace lengths of this set clearly do not form a normal distribution as a few longer faults skew the population to the right (Appendix C).

Of the 54 NW-striking faults in set I, 44 faults record 47 measured slip senses (Appendix C). Of the 47 slip-senses known from slickenlines, Reidel shears, and
offset units, three (6%) are sinistral, two (4%) are oblique-sinistral, 30 (64%) are
normal, five (11%) are oblique-dextral, and seven (15%) are dextral (Appendix C).
Slip orientations for three additional faults are deduced from known slip senses on
neighboring faults with similar orientations and geometries. These include two
strike-slip faults and one oblique-slip fault. Seven other faults showed no kinematic
data (Appendix C).

*Set II: NE-striking Faults*

The 32 conjugate faults of a second set strike between 010° and 080° about a
mean of 40 ± 20° (Appendix C). No faults in this set lay beyond 2σ from the mean.
Fault trace lengths of this set vary between 84 m (fault II-13; Plate 5; Appendix C)
and 1608 m (fault II-77; Plate 5; Appendix C) with a mean of 400 ± 300 m (Fig. 14;
Appendix C).

Twenty-four slip-senses are recorded on 23 faults. Of these, one (4.0%) is
sinistral, eight (33.0%) are oblique-sinistral, and 15 (63.0%) are normal (Appendix
C). Kinematic data on the nine other faults are insufficient to accurately know their
slip senses. However, slip orientations may be inferred for five faults from
neighboring faults' sense of slip. These include two strike-slip faults and three
oblique-slip faults (Appendix C).

*Set III: N-striking Faults*

Thirty-two faults of set III strike between 328° and 016° about a mean of 360 ±
10° (Appendix C). Fault III-59 (Appendix C) strikes 328° and is an outlier. Fault
trace lengths of this set vary between 66 m (fault III-11; Plate 5; Appendix C) and
2064 m (fault III-57; Plate 5; Appendix C) about a mean of 400 ± 400 m (Fig. 14;
Appendix C). The population of N-striking faults is skewed to the right towards longer fault trace lengths (Fig. 14).

Twenty-six senses-of-slip are recorded on 23 faults. One fault contains normal and oblique-sinistral slip directions (fault III-58; Plate 5; Appendix C) and a second fault displays normal, oblique-dextral, and dextral offset (fault III-59; Plate 5; Appendix C). Faults with multiple slip histories contain overprinted slickenlines with different trends and/or different rakes on various parts of the fault. Of the 26 separate slip-senses, one (4 %) is sinistral, five (19 %) are oblique-sinistral, 17 (65 %) are normal, two (8 %) are oblique-dextral, and one (4 %) is dextral. Nine other faults lacked direct kinematic data (e.g., slickenlines and Reidel shears) and their slip orientations were inferred to be six strike-slip and two normal-slip from known kinematic information on neighboring faults of similar orientation and geometry (Appendix C). The slip orientation of one fault (fault III-114; Plate 5; Appendix C) was indeterminable.

Set IV: E-W-striking Faults

Three faults strike between 089° and 099° (Appendix C). Four senses-of-slip are recorded, including one fault (fault 4-42) displaying sinistral and normal displacement, and another fault (fault IV-106) recording normal and oblique offset (Plate 5; Appendix C). Of the four slip values, one (25 %) is sinistral, one (25 %) is oblique-sinistral, and two (50 %) are normal (Appendix C).
Orthorhombic Faults

One-hundred and nineteen orthorhombic faults cut the 13.5 Ma volcanic rocks of the River Mountains and the 12-10.6 Ma Red Sandstone Unit (Fig. 6a; Plate 1). Orthorhombic faults are covered by and do not cut late-Pliocene(?)-Quaternary fanglomerates (Fig. 6; Plate 1). An orthorhombic fault is counted as a single fault if it is continuously exposed or is intermittently exposed with identical outcrop geometries between areas of alluvial covering. Orthorhombic faults in the River Mountains map area are not evenly distributed and spatially cluster along the northwest flank of the range and to the west of the Interior Valley (Fig. 6b; Plates 1 and 5).

For clarity in proceeding sections, a brief introduction to the terminology used here to describe the hierarchal arrangement of orthorhombic faults is warranted. This terminology is an adaptation from earlier studies of orthorhombic faulting (Reches, 1983; Reches and Dieterich, 1983) and differs slightly from the terminology used to describe conjugate faults. From the broadest category down, orthorhombic faults are categorized first into zones, then groups, and finally sets. An orthorhombic zone describes the overall configuration of two or more groups whose unique arrangement form the five, spatially-distinct orthorhombic patterns visible in the River Mountains map area (Figs. 13b1 and 5b; Plates 1 and 5). An orthorhombic zone is thus composed of at least two different groups of similarly striking faults, irrespective of dip direction. Faults within a particular group with similar strike that contain antithetic dip directions are placed into two separate sets. A group may not contain more than two sets. If only one dip direction exists, then that group contains one
polygonal set. Faults with dip magnitudes near 90° can be approximated by either of two sets within a group.

Orthorhombic faults, as labeled here, are first identified by the alphabetical letter A-E corresponding to the zone, A-E, which contains them (Fig. 6b; Plate 5). Groups are designated by an Arabic number. Sets are designated by a Roman numeral. Individual faults are then referenced numerically by an italicized number following a dash. For example, an A₃-8 designation would refer to orthorhombic fault number eight of group 3, zone A.

This hierarchical arrangement also allows for the proper analysis of strain via the odd-axis model technique (see Chapters 4 and 6) in addition to investigating correlations between strain efficiencies and fault trace lengths of fault populations (e.g., groups and sets) within these zones.

Orthorhombic zones are readily distinguishable from one another in the River Mountains map area based on the geometric properties and cross-cutting relations in map view (Fig. 6b; Plates 1 and 5). A detailed description of the geometric properties and patterns of orthorhombic zones A-E is found in the following pages of this chapter.

Slip senses for most orthorhombic faults are accurately known based on measurements of offset units, slickenlines, and Riedel shears present in the River Mountains map area (Fig. 6; Plates 1 and 5).

A group’s clustering, given by the standard deviation value, follows the same criteria as the conjugate faults. When σ ≤ 10°, the orthorhombic fault population is
considered to be tightly clustered. When $30^\circ > \sigma > 10^\circ$, the orthorhombic fault population is considered to be moderately clustered.

**Zone A Orthorhombic Faults**

Twenty-two polygonal faults from two groups are contained in Zone A (Fig. 6b; Plate 5). One set strikes NNE and intersects two NW-striking sets in a 60-120$^\circ$ diamond-like pattern.

Group A$_1$ consists of nine faults striking between $012^\circ$ and $047^\circ$ about a mean of $30 \pm 10^\circ$ with a NW dip direction (Appendix C). An antithetic set is not present, thus only polygonal faults from set A$_1$I are included in group A$_1$ (Appendix C). Fault trace lengths for this group vary from 156 m to 1200 m about a mean of $400 \pm 300$ m (Fig. 15; Appendix C).

Each of the nine faults contains one slip sense indicator (Appendix C). Of these, six (67%) are sinistral, and three (33%) are oblique-dextral (Appendix C).

Group A$_2$ consists of 13 faults striking between $284^\circ$ and $344^\circ$ about a mean of $310 \pm 20^\circ$ (Appendix C). Of these faults, nine dip to the SW and comprise polygonal set A$_2$I. The additional four faults dip NE and are defined as polygonal set A$_2$III. Fault trace lengths for this group vary from 90 m to 1440 m about a mean of $400 \pm 400$ m (Fig. 15; Appendix C).

Kinematic values were measured directly on 13 faults and each fault has one slip sense. Of these 13 kinematic values, four (31%) are oblique-sinistral, three (23%) are normal, and six (46%) are oblique-dextral (Appendix C). Slip senses do not show strong correlation with polygonal sets (Appendix C).
Cross-cutting relations suggest Zone A polygonal faults are younger than Zone B faults because NW-striking faults of sets A_2II and A_2III terminate against and transfer slip onto ENE-striking faults of Zone B. In this case, a fault that terminates at another fault, and is not repeated across it, transfers its slip onto the terminating fault. Thus, the second fault in this example is older (e.g., Zone B orthorhombic faults).

**Zone B Orthorhombic Faults**

Forty-two polygonal faults from three groups compose Zone B (Fig. 6b; Plate 5). One group of faults (group B_1) strikes E-W, another (group B_2) strikes NE, and a third (group B_3) strikes NW. Zone B polygonal faults cut 13.5 Ma volcanic rocks of the River Mountains but are not exposed cutting 12-10.6 Ma rocks of the Red Sandstone Unit due to a lack of occurrence near the younger unit (Plate 5).

Group B_1 contains 10 faults that strike between 080° and 102° about a mean of 090 ± 7° (Appendix C). Three dip south and six dip north, belonging to sets B_1I and B_1II, respectively (Appendix C). The tenth fault (B_1-20; Plate 5; Appendix C) dips 90° and belongs to both sets equally. Fault trace lengths for this group vary from 60 m to 840 m about a mean of 300 ± 200 m (Fig. 15; Appendix C).

Seven kinematic values were determined for these ten faults though direct field measurements. Of these known values, one (14 %) is sinistral, three (43 %) are oblique-sinistral, and three (43 %) are normal (Appendix C). Three faults produced no kinematic data and are deduced to have oblique slip from neighboring faults with similar strikes and dips (Plate 5; Appendix C).

Group B_2 contains 15 faults striking between 005° and 073° about a mean of 040 ± 20° (Appendix C). Of these, four faults dip to the SE and comprise polygonal set
B_2III and five dip to the NW and belong to polygonal set B_2IV. Six additional faults dip 90° and are assigned to both sets B_2III and B_2IV. Fault trace lengths for this group vary from 60 m to 960 m about a mean of 300 ± 300 m (Fig. 15; Appendix C).

Thirteen kinematic values were measured on 11 faults with one fault (B2-38) containing sinistral, oblique-sinistral, and normal slip senses (Plate 5; Appendix C). Of these 13 values, two (15 %) are sinistral, one (8 %) is oblique-sinistral, seven (54 %) are normal, and three (23 %) are oblique-dextral (Plate 5; Appendix C).

Polygonal sets B_2I-III do not display recognizable slip patterns, however, sets B_2IV-VI contain mostly normal offset (Plate 5; Appendix C). One fault (fault B2-25; Plate 5; Appendix C) was determined to have oblique slip based on slip senses of neighboring faults with similar strikes and dips. Three faults lack kinematic data entirely and slip sense could not be estimated from neighboring faults.

Group B_3 consists of 17 faults striking between 282° and 349° about a mean of 320 ± 20° (Appendix C). Of these faults, 12 dip NE and comprise polygonal set B_3V, four dip to the SW and form set B_3VI. An additional fault dips 90° and belongs to both sets B_3V and B_3VI. Fault trace lengths for this group vary from 60 m to 1548 m about a mean of 400 ± 400 m (Fig. 15; Appendix C).

Fourteen kinematic values were measured on 13 faults. One fault (B3-2; Plate 5; Appendix C) displays an oblique-dextral and a normal slip sense. Of these 14 values, 11 (79 %) are normal and three (21 %) are oblique-dextral. Two faults (B_3-32 and B_3-18; Plate 5; Appendix C) were determined to have oblique slip from neighboring faults with similar strikes and dips, but exact slip sense was not determinable. Two
faults (B3-15 and B3-10; Plate 5; Appendix C) lack kinematic data entirely and
kinematics could not be estimated from neighboring faults.

**Zone C Orthorhombic Faults**

Twenty-two polygonal faults from two groups are contained in Zone C (Fig. 6b;
Plate 5). One group of faults (group C1) strikes NE and the other (group C2) strikes
NW. Zone C polygonal faults cut the 13.5 Ma volcanic rocks of the River Mountains
and the tuffaceous rocks of the Three Kids Mine, but do not occur near the 12-10.6
Ma Red Sandstone Unit.

Group C1 consists of 10 faults striking between 001° and 066° about a mean of
020 ± 20° (Appendix C). These faults dip both westerly (set C1I) and easterly (set
C1II). Fault trace lengths for this group vary from 120 m to 1140 m about a mean of
500 ± 300 m (Fig. 15; Appendix C).

Nine kinematic values were determined for the 10 faults through direct field
measurements of slickenlines, Reidel shears, and offset units. Of these known values,
four (45 %) are sinistral, one (11 %) is oblique-sinistral, three (33 %) are normal, and
one (11 %) is oblique-dextral (Appendix C). The style of faulting on the tenth (fault
C1-14) is indeterminable due to a lack of neighboring faults with similar geometries
and kinematic measurements.

Group C2 contains nine faults striking between 287° and 345° about a mean of
300 ± 20° (Appendix C). Of these faults, four faults dip to the NE and comprise
polygonal set C2III, two dip to the SW and belong to set C2IV, and three additional
faults dip 90° and can be treated as equally both sets C2III and C2IV. Fault trace
lengths for this group vary from 84 m to 900 m about a mean of 400 ± 300 m (Fig. 15; Appendix C).

A total of 10 kinematic values were recorded for the nine faults with one containing both a normal and sinistral slip sense (fault C2-18; Plate 5; Appendix C). Of these 10 kinematic values, five (50 %) are sinistral, one (10 %) is oblique-sinistral, and four (40 %) are normal (Appendix C).

**Zone D Orthorhombic Faults**

Nineteen polygonal faults from three groups are contained in Zone D (Fig. 6b; Plate 5). Group D1 faults strike NW, group D2 faults strike ENE, and a third group strikes NNE. Zone D polygonal faults cut the 13.5 Ma volcanic rocks of the River Mountains but are not exposed near the 12-10.6 Ma Red Sandstone Unit (Plate 5).

Group D1 consists of 10 faults striking between 318° and 355° about a mean of 340 ± 10° (Appendix C) with NE and SW dip directions of sets D1I and D1II, respectively (Appendix C). Fault trace lengths for this group vary from 318 m to 355 m about a mean of 340 ± 10 m (Fig. 15; Appendix C).

One sense of slip was determined for each of the 10 faults through direct field measurements of slickenlines, grooves and mullions, Reidel shears, and offset units. Of these kinematic styles, one (10 %) is oblique-sinistral, eight (80 %) are normal, and one (10 %) is oblique-dextral (Appendix C).

Group D2 contains four faults striking between 057° and 075° about a mean of 068 ± 8° (Appendix C). Two of these faults dip to the N and belong to polygonal set D2III, two more dip to the S and belong to set D2IV. Fault trace lengths for this group vary from 132 m to 756 m about a mean of 400 ± 300 m (Fig. 15; Appendix C).
The four faults in this group have normal offset based on slickenlines and Riedel shears. None of these faults display multiple rakes.

Group D₃ consists of five faults striking between 006° and 047° about a mean of 030 ± 20° (Appendix C). One fault dips to the NE and forms polygonal set D₃V, one fault dips to the SW and belongs to set D₃VI. Three additional faults dip 90° and belong equally to both sets. Fault trace lengths for this group vary from 132 m to 324 m about a mean of 230 ± 70 m (Fig. 15; Appendix C).

Eight rakes were measured on the five faults with one containing sinistral, oblique-sinistral, and oblique-dextral kinematic indicators (fault D₃-19; Plate 5; Appendix C), and a second fault displaying normal and strike-slip rakes (fault D₃-10; Plate 5; Appendix C). Seven of these rakes demonstrate the sense of slip of the faults. Of these, one (14 %) is sinistral, one (14 %) is oblique-sinistral, three (43 %) are normal, and two (29 %) are oblique-dextral (Appendix C).

Zone E Orthorhombic Faults

Fourteen polygonal faults from three groups comprise Zone E (Fig. 6b; Plate 5). Group E₁ faults strike NNE, group E₂ faults strike WNW, and group E₃ faults strike NW. Zone E polygonal faults mostly cut the 13.5 Ma volcanic rocks of the River Mountains and the tuffaceous rocks of the Three Kids Mine, in addition to locally cutting the 12-10.6 Ma Red Sandstone Unit (Fig. 6b; Plates 1 and 5).

Group E₁ consists of six faults striking between 006° and 026° about a mean of 016 ± 7° with westerly and easterly dip directions of sets E₁I and E₂II, respectively. Fault trace lengths for this group vary from 192 m to 912 m about a mean of 500 ± 300 m (Fig. 15; Appendix C).
Each fault contains one sense of slip that was determined though direct field measurements of slickenlines, grooves and mullions, Reidel shears, or offset markers. Of the six kinematic values, three (50%) are sinistral, one (17%) is oblique-sinistral, and two (33%) are normal (Appendix C).

Group E₂ contains six faults striking between 281° and 321° about a mean of 290 ± 10° (Appendix C). Of these, four faults dip to the south and comprise polygonal set E₂III, two dip to the north and belong to set E₂IV. Fault trace lengths for this group vary from 84 m to 924 m about a mean of 400 ± 400 m (Fig. 15; Appendix C).

Five of the six faults show normal offset with the sixth having oblique slip. It is not possible to determine whether the oblique component of the sixth fault is sinistral or dextral based on present exposure.

Group E₃ contains two faults striking 331° and 342° with vertical dips (Appendix C). The faults in this group belong to polygonal set E₃V. Both faults display normal offset. Fault trace lengths for this group vary from 420 m to 1140 m about a mean of 800 ± 500 m (Fig. 15; Appendix C).

**Map Scale Folds**

The 12-10.6 Ma Red Sandstone Unit and older rocks are deformed into gentle, class 1 folds with planar limbs and interlimb angles between 170° to 90° (Plates 1 and 3).

Generally, folds in the Red Sandstone Unit are localized and lie close to neighboring faults. Of the approximately 15 folds documented in the Red Sandstone Unit, two are oriented perpendicular to, 11 lie parallel to, and two are oblique to
neighboring faults (Table 6.4; Fig. 6a; Plate 1). Measured fold lengths range from 192 m (fold /70; Plate 1) to 1,392 m (fold /3; Plate 1) with a median axial trace length of 348 m. Folds are present primarily in the hangingwall blocks. However, a syncline (fold /8; Plate 1) in the northern Interior Valley folds a high-angle fault that cuts the Red Sandstone Unit.

**Pliocene(?) – Quaternary Faults**

Faults that cut Pliocene and Pleistocene sediments occur in the Frenchman Mountain map area and in the northwestern River Mountains east of Ithaca Avenue (Figs. 2, 6a, and 7; Plates 1 and 2).

**Ithaca Avenue Fault**

Two strands of the IAF cut a late Pliocene(?) to early Quaternary fanglomerate along the northwestern flank of the River Mountains east of Ithaca Avenue (T 21 S, R 63 E, section 3) (Fig. 6a; Plate 1). Both strands strike 335-340° and dip 70° W (Fig. 6a; Plate 1).

The IAF is recognized by the presence of disturbed bedding in the Red Sandstone Unit in a small wash where the two strands bifurcate and by the presence of offset pediment surfaces on the late Pliocene(?)-Quaternary fanglomerate (Fig. 6a; Plate 1). To the south, the joined strands are covered by modern alluvial and colluvial sediments at the base of the mountain front (Fig. 6a; Plate 1). Minor, poorly exposed scarps in young sediments are present along the western mountain front south of the Interior Valley drainage at the River Mountains Water Treatment Facility (C.M. dePolo, 2006 personal communication; D.B. Slemmons, 2006 personal communication).
communication). Drainages along the presumed trace of the IAF display multiple stream terraces and beheaded drainages. In addition, the mountain front is linear and strongly beveled in profile with prominent 10-20 meter-high ledges at the base locally (D.B. Slemmons, 2006 personal communication). To the north, the strands appear to die out and/or are obscured on the surface by human activity resulting from the construction of high-tension power lines and a bike path. The presence of faulted Quaternary sediments exposed in a trench north of the Las Vegas Wash (W.J. Taylor, 2006 personal communication), however, suggests that the IAF indeed cuts the immediate subsurface to the north through the Las Vegas Wash on the west side of Calico Hills, and may join the Frenchman Mountain Fault under the Sunrise Landfill (Fig. 2).

East of Ithaca Avenue, the western strand is the more prominent one and can be traced for nearly 900 m from the mountain front (Fig. 6a; Plate 1). A topographic profile measured along a ridge in a Quaternary fanglomerate indicates an 8.4 m vertical offset (Fig. 8) of the fan surface (Fig. 6a; Plate 1). The throw was measured by: (1) determining the far-field slopes of the current fan surface, which are presumed to be that of the pre-faulted surface; (2) drawing a best fit line through the far-field slopes; and (3) measuring the vertical offset ($\Delta y$) at any point ($x$) on the graph (Chapter 3; Pinter, 1996).

The eastern strand is 650 m long, is less sinuous, and has a smaller vertical offset value of 1-2 m (Fig. 6a; Plate 1). Because the scarp-face and footwall are badly eroded, a profile was not measured.

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Frenchman Mountain Faults

Eight fault scarps offset young alluvial and lacustrine sediments on the west flank of Frenchman Mountain east of Hollywood Boulevard, south of Owens Road, and north of the Sunrise Landfill (36° 10' 0" - 36° 08' 0" N, 115° 00' 0" - 115° 00' 0" W) (Fig. 7; Plate 2).

In this area, the main range-bounding fault, the Frenchman Mountain Fault (FMF), is curvilinear and is composed of two geometric segments based on strike and dip-magnitude variations (this study) (Figs. 2 and 7). The main strand of the FMF is mapped continuously for over 3 km from north to south as it passes through the map area. Geomorphic features such as 10-15 meter-high, hanging stream channels and dry waterfalls in the limestone footwall, suggest recent offset is significant. However, exact magnitudes of Quaternary displacement are not known due to a lack of appropriate piercing points or offset marker beds on both hangingwall and footwall blocks.

The southernmost geometric segment in the study area is 2.3 km long, moderately sinuous, and concave to the west (Fig. 7; Plate 2). Field measurements and 3-point calculations (Fig. 12) indicate a fault orientation of 347°, 70° W along a 1.5 km trace just north of the landfill (Fig. 7; Plate 2). A northern bend in this segment has a strike and dip of 310°, 70° W, and an 800 m scarp length. Fault exposure is continuous along both strikes of the southern geometric segment.

The northern geometric segment is distinguishable from the former by a marked change in both strike and dip of the fault plane. This ~700 m long segment has an average strike and dip of 005°, 40° W (Figs. 2 and 7; Plate 2).
Immediately south of Frenchman Mine (Fig. 7; Plate 2) are localized outcrops of a late Pliocene(?) and Pleistocene (Matti et al., 1993) lacustrine rocks capped by a well-indurated, course conglomerate (Fig. 7; Plate 2).

A two-meter wide, one-half meter deep trough parallels the top of the main FMF strand and appears to represent lateral stream flow prior to modern arroyo incision. A fault-generated hangingwall graben is also possible but no antithetic faults were visible in modern arroyos.

A second strand on the southern segment of the FMF steps basinward 20-50 m and places the Pliocene-Pleistocene units against Quaternary fanglomerates (Fig. 7; Plate 2). This strand closely mimics the westward convexity of the main FMF strand and dips 80°W where present in an excavation on the bank of a deep arroyo. A measured scarp profile indicates a minimum of 12.9 m of vertical offset because the original hanging wall surface is beneath the modern alluvial surface (Fig. 9). Small exposures of the lacustrine and conglomerate units occur locally downstream along the bottoms of the active wash banks and suggest a maximum vertical offset of the lacustrine-conglomerate interface of 15-20 m.

The excavated stream bank exposure measures 1.5 m wide, 0.25 m deep, and 10 m high and revealed three colluvial wedges in the top meter of the hanging wall (Fig. 16; Plate 4). Wedge heights of 0.4 m, 0.5 m, and 1.2 m, from top to bottom, were measured (Plate 4).

Soil samples were twice collected from wedges two and three and shipped to the Paleo Research Institution™ lab for AMS ¹⁴C dating and pollen analysis. The duplicity was necessary because the first shipment contained too little carbon for
analyze. However, a larger second sample proved equally ineffective. It was determined that the colluvial wedges themselves did not contain appropriate-sized carbon fragments and no soil dates were determinable (Paleo Research Institution™, 2006 written communication).

Three, west-dipping strands of the FMF are exposed 800 m west of the trench site. These strands strike more N-S and appear to project north into the northern segment north of Charleston Boulevard and the gravel prospects. Collective offset magnitude on the three strands is approximately 2-3 m. Dip magnitudes are not known for these three faults due to poor exposure.
CHAPTER 6

STRUCTURAL AND TECTONIC INTERPRETATIONS

Timing of Extension

Two periods of extension are distinguishable in the River Mountains. The first stage is bracketed between 13.5 and ~9 Ma. Bohannon (1984) and Beard (1996) showed that extension in the Lake Mead tectonic domain initiated at ~16 Ma, and continued uninterrupted through at least 10 Ma. However, because exposures of 16-14 Ma strata are spatially limited in the study area (Fig. 6a; Plate 1), and the 13.5 Ma volcanic rocks of the River Mountains provide a blank slate for subsequent faulting, this thesis “brackets” the initiation of extension at 13.5 Ma for purposes of describing strain. Termination of extension in the River Mountains at 9 Ma is loosely suggested by (1) the presence of faulted and tilted 10-8.5 Ma Callville Mesa basalt on northwest Lake Mead, (2) the largely flat-lying and un-faulted 10(?)-6 Ma Muddy Creek Formation and 5.88 Ma Fortification Hill basalt (Damon et al., 1978; Bohannon, 1984) to the east of the River Mountains and (3) documented cessation of major extension in the northern Death Valley region at ~9 Ma (Snow and Wernicke, 2000). In addition, the earliest Muddy Creek Formation deposits are poorly dated (Bohannon, 1984) and may in fact be better interpreted as Red Sandstone Unit (S. Beard, 2006 personal communication). A cessation age of 9 Ma for the first extensional event is viewed as the most appropriate estimate in this thesis. The
second period is late Pliocene(?) to Holocene as expressed by the active IAF (Fig. 6a; Plate 1), strands of the active FMF, and numerous faults in the CBR (Fig. 2).

Evidence for the SID

This existence of a LANF beneath the River Mountains is speculative but required. Although a classic metamorphic core complex (e.g., Lister and Davis, 1989) is not exposed between the River Mountains and the Wilson Ridge Pluton (Fig. 1), two lines of evidence suggest its presence. First, ductilely deformed amphibolites crop out locally on Saddle Island and record a top to the west slip sense (Duebendorfer et al., 1990) of an upper plate. Second, similar geochemistries where shown to exist between the River Mountains volcanic units and the intrusive rocks of the Wilson Ridge Pluton.

Additional evidence for the existence of the SID beneath the River Mountains was collected through this study and includes the presence of: (1) numerous conjugate high-angle normal faults with limited spatial extent and minimal offset (Plate 1; Appendix C), and (2) orthorhombic faults. The conjugate high-angle normal faults accommodate vertical shear in the upper plate of a LANF and these typically show small offsets because most strain is localized on the detachment surface. Orthorhombic faults indicate the presence of tri-axial strain and may be a consequence of a corrugated detachment (Fig. 17).
Strain Patterns

As mentioned above, the two extensional periods affecting the River Mountains include (1) 13.5-9 Ma. and (2) Pliocene(?)-Quaternary events. The earliest of these faulting events involves both triaxial (3-D) and plane (2-D) strain. The younger period, presumed to post-date deposition of the Red Sandstone Unit, involves entirely plane-strain faulting.

Orthorhombic Faults

*Principal Strain Axes*

Application of Reches’ 3-D faulting principles (1983a & b) and Krantz’s Odd-Axis model (1988, 1989) to orthorhombic fault zones A-D (Chapter 3) reveals the three principle strain axes during mid-Miocene extension (Table 6.1). Zone E faults do not have sufficient kinematic data to test these ideas and no statistical analysis was performed on them.

Triaxial strain in an upper plate is a consequence of irregularities on the detachment at depth (Fig. 17). These irregularities, or corrugations, may form through the incisement of new detachments into the footwall to maintain an optimum fault orientation (Fig. 17a). The corrugation formed in this fashion will expand in the transport direction of the upper plate, creating a void space that must be accommodated through orthorhombic faulting (Fig. 17b). If the transport direction of the upper plate changes, new corrugations oriented parallel to the slip direction would form, imparting a second generation of orthorhombic faults.
Table 6.1. Plunge and trend orientations (eigenvectors, $\varepsilon$) of the principal strain axes for orthorhombic zones A, B, C, and D. $\varepsilon_1$ is the maximum shortening axis, $\varepsilon_2$ is an intermediate strain axis, and $\varepsilon_3$ is the maximum elongation axis.

<table>
<thead>
<tr>
<th>Zone</th>
<th>$\varepsilon_1$</th>
<th>$\varepsilon_2$</th>
<th>$\varepsilon_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23°, 039°</td>
<td>17°, 300°</td>
<td>60°, 117°</td>
</tr>
<tr>
<td>B</td>
<td>86°, 320°</td>
<td>4°, 145°</td>
<td>0°, 056°</td>
</tr>
<tr>
<td>C</td>
<td>49°, 067°</td>
<td>28°, 298°</td>
<td>27°, 193°</td>
</tr>
<tr>
<td>D</td>
<td>50°, 055°</td>
<td>10°, 157°</td>
<td>38°, 256°</td>
</tr>
</tbody>
</table>

The four orthorhombic zones A-D have dissimilar principal strain axes orientations. The uniqueness of each zone may be a consequence of either: (1) two differently oriented corrugations on the SID (Fig. 18a), (2) one corrugation on the SID producing dissimilar fault zones (Fig. 18b), or (3) one corrugation with subsequent tilting and/or vertical axis rotation during continued extension (Fig. 19). Hypothesis three allows for the possibility of conjugate slip during or post-dating an initial period of orthorhombic faulting.

Triaxial strain fields may develop orthorhombic fault sets in the upper plates (e.g., River Mountains) of LANFs (e.g., SID) where irregularities in the shape of the detachment exist. The idea that multiple corrugations (Fig. 18a) existed on the SID fault during 13.5-9 Ma extension is considered here to be the most robust explanation of the observed strain field patterns. An older corrugation would be oriented NE-SW and be cut by a corrugation that widens to the NW (Fig. 18a). This seems reasonable because zone A faults terminate against and transfer strain onto zone B faults (Fig. 6b, Plate 1), indicating that zone B formed over an older SID corrugation that opened.
to the SW before later passing over a second corrugation (Fig. 18a). This second
corrugation would presumably form zone A orthorhombic faults.

Intuitively, it is expected for the younger strain field to skew or overprint
kinematic indicators observed on older orthorhombic faults (e.g., zone B) making
determinations of any earlier strain field less reliable. In this study, however, it is still
possible to differentiate the two orthorhombic faulting events based on the distinct
geometries and cross-cutting relations of faults (Plate 5). Thus, the resolved strain
field for the older zone B is interpreted as a hybrid of all proceeding events.

Another possibility is that one corrugation on the SID fault (Fig. 18b) produced
orthorhombic fault zones A-E. In this case, dissimilarities between fault zones A-E
are coincidental and are attributed to pre-existing fault structures separating the five
zones. It is possible that such faults acted as strain boundaries, allowing somewhat
different strain conditions to coexist simultaneously above a single corrugation (Fig.
18b). Though this may be considered the least likely explanation, it cannot be ruled
out due to (1) poor age constraints on the spatially surrounding conjugate faults and
(2) uncertainties of the magnitudes of the principal strain directions of orthorhombic
faults.

A third possibility is that a single corrugation on the SID detachment faulted
zones A-E in an identical fashion (Fig. 18a), but subsequent tilting and/or vertical
axis rotation during continued extensional locally altered some fault orientations
(efficiencies) with respect to regional strain field (Fig. 19). In one variation of this
model, a suite of orthorhombic faults that formed over an initial corrugation is
fragmented away from the other by a through-going fault and preferentially tilted
about a horizontal axis as it travels over a ramp in the detachment (Fig. 19a). Along strike variations in the detachment ramp geometry would exacerbate this partitioning of local strain. A similar condition may result if the corrugation changes width suddenly.

Three independent lines of evidence suggest that this third hypothesis cannot be the most probable solution. Both earlier 1:24,000 scale mapping (Bell and Smith, 1980) and new 1:12,000 scale mapping (this study) indicate relatively uniform, northwest tilting of the 13.5 Ma volcanic rocks along northwestern flank of the River Mountains. Thus for hypothesis three to have merit, the blocks cut by the orthorhombic faults in zones A, B, C, and E, would show different magnitudes of tilting and/or rotation during or following triaxial strain. It also seems unlikely that simultaneous tilting and/or rotation of zones A and C or B and D, could occur without tilting and/or rotating the intervening zone B or A, respectively.

Because the five orthorhombic zones have unique numbers of fault sets, fault geometries, and cross-cutting relationships, the best explanation for the formation of these zones is that they formed under unique strain conditions (Fig. 18a). Thus, the first hypothesis is preferred.

However, should my hypothesis be incorrect, and tilting and/or vertical axis rotation of the orthorhombic zones does play a significant role in perturbing the local strain field, then the most likely candidates are the NW-striking conjugate faults. This interpretation is based on the observation that the five orthorhombic zones are elongated roughly NNW to NW (Plate 5) and that bounding structures (i.e. NW-striking conjugate faults) controlling local strain perturbations strike NW as well.
Strain Distribution

Many faults within the five orthorhombic zones contain multiple rake orientations (Fig. 6b; Plates 1 and 5), which is indicative of 3-D strain as described in Reches’ (1983a & b) and Krantz’s (1988, 1989) orthorhombic fault models. As interpreted in the above section, multiple slickenline orientations on these faults could indicate (1) changing strain fields with time (regional or local) (Figs. 18 and 20), (2) altered efficiencies for the whole zone or some of the orthorhombic sets through tilting and/or vertical axis rotation (Fig. 19) as previously described, or (3) a combination of the two.

Although Reches (1983) and Reches and Dieterich (1983) documented multiple slickenline rakes in each of their samples, it was determined that the efficiency of a particular orthorhombic set should not change unless the system is perturbed. Because the results of applying the odd-axis model to the River Mountains orthorhombic faults suggest such a heterogeneous three-dimensional strain field, caution is exercised when interpreting any specific trends. Thus the distribution of strain, as determined for orthorhombic zones A, B, C, and D, should more appropriately be interpreted as the average of two or more superimposed faulting events with varying orientations in response to varying strain magnitudes on the LVVSZ and LMFS (this study). In other words, the NE-SW oriented corrugation was active when the SID was transferring strain onto the LMFS and when the NNW-SSE corrugation was active, the SID transferred strain onto the LVVSZ.
Conjugate Faults

*Principle Strain Axes*

A linked Bingham distribution describes the unweighted moment tensor sum of the P (compression) and T (tension) axes and includes the orientations (eigenvectors) and relative magnitudes (eigenvalues) of the three principal strain axes for individual measured fault segments (Table 6.2a) and for faults with calculated orientations (Table 6.2b). Ten stereonet plots compare and contrast these strain axes for the conjugate faults (Figs. 10 and 11). A brief description and justification of the procedures used were presented in Chapter 3.

Table 6.2a. Orientations (eigenvectors, $\varepsilon$) and magnitudes (eigenvalues, EV) of the principal strain axes on all measured conjugate fault segments and their corresponding sets (I-IV).

<table>
<thead>
<tr>
<th>Set #</th>
<th>$\varepsilon_1$</th>
<th>$\varepsilon_2$</th>
<th>$\varepsilon_3$</th>
<th>EV$_1$</th>
<th>EV$_2$</th>
<th>EV$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL</td>
<td>84°, 253°</td>
<td>0°, 347°</td>
<td>6°, 077°</td>
<td>-0.23</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>I NW-striking</td>
<td>79°, 284°</td>
<td>8°, 144°</td>
<td>7°, 053°</td>
<td>-0.25</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>II NE-striking</td>
<td>77°, 191°</td>
<td>12°, 024°</td>
<td>3°, 293°</td>
<td>-0.25</td>
<td>-0.04</td>
<td>0.29</td>
</tr>
<tr>
<td>III N-striking</td>
<td>84°, 008°</td>
<td>6°, 165°</td>
<td>2°, 255°</td>
<td>-0.22</td>
<td>-0.05</td>
<td>0.27</td>
</tr>
<tr>
<td>IV E-W-striking</td>
<td>37°, 229°</td>
<td>53°, 058°</td>
<td>4°, 323°</td>
<td>-0.43</td>
<td>0.04</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Table 6.2b. Orientations (eigenvectors, $\varepsilon$) and magnitudes (eigenvalues, EV) of the principal strain axes on all calculated conjugate fault orientations and their corresponding sets (I-IV).

<table>
<thead>
<tr>
<th>Set #</th>
<th>$\varepsilon_1$</th>
<th>$\varepsilon_2$</th>
<th>$\varepsilon_3$</th>
<th>EV 1</th>
<th>EV 2</th>
<th>EV 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL</td>
<td>87°, 329°</td>
<td>3°, 182°</td>
<td>2°, 092°</td>
<td>-0.22</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>I NW-striking</td>
<td>78°, 314°</td>
<td>11°, 157°</td>
<td>5°, 068°</td>
<td>-0.23</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>II NE-striking</td>
<td>84°, 116°</td>
<td>1°, 217°</td>
<td>6°, 307°</td>
<td>-0.22</td>
<td>-0.03</td>
<td>0.19</td>
</tr>
<tr>
<td>III N-striking</td>
<td>78°, 024°</td>
<td>9°, 162°</td>
<td>8°, 253°</td>
<td>-0.26</td>
<td>-0.01</td>
<td>0.26</td>
</tr>
<tr>
<td>IV E-W-striking</td>
<td>37°, 234°</td>
<td>52°, 063°</td>
<td>5°, 327°</td>
<td>-0.43</td>
<td>0.05</td>
<td>0.38</td>
</tr>
</tbody>
</table>

A comparison of the orientations of the principal strain axes for conjugate faults with calculated orientations to the measured fault segments and their kinematics shows a small clockwise difference of 10-15° in trend and a 0-5° NE plunge difference for the NW- and NE-striking faults. Strain axes plots of the N- and E-W-striking fault sets show little rotation or tilting. Because the majority of the conjugate faults strike NW and NE, the principal strain axes for all the calculated fault orientations have similar differences in trend and plunge compared to the individual measured fault segments.

Another part of the conjugate fault strain tensor is the relative magnitudes of the strain axes. The eigenvalues determined for the NW-striking fault measured segments suggest a lower component of strain along the intermediate axis (9.0% $\varepsilon_2$, Fig. 10) than that determined for calculated fault plane orientations (11.1% $\varepsilon_2$, Fig. 11), although that small difference may not be significant. Interestingly, the intermediate strain for the NE- and N-striking fault measured segments is compressional (6.6% $\varepsilon_2$ and 9.0% $\varepsilon_2$, respectively, Figs. 10 and 11) whereas they are extensional (7.1% $\varepsilon_2$ and 1.1% $\varepsilon_2$, respectively, Figs. 10 and 11) for the calculated
fault orientation. Strain tensors for the four E-W-striking fault measured-segments and faults with calculated orientations are very similar (5.0% $\varepsilon_2$ and 5.6% $\varepsilon_2$, respectively (Figs. 10 and 11), and $\varepsilon_1$ and $\varepsilon_3$ essentially are identical too. Compiled together, the strain tensor for all calculated conjugate faults has a larger intermediate strain component (14.6% $\varepsilon_2$ vs. 10.7% $\varepsilon_2$, Figs. 10 and 11) than that of the individual measured fault segments population.

In summary, the apparent discrepancies among the strain tensors of the measured fault segments and calculated fault orientations are not viewed as significant. Some fault measurements switch sets depending on the orientations used (e.g., calculated versus individual measured segments). Also, calculated fault geometries may differ slightly from measured planes along the same fault because of strike irregularities along a sinuous fault plane. It should also be noted that the uncertainty in calculating the strain axes is not readily quantifiable (e.g., human error in the field, inherent uncertainties associated with rock mechanic assumptions used in all stereonet programs, and error propagation through subsequent analyses), and that an understanding of what trends are significant or not is clouded.

**Strain Distribution**

The presence of 5-15% strain on the intermediate ($\varepsilon_2$) axis of the summed strain tensor is interpreted as the reflection of multiple phases of plane strain extension with alternating orientations from the southwest to the northwest. Reasons for these kinematic changes will be discussed further in following sections of this chapter.

Figures 10 and 11 show that the $\varepsilon_{1,3}$ planes (maximum shortening and extension) are oriented approximately perpendicular to the NW-, N-, and NE-striking conjugate
faults, respectively. These strain plots suggest that the primary kinematic style of the NW-, NE-, and N-striking sets were dip slip. In fact, ~64%, 63%, 65%, and 50% of the slip senses measured on the NW-, NE-, N-, and E-W-striking faults, respectively, are dip slip (Chapter 5, Appendix C). The additional slip senses are interpreted to result from multiple discrete reorientations in the Miocene strain field in the River Mountains that may overprint existing fault sets.

Because the preserved slip senses on both the NE- and NW-striking faults are primarily dip-slip, the idea of synchronous slip transfer among orthogonal faults during extension (e.g., Faulds and Varga, 1998) appears contradictory. Slip transfer would necessitate dip slip on one set of faults and strike slip on an orthogonal fault set during synchronous slip on both sets. However, many faults do terminate against, and are not repeated across other, orthogonally-striking faults (Fig. 6; Plate 1), implying that some amount of slip transfer and/or synchronous faulting occurred. Therefore, it does appear that slip transfer occurs among the more preferentially-oriented fault sets (e.g., NW- and NE-striking faults).

The resolved strain fields of the orthorhombic faults (Table 6.1; Appendix C) and the conjugate faults (Table 6.2a & b; Figs. 10 and 11; Appendix C), do not appear to correlate. This is expected for several reasons. First, the geometric patterns and cross cutting relationships of the exposed orthorhombic faults of zones A-E are different from conjugate faults (Plate 5). Second, the relatively small number of kinematic data per orthorhombic zone, and its limited spatial distribution, increases the likelihood of no correlations among conjugate and orthorhombic sets, including the combined conjugate fault data set. Third, the orthorhombic faults are interpreted to
reflect local stress and strain fields related to corrugations in the SID. The conjugate faults should reflect the regional stress and strain fields at the time that they formed.

Qualification of Fault Data and Interpretations

It is possible to challenge the statistical assertions made in this thesis based on the size of the sample dataset (E.I. Smith, 2007 personal communication). Appendix D discusses the issue of sample size and sample variance’s effect on the estimated population mean in detail.

The variance of a population mean is inversely proportional to the sample size with an asymptotic slope. A sharp change in slope is present at around 20 sample measurements. Above this value, greater sample numbers have less of an effect on population variance (Appendix D). For smaller samples, the effect of sampling bias on a population mean can be estimated through the use of the Student’s t-multiplier (Appendix D).

Because the measured uncertainty of this study is not readably quantifiable (see prior discussions), three hypothetical 1σ uncertainty values of 5°, 10°, and 15° are chosen (Appendix D). Where the uncertainty of the estimated population mean is greater than one-half of the sample variance at the 95% confidence level, the sample data should be viewed with caution. This corresponds to samples with fewer than 20 measurements. For the NW- and N-striking conjugate faults, this is not a problem as the t-multiplier is small.

Another issue to consider is that the real fault population may not be homogeneously distributed across an area outside the western River Mountains study.
area. It is possible that the real fault population is limited spatially and that small sample sizes can still accurately reflect the true fault and strain populations. Because all exposed faults were mapped in great detail, it appears that the sample data is an accurate reflection of the strain data for the true population within the bounds of the western River Mountains study area.

Offset Magnitudes

Orthorhombic and conjugate faults in the River Mountains are reclassified into three qualitative groups based on their inferred offset magnitude potential (Table 6.3). Because accurate stratigraphic markers are lacking in the River Mountains, I interpret a fault’s measured trace length as a first-order approximation of a fault’s potential for slip accommodation. Therefore, assuming all conjugate and orthorhombic faults in the River Mountains have approximately an equal ratio between offset magnitude and fault trace length, a fault can be described as either significant, moderate, or minor. In this thesis, a fault is assumed to accommodate significant slip if its fault trace length exceeds 1 to 2 km, generally. A moderate fault has a measured fault trace length between ~400 and ~1500 m. Fault traces less than ~400 m are assumed to have minor slip potential. This first-order approximation of fault slip magnitude is somewhat subjective for several reasons: (1) fault exposure variability, (2) faults projecting out of the mapped study area, and (3) structural barriers inhibiting fault propagation (e.g., genetically-related accommodation structures). For these two reasons, the conditions for having significant, moderate, or minor slip overlap somewhat.
Table 6.3. Offset magnitudes for conjugate and orthorhombic faults in the River Mountains.

<table>
<thead>
<tr>
<th></th>
<th>% Significant (&gt;50 m)</th>
<th>% Moderate (50≤, ≥10 m)</th>
<th>% Minor (&lt;10 m)</th>
<th># - faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conj. set I NW-striking</td>
<td>11</td>
<td>26</td>
<td>63</td>
<td>54</td>
</tr>
<tr>
<td>Conj. set II NE-striking</td>
<td>3</td>
<td>19</td>
<td>78</td>
<td>32</td>
</tr>
<tr>
<td>Conj. set III N-Striking</td>
<td>5</td>
<td>26</td>
<td>69</td>
<td>32</td>
</tr>
<tr>
<td>Conj. set IV E-W-striking</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>Ortho. zone A</td>
<td>0</td>
<td>14</td>
<td>86</td>
<td>22</td>
</tr>
<tr>
<td>Ortho. zone B</td>
<td>0</td>
<td>14</td>
<td>86</td>
<td>42</td>
</tr>
<tr>
<td>Ortho. zone C</td>
<td>0</td>
<td>21</td>
<td>79</td>
<td>19</td>
</tr>
<tr>
<td>Ortho. zone D</td>
<td>0</td>
<td>21</td>
<td>79</td>
<td>19</td>
</tr>
<tr>
<td>Ortho. zone E</td>
<td>0</td>
<td>36</td>
<td>64</td>
<td>14</td>
</tr>
</tbody>
</table>

A comparison of inferred offset magnitudes between orthorhombic and conjugate faults suggests a higher percentage of conjugate faults accommodated moderate and significant amounts of upper-plate strain (Table 6.3). All but one fault (fault C_1/2-8; Plate 5; Appendix C) of the 116 orthorhombic faults had fault trace lengths less than ~1.5 km, and therefore were unlikely to have accommodated significant slip. Between 14% and 36% of the orthorhombic faults have inferred moderate offsets and 64% to 86% have minor offsets. Eight of the 121 conjugate faults measured had fault trace lengths in excess of ~1100 m and were inferred to have significant offset magnitudes (Table 6.3). Excluding the three E-W-striking faults of conjugate set IV (Table 6.3), 19-26% and 63-78% of conjugate faults have
moderate and minor offset magnitudes, respectively. Excluding the three conjugate set IV faults again (Table 6.3), all orthorhombic and conjugate faults appear to have similar proportions of moderate and minor fault offsets.

A first-order interpretation of this data indicates that strain values on the upper-plate orthorhombic and conjugate faults are approximately uniform with only a handful of conjugate faults potentially accommodating significant offset amounts. This conclusion is compatible with the idea that the SID, as first proposed by Weber and Smith (1987), was highly effective at localizing strain onto the through-going LANF with limited disruption to the upper plate. Only a handful of the NW-striking conjugate faults, including the Quaternary-aged faults, appear to accommodate larger amounts of strain.

Relations Between Faults and Folds

Two styles of folds are present in the western River Mountains. Most folds are synextensional and are related to either (1) fault propagation, (2) irregularities in the fault plane with depth, (3) displacement gradients along faults, or (4) some unknown mechanism (Plates 1 and 3). The terminology and interpretations used to describe these extension-related folds (Table 6.4) are adopted from Janecke and others (1998). Two other folds (f3 and f4, Table 6.4) are not tectonic but instead are interpreted to be related to salt withdrawal from Horse Spring Formation rocks (Plate 3a) and diapirism north of Lake Mead Parkway (Plate 1).

The presence of a 230 m by 380 m, domal gypsum and anhydrite mound (36° 05; 06” N, 114° 56’ 41” W) 40 m high north of Lake Mead Parkway and east of the
Calico Hills cuts the Red Sandstone Unit, the Bitter Ridge Limestone Member of the Horse Spring Formation, and an unnamed Miocene basalt flow (Plate 1). The diapir, mapped as “Thrte” on Plate 1 is interpreted to follow a fault contact that would juxtapose a now removed Red Sandstone Unit in the hangingwall against the Bitter Spring Limestone Member. A broad fold train of synclines (f1 and f4) and anticlines (f2) parallel the NW-striking normal faults that cut the Red Sandstone Unit to the southeast of the salt diapir (Plate 1). It is not clear if folds f1 and f2 are more a consequence of salt diapirism or tectonic faulting (Table 6.4). The source of the salt is tentatively assigned to gypsiferous facies at the top of the Rainbow Gardens Member and/or gypsiferous facies within the Thumb Member of the Horse Spring Formation. Exposures of thick gypsum deposits are exposed in these units north of the study area east of Frenchman Mountain (Figs 1 and 2) (Bohannon, 1984).
Table 6.4. River Mountains fold interpretations.

<table>
<thead>
<tr>
<th>Fold</th>
<th>Relation to fault</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>parallel to 1-91</td>
<td>fault-bend fold or salt diapirism (?)</td>
</tr>
<tr>
<td>f2</td>
<td>parallel to 1-91</td>
<td>fault-bend fold or salt diapirism (?)</td>
</tr>
<tr>
<td>f3</td>
<td>perpendicular to 1-108 and 1-109</td>
<td>salt diapirism</td>
</tr>
<tr>
<td>f4</td>
<td>parallel to 1-108 and 1-109</td>
<td>salt diapirism</td>
</tr>
<tr>
<td>f5</td>
<td>? footwall of C12-8</td>
<td>transtensional, fault-bend, or compound fold</td>
</tr>
<tr>
<td>f6</td>
<td>parallel to C12-8</td>
<td>fault-bend fold and/or fault propagation fold</td>
</tr>
<tr>
<td>f7</td>
<td>perpendicular to II-79</td>
<td>displacement gradient fold</td>
</tr>
<tr>
<td>f8</td>
<td>parallel to I-115</td>
<td>fault-bend fold</td>
</tr>
<tr>
<td>f9</td>
<td>parallel to I-115</td>
<td>fault-bend fold</td>
</tr>
<tr>
<td>f10</td>
<td>parallel to I-115 and I-112</td>
<td>fault-bend fold</td>
</tr>
<tr>
<td>f11</td>
<td>parallel to I-115 and I-112</td>
<td>fault-bend fold</td>
</tr>
<tr>
<td>f12</td>
<td>parallel to I-115 and I-112</td>
<td>fault-bend fold</td>
</tr>
<tr>
<td>f13</td>
<td>oblique to I-16</td>
<td>? transtensional fold</td>
</tr>
<tr>
<td>f14</td>
<td>parallel to II-2</td>
<td>fault-bend fold and/or fault propagation fold</td>
</tr>
<tr>
<td>f15</td>
<td>parallel to III-3</td>
<td>fault-bend fold and/or fault propagation fold</td>
</tr>
</tbody>
</table>

Model of Strain Evolution in the River Mountains and on the SID

The timing and number of discernible strain events in the River Mountains study area are slightly different from previous studies of adjacent regions between 13.5 and 9 Ma (e.g., Scott, 1988; Duebendorfer and Wallin, 1991). In previous sections of this thesis, where I state that extension is continuous from 13.5-9 Ma, I am referring to the region incorporating the LVV and western Lake Mead. However, when describing the River Mountains study area, the relationship of fault and fold patterns, and deposition of the 12-10.6 Ma Red Sandstone Unit suggest the existence of two,
loosely defined periods of extension between 13.5-9 Ma. In the western River Mountains, I documented a syndepositional fault (I11-75; Plates 1 and 5) near the base of the exposed Red Sandstone Unit with subsequent faults post-dating deposition, indicating two episodes of extension.

Scott (1988) however, documented a sharp waning of extension during early and middle deposition of the 10.6-5.88 Ma Muddy Creek Formation. I discount the age and formational interpretations in his thesis for two reasons: (1) none of the available ash deposits were collected and dated, and (2) rocks mapped in Scott's (1988) study more closely match the Red Sandstone Unit exposed in the Las Vegas Wash and the western River Mountains (S. Beard, 2006 personal communication). I reinterpret at least some of his Muddy Creek Formation deposits as the Red Sandstone to better correlate his documented period of waning extension with that described in the western River Mountains around 12-11 Ma.

North of Frenchman Mountain, Dubendorfer and Wallin (1991) documented growth faults and fanning of tilted beds in the Red Sandstone Unit, related to coeval activity on the LVVSZ. Continued extension throughout the Red Sandstone Unit deposition to the north conflicts with those relations expressed in the western and northeastern River Mountains. Consequently, it is considered that upper plate extension on the SID became briefly focused to the west of the River Mountains in the modern LVV and to the north of Frenchman Mountain during deposition of the Red Sandstone Unit.

Documentation of faulting events before, during and after Red Sandstone deposition (see subsequent Triaxial and Plain Strain subsections, Chapter 6) in the
River Mountains may indicate multiple stages of motion on the SID. The two events affecting the study area involved triaxial strain in the upper plate overtop corrugations and ramps, and plane strain where the detachment was planar (Figs. 17 and 18). It is likely that two corrugations on the SID generated localized triaxial strain within the upper plate (Fig. 18a), producing the orthorhombic faults of zones A-E (Plate 5).

This would imply different slip directions on the SID at different times with some amount of strain overprint on neighboring and slightly older orthorhombic faults to produce the observed slip patterns (Plate 1) and strain orientations (Table 6.1).

**Triaxial Strain**

The basic timing relationships of orthorhombic faulting relative to each zone and the Red Sandstone Unit are unclear. Faults composing zones A, C, and E cut the 12-10.6 Ma Red Sandstone Unit. However, the lack of Red Sandstone Unit exposure near zones B and D preclude making this interpretation for these other orthorhombic faults. Furthermore, cross cutting relationships between the orthorhombic zones is cryptic (e.g., zone A and B) and a relative order cannot be established. Consequently, three scenarios for the development of orthorhombic faulting in the River Mountains are proposed. The first suggests that all orthorhombic faults predate the Red Sandstone Unit and that 10.6-9 Ma tectonism reactivates orthorhombic faults that were covered by the Red Sandstone deposits during the intervening time. Another possibility is that orthorhombic faulting occurred both before (e.g., zones B and D) and after (e.g., zones A, C, and E) deposition of the Red Sandstone unit. However, because the relative order among the five orthorhombic zones cannot be accurately established, and several orthorhombic faults are demonstrably younger than the 12-
10.6 Ma Red Sandstone Unit, these two hypotheses are not considered favorable. A simpler explanation is that all orthorhombic faults, at least in their present configurations, are the result of triaxial strain between 10.6-9 Ma. This model does not discount the possibility of one or more orthorhombic fault sets initially forming between 13.5-12 Ma and becoming incorporated into a younger set.

Geometric similarities among the basin-bounding faults (C12-8, III-59, and III-58) cutting the Red Sandstone Unit in the Three Kids Mine area (T 21 S, R 63 E, section 35) (Fig. 6; Plates 1 and 5) and other orthorhombic faults in zones C and E suggest that these basin-bounding faults were initially formed under triaxial strain between 13.5-9 Ma. The amount of slip on these NW-striking faults however, is significantly greater than others within zones C and E. This presents a contradiction to orthorhombic theory, which assumes equal efficiencies among all orthorhombic faults (Reches, 1983; Reches and Dieterich, 1983). It is herein interpreted that post-Red Sandstone slip on some NW-striking, orthorhombic faults was plane-strain that occurred as local and regional strain fields were changing. Thus, these three faults were in a more preferable orientation to the new strain conditions between 10.6 and 9 Ma.

The presence of mostly NW-striking conjugate faults adjacent to the orthorhombic faults helps demonstrate (1) the size of the irregularities (i.e., corrugations) on the LANF and (2) the compatibility of the different faulting mechanisms that facilitated extension in the upper plate to the SID. If the NW-striking conjugate faults demark those locations on the upper plate that did not override a corrugation(s) on the SID, then their presence provides excellent
constraints on the geometries of the corrugation(s) in question in this study. Using these criteria, the five orthorhombic zones are elongated about a trend of 329° and range in length from 720-1280 m and width from 400-630 m. However, assuming the true motion vector of the upper plate block during triaxial strain was to the southwest (Weber and Smith, 1987; Sewall, 1988; Duebendorfer et al., 1990; Rowland et al., 1990; Fryxell and Duebendorfer, 2005), a second estimate of the width of the corrugations becomes approximately 700 m to 1300 m across.

These inferred corrugations are significantly smaller than corrugations exposed on the Catalina detachment near Tucson, AZ. (Dickinson, 1991; Dickinson et al., 2002). The mapped corrugations on the Catalina detachment have wavelengths of 10-20 km (Dickinson, 1991; Dickinson et al., 2002). Other detachments have much smaller corrugations with wavelengths of 0.5-1 km (Langrock, 1995), similar in scale to those inferred on the SID in this thesis. Although these size differences are intriguing, they are not unreasonable because there is no conclusory evidence that corrugations must be of a particular size range.

Plane Strain

Distinguishing slip on pre- and early syn-Red Sandstone conjugate faults from the more prevalent post-Red Sandstone faults, for purposes of documenting and analyzing the evolving strain field, is equally as problematic as with the orthorhombic faults. Many of these faults are either extensively overprinted by post-Red Sandstone extension or are buried by the younger Red Sandstone Unit. However, the excellent exposure of one short-lived growth fault (III-75; Plate 5), near the base of the exposed Red Sandstone Unit east of Ithaca Avenue (T 22 S, R 63 E, section 2; Plate 1), proves
the existence of an earlier conjugate faulting stage. A half-meter thick ash-fall layer deposited within the syn-faulting strata, and a second tephra layer in sediments postdating slip on fault III-75 (Plate 5) brackets the timing of fault motion around $11.79 \pm 0.02$ Ma and $11.79 \pm 0.03$ Ma (1σ), respectively (J. Slate, 2006 personal communication; M. Perkins, 2006 personal communication) (Appendix A).

Because of the impossibility of determining relative ages of the fault offset(s), with respect to the 12-10.6 Ma Red Sandstone Unit for faults only exposed cutting the 13.5 Ma volcanic rocks, all kinematic data are interpreted to represent the younger extensional event. The lone exception is the aforementioned, syndepositional fault east of Ithaca Avenue at the base of the Red Sandstone Unit. Otherwise, this assumption is valid because all four conjugate fault sets cut the Red Sandstone Unit with many of these faults displaying multiple slip senses (e.g., slickenline rakes, offset units, fault propagation folds, and R-shears) (Plates 1 and 5; Appendix C).

Furthermore, the youngest faulting events commonly are considered having the best preservation potential, and thus be the best expressed, of all previous 13.5-9 Ma slip events on any fault in the River Mountains.

As alluded to in preceding sections of this thesis, multiple slickenline orientations on the NW-, N-, and NE-striking conjugate faults (Fig. 10) cannot be explained by modeling a uni-direction extensional event (e.g., Angelier et al., 1985; Angelier 1989) with slip-transfer occurring on NE- and NW-striking faults. A more logical explanation is that 13.5-9 Ma extension in the River Mountains has alternated from the SW to the NW, and has done so at least twice since deposition of the Red Sandstone Unit. The new model proposed here, discussed more thoroughly in the
following sections, visualizes an intricate strain relationship between NW-directed translation and extension on the LVVSZ and WSW-directed translation and extension on the LMFS (Fig.20). It is the interplay between these two systems with the SID and its upper plate that results in discrepant cross-cutting relationships and slickenline orientations on the different fault sets (Fig. 20).

Regional Implications

Together, the LVVSZ and LMFS accommodate much of the Miocene CBR extension between the Spring Mountains and the Colorado Plateau (Figs. 4 and 20) (Longwell, 1974; Guth, 1981; Wernicke et al., 1982; Weber and Smith, 1987; Wernicke et al., 1988; Rowland et al., 1990; Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992; Wernicke, 1992; Campagna and Aydin, 1994; Duebendorfer and Simpson, 1994; Duebendorfer et al., 1998; Snow and Wernicke, 2000; Fryxell and Duebendorfer, 2005). Prior to the onset of CBR extension around 16 Ma (Beard, 1996), Frenchman Mountain was positioned above the present location of Gold Butte (Fryxell and Duebendorfer, 2005) (Fig. 20). The Spring Mountains were continuous with the Sheep Range and Las Vegas Range to the north, all of which lay considerably closer to the joined Frenchman Mountain-Gold Butte block than today (Snow and Wernicke, 2000). The Sierra Nevada Block lay approximately 90 km WSW of the Spring Mountains block (Snow and Wernicke, 2000). Additionally, a proto-LVV would have been located ~130 km east of the Sierran block in comparison to its current distance of ~250 km today (Snow and Wernicke,
These restorations (e.g., Snow and Wernicke, 2000) suggest a more proximal position for the LVV with respect to the San Andreas transform system at 16 Ma.

By 13.5 Ma (the time of emplacement of the River Mountains volcanic rocks), the Spring Mountains-Sheep Range-Las Vegas Range are bisected and dextrally offset via the LVVSZ (Fig. 20). To the east, tectonic removal of Frenchman Mountain from atop the Gold Butte (GB) block via the Lakeside Mine detachment fault (LMF) was complete (Fig. 20). The southern portion of the Frenchman upper plate was subsequently intruded by the Wilson Ridge Pluton and capped by volcanic rocks of the River Mountains. Exact locations, and therefore offset magnitudes of the aforementioned features can only be assumed to lie east of their present positions. It is known that extension on several LANF's (e.g., SID, Mormon Peak detachment, Grand Wash Cliffs detachment, Tule Springs detachment) and their genetically related transform faults (e.g., LMFS and LVVSZ) occurred after 13.5 Ma (Weber and Smith, 1987; Sewall, 1988; Duebendorfer et al., 1990; Duebendorfer and Wallin, 1991; Fryxell and Duebendorfer, 2005).

Near the end of Red Sandstone Unit deposition, around 10.6 Ma, active slip on the LVVSZ and the Bitter Spring fault (Weber and Smith, 1987) intermittently accommodated strain transfer and/or captured the SID and the upper plate containing the River Mountains and Frenchman Mountain (Fig. 20). As much as two-thirds of the 30-40 km total current offset between the River Mountains and the WRP may have occurred by this time. Higher rates of extension likely migrated to west of the WRP post-13.5 Ma as the SID accommodates much of the east-west expansion of the Lake Mead area between the Spring Mountains and GB during this time (Fig. 20).
The SID is herein interpreted as kinematically and genetically linked to the LMF system (Fig. 20).

The culmination of all preceding extensional events prior to today formed the modern physiographic and geologic configuration of the region shown in Figure 20. Spreading between the River Mountains and the WRP occurred prior to 9 Ma, but not during the Pliocene(?) to Quaternary extensional stage (Fig. 3). The return of extension in the Pliocene(?) is mostly north of Lake Mead with the exception of the Mead Slope fault and the Black Hills fault (Fossett, 2006) (Figs 2 and 20). The Mead Slope is the only Pliocene(?) to Quaternary fault that lies between the WRP and River Mountains (Fig. 20). With the exception of the Mead Slope fault, strike-slip faults play a minor role in the modern extension of the eastern CBR.

**CBR Extensional Models**

An extensional model with normal and strike-slip faults is required to explain extension in the CBR. Two variants include; (1) primary normal faulting and the necessary accommodation of differential extension via transform faulting (Davis and Burchfiel, 1973; Guth, 1981; Wernicke et al., 1982; Wernicke and Snow, 1998; Snow and Wernicke, 2000); and (2) primary transform faulting on the LVVSZ with normal faulting driving transcurrent slip along the LMFS (this study).

**General Model**

One model that has gained widespread acceptance suggests that the LVVSZ and LMFS separate discrete regions of major normal faulting (e.g., the northern Death Valley-Nevada Test Site region, northern Colorado River extensional corridor, and the eastern Lake Mead area) from lesser extended regions such as the Spring...
Mountains (Davis and Burchfiel, 1973; Guth, 1981; Wernicke et al., 1988; Faulds et al., 1990; Faulds and Varga, 1998; Snow and Wernicke, 2000). In this model, which is loosely referred to as the "general" model, east-west directed extension on the normal faults is the primary tectonic driver controlling the timing, magnitude, and location of secondary, passive strike-slip faulting (Anderson, 1973; Davis and Burchfiel, 1973; Guth, 1981; Wernicke et al., 1982; Guth and Smith, 1987; Weber and Smith, 1987; Wernicke et al., 1988; Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992; Wernicke, 1992; Campagna and Aydin, 1994; Duebendorfer and Simpson, 1994; Duebendorfer et al., 1998; Snow and Wernicke, 2000).

An important requirement of this model is a component of north-south shortening, orthogonal to the extension direction (Wernicke et al., 1988; Michel-Noel et al., 1990; Snow and Wernicke, 2000). Snow and Wernicke (2000) postulated that 20% of total E-W extension is compensated through N-S contraction and 80% by lithospheric thinning. Evidence of N-S contraction has been suggested from the oroflexural folding along the LVVSZ between the Spring Mountains and the Sheep Range, and in the Spector Range oroflexure at the NW termination of the LVVSZ (Snow and Wernicke, 2000). Other suggestions of N-S shortening were made for the LMFS (Anderson, 1973; Bohannon, 1983; Wernicke et al., 1988; Cakir and Aydin, 1990; Anderson et al., 1994; Duebendorfer et al., 1998), however, at least one example of a contractional structure is controversial (e.g., Echo Hills, Campagna and Aydin, 1991) because it occurs along a restraining bend of a major LMFS strand and is not indicative of regional shortening.
Alternative Model

There are two seemingly contradictory but interrelated conditions and/or implications of the alternative CBR extensional model proposed here. The first condition concerns the primary role that some strike-slip faults (e.g., NW-striking sets) play in CBR extension. The second condition with important implications is the relation between older N- and NW-striking normal faults and the present NW-striking dextral fault systems in the CBR.

The first aspect of the alternative model is similar to an idea proposed by Ron and others (1986) and Nur and others (1987) in that some of the Basin and Range strike-slip faults are primary structures controlling the local extension of an area. Here it is suggested that strike-slip motion on the LVVSZ is largely a consequence of early, inboard dextral shear related to a proto-San Andreas fault system. The implication of this idea is that the normal faults, including the SID, which open the LVV, are secondary structures that accommodate spatially-variable strain. This contrasts with the general model which views the LVVSZ as a secondary transform structure accommodating higher magnitudes of extension on primary normal faults in the LVV and northern Death Valley.

Not all major strike-slip faults are recognized as primary features, however. In this proposed model, the northeast-striking LMFS remains a secondary tectonic structure accommodating primary extension on N-S-striking normal faults east of the Spring Mountains and Sheep Range.

A second aspect of the alternative model highlights a possible hereditary link between the N-S-striking normal faults related to the east-west expansion of the CBR.
and the NW-striking dextral faults related to North America and Pacific plate motions. Although speculative, spatial and temporal trends of CBR extension and NW-directed primary strike-slip appear to coincide and initiation of both becomes younger to the west. In the eastern portion of the CBR, major extension occurs between 16-14 Ma on the Lakeside Mine detachment (Fitzgerald et al., 1991; Duebendorfer and Sharp, 1998), 16-9 Ma on the LMFS (Bohannon, 1984; Beard, 1996; Duebendorfer and Wallin, 1991), 16-9 Ma on the LVVSZ (Anderson et al., 1972; Duebendorfer and Wallin, 1991), and 16-13 Ma in the east-tilted blocks of the northern Colorado River extensional corridor (Anderson et al., 1972; Faulds et al., 1990; Gans and Bohrson, 1998). The initiation of extension in the northern Death Valley area-Nevada Test site is bracketed between 15.7-15.1 Ma based on a documented angular unconformity between the Tuff of Unconformity Hill and the Tuff of Buck Spring (Snow and Lux, 1999). Just west of the Spring Mountains and the Sheep Range, extension begins around 13.5 Ma on the Point of Rocks breakaway detachment (Snow and Wernicke, 2000) and 13-12 Ma on the Sheep Range detachment (Guth et al., 1988).

By 9 Ma, extension largely ceased on the aforementioned structures with the locus of tectonism migrating westward into the southern Death Valley region (e.g., Furnace Creek fault system) (Snow and Wernicke, 2000).

During Pliocene and Quaternary time, areas in and west of the Death Valley region become tectonically fragmented through continued detachment faulting and major dextral shearing along ECSZ and WLB faults. Not incidentally, these faults decrease in age toward the Sierra Nevada (Snow and Wernicke, 2000). Separation of
the Cottonwood Mountains from the Panamint Mountains via the Tucki Mountain
detachment fault occurs between 6.1-3.2 Ma (Snow and Lux, 1999). Elsewhere in
the southern Death Valley region, the Garlock Fault and the Furnace Creek fault
system are active during this time (Snow and Wernicke, 2000). Fish Lake Valley
begins opening around 5 Ma (Reheis, 1993; Reheis and Sawyer, 1997). Owens
Valley, the westernmost CBR valley, began opening between 3.4-2.3 Ma (Bachman,
1978). Extension in the modern Panamint Valley and Saline Valley via the Hunter
Mountain fault occurs after 2.8 Ma (Ross, 1968; Burchfiel et al., 1987; Conrad et al.,
1994).

A mechanistic discussion of this second aspect of the alternative model is found
in proceeding sections of this chapter (i.e., relation of LVVSZ to plate boundary
strain).

Alternative Model of Post-13.5 Ma SID Extension

The two major strike-slip fault systems responsible for much of the post-13.5 Ma
extension on the SID are the LVVSZ and LMFS. It is interpreted that these transform
systems as sharing a genetic relationship in space and time and that their confluence
on the SID facilitates the apparent variant motions on the SID (Fig. 20). Variations in
both the aforementioned triaxial strain field and the plane strain field support this SID
model.

Although somewhat speculative, and certainly non-unique, the palinspastic
restorations of the River Mountains through the last 13.5 m.y. highlight the dynamic
motions of the upper plate block between 13.5-9 Ma (Fig. 20) as suggested by
conjugate and orthorhombic faulting patterns (Fig 6; Plates 1 and 5). The model uses
~27 km of SW-directed offset on the Bitter Spring fault (BSF) and ~21 km of WNW motion on the LVVSZ for a summed vector displacement of 31 km at 254° with respect to the Wilson Ridge Pluton (WRP) during this time (Fig. 20). Motion on the other LMFS faults are implied in this stage of model as well, however, because motion of the River Mountains with respect to the WRP is largely accommodated by the Bitter Spring fault, offset magnitudes of the remaining LMFS faults are not suggested. The 31 km of displacement is also a maximum estimate because the model does not distinguish east-west expansion of the Wilson Ridge pluton via dike injections (e.g., Feuerbach, 1986; Anderson et al., 1994) from active faulting.

As mentioned before, evidence for an LVVSZ-LMFS relationship lies in the multiple slickenline orientations and crosscutting relationships among conjugate and orthorhombic faults that cut the Red Sandstone Unit. This thesis favors a hybrid of the models proposed by Weber and Smith (1987) and Duebendorfer and Wallin (1991) whereby the SID's proximity to the LVVSZ and BSF results in the River Mountains block being intermittently captured by the LVVSZ and LMFS. In other words, slip on the SID is sometimes parallel to synchronous with the LVVSZ and the LMFS. The time elapsed between the four stages of the model (Fig. 20) is too large to accurately highlight the transient velocity gradients that are assumed to exist on the LVVSZ and LMFS (this study).

*The Las Vegas Basin*

The Las Vegas basin (LVB) is a large pull-apart basin located at the end of the LVVSZ west of Lake Mead (Fig. 20). The LVB, similar to the River Mountains, has evolved through multiple extensional phases (Figs. 20 and 21). Synchronous faulting
on the LVVSZ and Lakeside Mine detachment fault (LMF) (Fig. 20), prior to 13.5 Ma River Mountains volcanism, may have generated an initial elongated and asymmetrical deep that is imaged adjacent to the LVVSZ in the northern and eastern valley by Langenheim and others (2001).

The Miocene structures recorded in the River Mountains study area (Fig. 6; Plate 1) may be key to understanding the slip histories for post-13.5 Ma structures imaged through gravity studies, reflection-refraction studies, and bore-hole logging (Fig. 21). Structural lows associated with strands of the LVVSZ beneath the northern and eastern LVV are the likely result of horse-tail splays at the end of a strike-slip fault system where NW extension is accommodated through oblique and normal faulting. Other lows that parallel the NW-striking strands may have formed during periods of WSW-directed extension and may be analogous to similar features in the River Mountains.

The late-Pliocene(?) to Holocene subbasin is more symmetrical with respect to the Miocene LVB (Fig. 21). One possibility is the cessation of major strike-slip and low-angle normal faulting on the LVVSZ, LMFS, and SID followed by E-W extension on the N-S-striking normal faults within the LVV. A more symmetric basin geometry results because of the east-dipping Las Vegas fault system that lies in the central LVB (Fig. 21).

**Central Basin & Range Province and the Southwestern United States**

The two important Cenozoic tectonic drivers of CBR and southwestern US tectonism are (1) primary dextral shear of the North American plate margin and (2)
intraplate east-west expansion. Dextral motion through the diffuse plate boundary along the western CBR is herein viewed as independent of east-west extension, with the exception of its initiation (see subsequent discussion). The translation of the Sierra Nevada block to the northwest may reduce extension-inhibiting boundary forces in the CBR in the last 16 m.y.

Slip on the LMFS is directly related to temporal and spatial variations in east-west extension east of the Spring Mountains and Sheep Range (Snow and Wernicke, 2000). However, in accord with the alternative model proposed for the CBR (see previous discussion), the LMFS is thus interpreted as being indirectly related to the dextral shear along the LVVSZ.

Relation of LVVSZ to plate boundary strain

In this section a mechanistic link for the close spatial and temporal correlation between N and NW-striking normal faults and NW-striking dextral faults in the River Mountains and LVV is proposed. It is suggested that the LVVSZ exploited a lithospheric weakness related to extension on the SID and LMF and other high-angle normal faults.

A first-order approximation of the strike of the LVVSZ is that it is not optimally oriented to accommodate dextral plate boundary motion. However, this assessment does not account for two important issues. First, most published regional tectonic maps and figures (e.g., Longwell, 1974; Wernicke et al., 1988; Duebendorfer and Simpson, 1994; Duebendorfer et al., 1998) do not depict the large strand of the LVVSZ projecting south beneath the eastern LVV (e.g., Langenheim et al., 2001) as depicted in Figures 1, 4, and 20. Accounting for this previously unrecognized strand,
in effect, gives a more northerly strike to the LVVSZ over its entire length. Second, in Figure 20 I suggest that the LVVSZ has undergone at least 6° of counterclockwise rotation in response to the east-west expansion on LANFs north of the LVV so that prior to today, the LVVSZ was oriented similarly to the dextral Furnace Creek fault zone in Death Valley, CA (Fig. 4).

Restoring the River Mountains back to the WRP at 13.5 Ma does not work without a substantial component of NW translation parallel to the LVVSZ (Fig. 20). This assumes that the component of translation of the River Mountains related to the LMFS also parallels the strike of the LMFS (Fig. 20). The same conditions hold true for the 13.5 to 16 Ma restoration of the Frenchman Mountain block back to the Gold Butte block (Fig. 20). Thus, I suggest that the west-southwest-directed slip on the LMF and SID are overprinted by NW-shear on the LVVSZ that results in an overall westward extension direction.

Prior to the initiation of CBR extension in the Lake Mead tectonic domain, distributed inboard shear stresses linked to a developing proto-San Andreas fault system in California (e.g., Atwater, 1970) are unable to overcome the strength of the lithosphere. Because \( \sigma_1 \) lies in the plane of the earth’s surface for strike-slip faults, the effective strength of the crust and lithosphere to resist this force could be too large to break new fault. However, the fragmentation of the lithosphere into large, N-S-orientated blocks during east-west extension may create a more efficient pathway for the accommodation of northwest-directed shear strain. Thus, in this model, the same mechanism of kinematic reversals acting on the NW-striking faults within the River
Mountains study area are analogous to the large-scale structures such as the SID, LMF, and LVVSZ.

Quaternary Extension and Seismic Hazards

Interior Valley Fault(s)

This study finds no definitive evidence to conclusively state that faults in the eastern and western portions of the Interior Valley cut Quaternary sediments. Suspicious morphologic features in several aerial photographs (provided by D.B. Slemmons) are actually 10.6-9 Ma faults that either juxtapose the Red Sandstone Unit and 13.5 Ma volcanic rocks or less resistive Red Sandstone against more resistant Red Sandstone units. The difference in their resistance to erosion is responsible for their apparent scarps. Similarly, no evidence of a splay of the IAF cutting the eastern side of the Interior Valley was found.

Ithaca Avenue Fault – River Mountains

The IAF is a previously recognized, but unnamed northwest-striking, west-facing fault along the northwest River Mountains (Bell and Smith, 1980; Slemmons et al., 2001) near Ithaca Avenue and Racetrack Road. Here, the IAF cuts a late-Pleistocene (50,000? year old) fanglomerate containing stage II carbonate soil development (D.B. Slemmons, personal communication 2006). Topographic profiling of the IAF documents: (1) the fan slope, scarp slope, and scarp height; and (2) the presence of a beveled scarp slope, indicating multiple rupturing events (Hanks et al., 1984) (Figs. 8 and 9).
Further evidence suggesting multiple rupturing events on the IAF is the 8.4 m scarp height, which is too large a slip for the magnitude of earthquake that can be induced from rupturing the entire length of the Frenchman Mountain-IAF system based on the regression plots of Wells and Coppersmith (1994). Using a surface rupture length of 10 km for the IAF south of the Las Vegas Wash (proceeding paragraph), and a surface rupture length of 38 km involving the entire trace of the Frenchman Mountain-IAF system (Slemmons, 2001), the maximum predicted vertical displacements are ~0.5 and 1.8 m, respectively (Fig. 22) (Wells and Coppersmith, 1994). Unfortunately, the presence of multiple rupturing events negates the usefulness of diffusion models to estimate a most recent (rupturing) event (MRE) age (Pinter, 1996).

Although the exposed trace of the IAF is less than 1 km for the two strands, the presence of such a large scarp height, and possible fault scarp-like morphologies along the southwestern River Mountains range front (C. dePolo, personal communication 2006; D.B. Slemmons, personal communication 2006), indicates a much longer rupture length. The limited exposure of the IAF is likely a combination of (1) discontinuous surface rupture during previous earthquakes, (2) subsequent erosion and deposition, and (3) human disturbance and urbanization. Therefore, if the IAF cuts the immediate substratum of the Las Vegas Wash, west of the Calico Hills neighborhood, to just south to the River Mountains Water Treatment Facility at the mouth of the Interior Valley drainage, the rupture distance is 8.5 – 10 km (Fig. 2; Plate 1). A regression plot of surface rupture length versus moment magnitude suggests then that the IAF is capable of producing a 6.2 $M_w$ earthquake (Fig. 22).
This is slightly less than the 6.4 Mw predicted by Slemmons and others (2001) due to them projecting the IAF further south to near Railroad Pass (Fig. 2).

Using only the 1 km of exposed surface rupture length on the IAF, a maximum magnitude of 4.9 – 5.1 is estimated (Fig. 22). However, < 5.0 magnitude earthquakes are not likely to produce surface rupture, and thus the aforementioned surface rupture lengths are better approximations (Slemmons et al., 2001).

Frenchman Mountain Fault – Frenchman Mountain

North of the IAF, the FMF cuts the heads of Quaternary alluvial fans flanking Frenchman and Sunrise mountains (Fig. 7; Plate 2). Like the IAF, the FMF dips to the west.

A topographic profile measured on the best-exposed strand of the Frenchman Mountain fault has a minimum scarp height of 12.9 m (Figs. 7 and 9; Plate 2). Young alluvium at the toe of the scarp obscures the original hangingwall fan surface and thus its total offset since formation of the fan.

Determination of total post-fan offset would require a larger paleoseismic trench being dug in order to locate the top of the pre-faulted fan surface. Without knowing this, and other potential piercing points, slip magnitudes remain unknown on this FMF strand.

In spite of the paucity of paleoseismic data, it is still evident that one earthquake-rupturing event could not have produced a 12.9 m offset. An earthquake resulting from a 12.9 m offset would be between Mw 7.5 and 7.8 and have a surface rupture length of over 100 km (Fig. 22) (cf., Wells and Coppersmith, 1994). Furthermore, the occurrence of beveling on a measured profile (Fig. 9) of this fault suggest multiple
rupturing events. The largest single displacement reported on the FMF is 2 m (Anderson and O'Connell, 1993), well below the 12.9 m height of the measured scarp (Fig. 9).

Ten meters south of the topographic profile, a small paleoseismic trench dug into the top meter of a five-meter deep natural dissection, reveals four colluvial wedges. These sediments have the same clast lithology as a capping conglomerate exposed in the footwall block and represent four surface rupturing events on the FMF (Fig. 16; Plate 4). From top to bottom, colluvial wedges were designated Qcw1, Qcw2, Qcw3, with thicknesses of 0.4 m, 0.5 m, and 1.2 m, respectively. The bottom-most wedge, Qcw4, was partially exposed and thus no thickness measurements were made. Minimum moment magnitudes of 6.6, 6.7, and 7.0 M were extrapolated for the three wedges by assuming the measured wedge heights approximated the average displacement of the FMF during rupture and plotting those values on the compilation of Wells and Coppersmith (1994) (Fig. 22). If it is assumed that the measured wedge heights were one half of the average ruptured scarp height, maximum moment magnitudes of 6.9, 6.9, and 7.2 M are estimated (Fig. 22).

Sediment samples collected from the middle two colluvial wedges were sent to Paleo Research and Beta Analytical for AMS radiocarbon dating. However, because of the extremely fine size of the charcoal fragments contained in the colluvial wedges, it was not possible to obtain a $^{14}$C date.

The FMF in the study area appears to be a composite earthquake fault composed of three geometric segments (Chapter 5). Its main trace, the one bounding the
mountain range, curves smoothly around from the NNE to the NW as it cuts north to south through the study area (Fig. 7; Plate 2).

From the available data in this study (i.e., geologic mapping), it does not appear that recent faulting has been limited to a specific geometric segment. No cross-cutting relationships could be deciphered among the NW- and N-striking faults. However, a more ideal site for testing rupture age relationships lies to the south of the Frenchman Mountain study area under the Sunrise landfill and is not accessible due to grading and burial. In the Frenchman Mountain study area, fault strands with NW- and N-strikes are documented cutting units as old as Qf3 and being covered by units as old as Qf2 (Plate 2). No instances were found where one segment was partially or completely covered by Qf3. Thus, it is possible that the entire length of the main FMF strand, south to the Las Vegas Wash, has ruptured at once in the past. This would imply a maximum \( M_w 6.6 \) for the FMF as estimated by Slemmons and others (2001) using a rupture length of 22 km (Fig. 22).

**Surface Rupture Correlation Between FMF and IAF Seismic Implications**

Two final questions concerning the pre-historical rupture patterns on the IAF and FMF are: (1) are these separately-named faults actually one fault and (2) do they have the potential to rupture together in a future earthquake? In addressing the first question, the FMF is interpreted as being a composite of the two faults whereby the IAF bifurcates off the FMF beneath the Sunrise Landfill.

One reason for linking the two differently named faults is that the strike and sense of slip on the IAF closely match that of the FMF. A second reason is the continuous
exposure of the main FMF strand as it cuts through the Frenchman Mountain study area (Plate 2), indicating a single rupture history. Lastly, several dip-slip fault planes with evidence of Quaternary offset were uncovered in a trench north of the Las Vegas Wash in line with the northward projection of the IAF (W.J. Taylor, 2006 personal communication).

Addressing the question of whether the IAF and FMF could potentially rupture together in a future earthquake holds the greatest societal relevance of this thesis. In this worst-case scenario, a maximum credible earthquake (MCE) of $M_w 6.9 \pm 0.3$ would be implied if the entire 38 km length of the integrated FMF-IAF ruptures (Fig. 22) (Slemmons et al., 2001). Although this estimate is slightly less than the extrapolated $M_w 7.2$ from measured colluvial wedge heights, the surface rupture length estimate of MCE is more reliable because scarp and colluvial wedge heights display large variability along a fault’s rupture length.

In summary, the IAF has propagated north (or south off the FMF) through successive rupturing events and is joined to the FMF. Aerial photographs south of the Sunrise Landfill indicate that the more prominent strand of the FMF bends to the SE along the mountain front in the direction of the Lake Las Vegas community (Fig. 1). To date, no surface rupture has been documented in the proposed path of the FMF and IAF between the landfill and Lake Mead Parkway, other than the aforementioned trench exposure. This lack of exposure here may be due to a lower preservation potential in the fine grained sediments and soils as the IAF and FMF step off the mountain fronts. Furthermore, the encroachment of urban development into this gap region has also obscured any trace that would have been present. In spite of these
obstacles, the IAF and FMF are viewed as a linked system with the potential for a future earthquake to rupture both faults.
CHAPTER 7

SUMMARY AND CONCLUSIONS

This study addressed the dual issues of 13.5-9 Ma extension in the western River Mountains and active extension in the western River Mountains and Frenchman Mountain. It is concluded in chapter 6 that the 13.5-9 Ma record of strain in the western River Mountains was a consequence of (1) NW-directed, dextral shear related to the proto-San Andreas plate margin, and (2) the WSW-directed extension and strike-slip faulting of LMFS.

The earliest extension actually pre-dates River Mountains volcanism by 2.5-0.5 m.y. and continues through 9 Ma before decreasing sharply. Locally in the River Mountains, extension appears to wane slightly during deposition of the 12-10.6 Ma Red Sandstone Unit. However, as this observation contrasts with that of Duebendorfer and Wallin (1991), who suggested that the Red Sandstone Unit was deposited syn-extensionally along the LVVSZ north of Frenchman Mountain. It may be that the two episodes in this 13.5-9 Ma extensional stage are local.

The second hypothesis of active extension in the western River Mountains and Frenchman Mountain was addressed as well. I concluded that the IAF and FMF are linked and have the potential to rupture simultaneously in future earthquakes. This modern extensional stage affecting the western River Mountains (and western Frenchman Mountain) may have initiated in late Pliocene time. Occasional

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seismicity and the occurrence of numerous normal and strike-slip faults with young scarps in southern Nevada, northwestern-Arizona, and southwestern Utah (Fig. 2) attest to the reality of this on-going extension.

Active extension on the IAF and FMF introduce the threat of future seismicity that would adversely affect the Las Vegas community. It was reasoned that although the IAF and the FMF appear as separate fault strands at the surface, they are likely connected at some depth and thus belong to the same system. This connection suggests that future earthquakes could rupture the combined 38 km trace to produce a credible earthquake of $M_w 6.9 \pm 0.3$.

A model of ~16 Ma-present extension is proposed (Fig. 20) whereby the major strike-slip faults, the LVVSZ and LMFS, are the primary structures driving the local stress and strain fields in the River Mountains.

Genetic relations between strike-slip and normal faults increase an extensional system’s efficiency of strain accommodation. Thus, the numerous kinematic reversals of conjugate faults in the River Mountains (Plates 1 and 5) give an indication of the instantaneous role reversal of these four fault sets in facilitating ongoing extension.

The transient stress and strain environments affecting the high-angle faults on the SID are also visible in the orthorhombic faulting patterns (Plate 5) in the western River Mountains. It appears that at least two differently-oriented corrugations existed on the SID beneath the western River Mountains indicating both a WSW and a NW transport direction of the upper plate along this detachment fault.
Figure 1. False color, shaded relief image of the Las Vegas-Lake Mead region. Yellow boxes outline the two study area locations. FM, Frenchman Mountain; LM, Lake Mead; LMFS, Lake Mead fault system; LV, Las Vegas; LVVSZ, Las Vegas Valley shear zone; RM, (River Mountains; SID, Saddle Island detachment fault; SM, Spring Mountains; WRP, Wilson Ridge Pluton. Picture courtesy of Michael Rymer.
Figure 2. (A) Quaternary fault map (red lines) of the Las Vegas-Lake Mead region. (B) Closeup map of the active Las Vegas Valley faults. AC, Arrow Canyon Range fault; BHF, Black Hills Fault; CWF, California Wash Fault; CWMF, Cashman-Whitney Mesa Fault; DLF, Dry Lake fault; DV, Death Valley; EDFS, Eglington-Decator fault system; EVF, El Dorado Valley Fault; FM, Frenchman Mountain; FMF-IAF, Frenchman Mountain Fault - Ithaca Avenue Fault; GF, Garlock Fault; GB, Gold Butte; MSF, Mead Slope Fault; MM, Mormon Mountains; VM, Virgin Mountains; PVF, Pahrump Valley faults; RM, River Mountains; RP, Railroad Pass; SLF, State Line fault; VVF, Valley View Fault.
Figure 3. Generalized map of the Basin and Range and surrounding domains. Dashed lines indicate northern and southern boundaries of the Central Basin and Range. CBR, central Basin and Range; WLB-ECSZ, Walker Lane belt - Eastern California shear zone. Asterisk denotes the location of the River Mountains. Modified from Dickinson (1992) and Wernicke (1992).
Figure 4. Tectonic map of Miocene faults in the Central Basin and Range province. Black faults with closely spaced ticks indicate low-angle faults. Black faults with ball and bars indicate other significant normal faults. Arrows and color indicate sense of strike-slip offset. Red faults have dextral offset, blue faults have sinistral offset. BM, Black Mountains; BSV, Bitter Spring Valley; DV, Death Valley; EM, Eldorado Mountains; EVF, Eldorado Valley Fault; FCFZ, Furnace Creek fault zone; FLVFS, Fish Lake Valley fault system; FM, Funeral Mountains; GB, Gold Butte; GF, Garlock Fault; GWF, Grand Wash Fault; HF, Hurricane Fault; HM, Hamblin Mountain; LMF, Lakeside Mine detachment fault; LMFS, Lake Mead fault system; LVV, Las Vegas Valley; LVVSZ, Las Vegas Valley shear zone; M, Mercury, NV; MM, Mormon Mountains; MPD, Mormon Peak detachment; NDVFZ, Northern Death Valley fault zone; NMR, Northern McCullough Range; NVM, Northern Virgin Mountains; PR, Panamint Range; PV, Panamint Valley; PVF, Panamint Valley Fault; SDVFZ, Southern Death Valley fault zone; SID, Saddle Island detachment; SM, Spring Mountains; SR, Sheep Range; TSD, Tule Springs detachment.
Figure 5. Palinspathic restoration of the Las Vegas-Lake Mead region. Shaded polygons outline the two study area locations in the western River Mountains and Frenchman Mountain. Changes in extension direction are facilitated by changing slip gradients on the LVVSZ and LMFS (inset graph). The Bitter Spring fault (BSF) is interpreted to be a continuation of the Gold Butte fault (GBF) that has been offset by the LVVSZ (see T$_{13.5}$ Ma block). See Appendix B for a detailed explanation of this restoration. BD, Beaver Dam detachment; BSF, Bitter Spring Fault; FM, Frenchman Mountain; GB, Gold Butte; GBF, Gold Butte fault; GPT, Gass Peak thrust; HH, Hoodoo Hills detachment; HSF, Hen Spring fault; KT, Keystone thrust; LMF, Lakeside Mine detachment fault; LRF, Lime Ridge fault; L.VV, Las Vegas Valley; LVVSZ, Las Vegas Valley shear zone; MMT, Muddy Mountain thrust; MP, Mormon Peak detachment; MSF, Mead Slope Fault; RM, River Mountains; SID, Saddle Island Detachment; TS, Tule Springs detachment; WPT, Wheeler Pass Thrust; WRP, Wilson Ridge Pluton.
Figure 6. (A1) 3-D conjugate fault diagram with summed stress and strain axes labeled. (A2) Map view display of a conjugate fault set. (A3) Lower-hemisphere stereo projection of a conjugate pair of normal faults. (B1) 3-D orthorhombic fault diagram with summed stress and strain axes labeled. (B2) Map view display of four orthogonal faults. (B3) Lower-hemisphere projection of orthorhombic normal faults. (C) Diagram depicting the instantaneous strain ellipsoid for a normal fault in the ε1 - ε3 plane. During shear, a hypothetical circle is deformed into an ellipsoid with instantaneous stretching and shortening axes oriented 45° from the shear plane. The strain plots constructed for this thesis use this strain principle.
Figure 7a. Simplified geologic map of the River Mountains study area. See Plate 1 for larger version.
Figure 7b. Simplified orthorhombic fault map of the River Mountains study area. See Plate 5 for larger version.
Figure 8. Simplified geologic map of Frenchman Mountain study area (See Plate 2). FMM, Frenchman Mountain mine. See Plate 2 for larger version.
Set I (NW-striking)
Mean: 1000 ± 1000 m
Median: 336 m
Number of faults = 54

Set II (NE-striking)
Mean: 400 ± 300 m
Median: 279 m
Number of faults = 32

Set III (N-striking)
Mean: 400 ± 400 m
Median: 288 m
Number of faults = 32

Figure 9. Fault trace length histograms for conjugate faults in the western River Mountains. Solid black bell curves represent an approximated fault trace length distribution for each histogram plot. See Appendix D for a more comprehensive conjugate-fault data analysis.
Zone A
Mean: 400 ± 300 m
Median: 240 m
Number of faults = 22

Zone B
Mean: 300 ± 300 m
Median: 240 m
Number of faults = 42

Zone C
Mean: 600 ± 500 m
Median: 513 m
Number of faults = 22

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Zone D
Mean: 400 ± 300 m
Median: 264 m
Number of faults = 19

Zone E
Mean: 500 ± 300 m
Median: 402 m
Number of faults = 14

Figure 10. Fault trace length histograms for orthorhombic faults in the western River Mountains. Solid black bell curves represent an approximated fault trace length for each histogram plot. See Appendix D for a more comprehensive conjugate-fault data analysis.
Figure 11. Topographic profile of alluvial fan and fault scarp across the Ithaca Avenue Fault (36° 03' 23" N, 114° 56' 07" W). Profile was measured in a line perpendicular to the fault scarp and the alluvial fan axis. Fault scarp is observed as an abrupt change in the surface elevation and in slope angles. Upper profile is vertically exaggerated 3x. Lower profile has no vertical exaggeration and shows a maximum scarp height of 8.4 m, an average scarp slope angle of 6°, a maximum scarp slope angle of 11°, and a fan slope angle of 3°. Arrows bracket the location of a fault scarp bevel. A beveled scarp suggests two rupturing events. Throw (vertical displacement) per earthquake rupture is not readily apparent.
Figure 12. Topographic profile of alluvial fan and fault scarp across the Frenchman Mountain Fault (36° 09' 17" N, 115° 00' 13" W). Profile was measured in a line perpendicular to the fault scarp. Fault scarp is observed as an abrupt change in the surface elevation and in slope angles. Upper profile is vertically exaggerated 3x. Lower profile has no vertical exaggeration and shows a maximum scarp height of >12.9 m, an average scarp slope angle of 13°, a maximum scarp slope angle of 18°, and a fan slope angle of 1.5°. Arrows bracket the location of a fault scarp bevel. A beveled scarp is the result of multiple rupturing events. Throw per earthquake rupture is not readily apparent.
Figure 13. Frenchman Mountain Fault trench exposure. For larger version, see Plate 4.
(A) Modified from Lister and Davis (1989).

(B) Modified from Novack and Taylor (in preparation).
Figure 14. (A) A model depicting a cross-sectional view of the development of different fault surfaces with time on the SID. As isostatic rebound in the footwall block denudes ductilely deformed rocks, slip along the detachment surface becomes increasingly difficult due to (1) back rotation of detachment surface and (2) cooling of the country rock causing the transition to a more brittle regime and greater friction (A-T₂). Eventually, a portion of the main detachment incises into the uplifted footwall and creates a new (corrugation) strain path beneath the brittle-ductile transition layer (A-T₃). As slip progresses on the SID, orthorhombic faults in the upper plate accommodate the newly formed void space between the surrounding detachment surface (lightly dashed lines, A-T₄) and the incised segment. (B) 3-D block model showing the development of triaxial strain and orthorhombic faulting. Upper plate block moves down and to the left where the corrugation widens, creating a void space (B-T₂) that strains the upper plate block (B-T₃). Once the upper plate has expanded to fit into the wider part of the corrugation, the orthorhombic faults may be overprinted by typical plane strain faults (B-T₄).
Figure 15. Map view of structure contours of hypothetical SID corrugation(s). (A) Two corrugations control the development of orthorhombic faulting in zones A-E. One corrugation (dashed) is concave up and opens to the southwest. A second corrugation (solid) is concave up and opens to the WNW. This model suggests two transport directions of the River Mountains block. No order of corrugation development is suggested in model A. (B) Orthorhombic fault zones A-E are formed synchronously in consequence to one concave up corrugation (detachment surface deepens in center) that opens and deepens to the southwest, in the direction of transport of the River Mountains block. Arrows on model B indicate orientation of $\varepsilon_3$ (Table 5.1 in Chapter 5).
Figure 16. Two models showing potential sources for strain field alteration among orthorhombic faults in the River Mountains. (A) Back-tilting of initially upright orthorhombic faults following passage over a detachment ramp. Dashed area beneath tilted block represents void space that is collapsed through progressive orthorhombic faulting. (B) Vertical axis rotation of the center orthorhombic zone occurs between two dextral-slip faults. In this model, orthorhombic faulting proceeds, but does not accompany later strike-slip faulting. However, the preserved orientations of original strain will appear different from neighboring orthorhombic zones. Striped tails on the ends of dark gray fault planes are the tails of the faults. All orthorhombic faults in models A and B display normal slip.
### Principal Strain Axes

#### ALL conjugate fault segments

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<tr>
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#### Set I: NW-striking fault segments

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Figure 17. Resolved paleostrain plots for the individual measured conjugate fault segments. The principal shortening axis ($e_1$) bisects the great circle containing the pole to the fault and the slip direction. The principal elongation axis ($e_3$) is orthogonal to $e_1$ on the aforementioned great circle. The intermediate axis ($e_2$) is orthogonal to $e_1$ and $e_3$ and is parallel to the fault plane. Eigenvectors and eigenvalues (negative = shortening, positive = elongation) give the orientation and magnitude, respectively, of the resolved strain tensor. “Percentage of total strain” is the relative magnitude (eigenvalue) of each of the three principal strain axes. Eigenvectors are given as the plunge and trend direction. The T and P symbols (open square and small solid circle, respectively) refer to the the individual elongation and shortening axes, respectively. The three principal strain axes are thus the average of these individual T and P axes.
Eigenvale % of Total Strain Eigenvector

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Set I: NW-striking faults

<table>
<thead>
<tr>
<th>Eigenvalue</th>
<th>% of Total Strain</th>
<th>Eigenvector</th>
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<tbody>
<tr>
<td>$\varepsilon_1$</td>
<td>-0.23</td>
<td>50</td>
</tr>
<tr>
<td>$\varepsilon_2$</td>
<td>0.05</td>
<td>11</td>
</tr>
<tr>
<td>$\varepsilon_3$</td>
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<td>39</td>
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Set II: NE-striking faults

<table>
<thead>
<tr>
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<th>% of Total Strain</th>
<th>Eigenvector</th>
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<tbody>
<tr>
<td>$\varepsilon_1$</td>
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<td>50</td>
</tr>
<tr>
<td>$\varepsilon_2$</td>
<td>0.03</td>
<td>7</td>
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<tr>
<td>$\varepsilon_3$</td>
<td>0.19</td>
<td>43</td>
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</table>

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Figure 18. Resolved paleostrain plots for conjugate fault planes for which the orientations were calculated by structure contours or the three point method. The principal shortening axis (ε₁) bisects the great circle containing the pole to the fault and the slip direction. The principal elongation axis (ε₃) is orthogonal to ε₁ on the aforementioned great circle. The intermediate axis (ε₂) is orthogonal to ε₁ and ε₃ and is parallel to the fault plane. Eigenvectors and eigenvalues (negative = shortening, positive = elongation) give the orientation and magnitude, respectively, of the resolved strain tensor. “Percentage of total strain” is the relative magnitude (eigenvalue) of each of the three principal strain axes. Eigenvectors are given as the plunge and trend direction. The T and P symbols (open square and small solid circle, respectively) refer to the the individual elongation and shortening axes, respectively. The three principal strain axes are thus the average of these individual T and P axes.
Figure 19. A 3-D model of the Las Vegas basin composed of Oligocene-Miocene sedimentary rocks (dark red) and Quaternary sediments (orange, yellow, and green) overlaying pre-Tertiary basement rocks (dark blue). The cross-sectional profile (front face) runs east to west (right to left) from Frenchman Mountain to Summerlin. The Tertiary sub-basin is asymmetric and deepens towards the east near Frenchman Mountain and to the north under US-95 and North Las Vegas. The Quaternary sub-basin is thickest in the center of the Las Vegas Valley. Modified from Taylor and Wagoner (unpublished data).
Figure 20. (A) Maximum displacement (m) as a function of surface rupture length (km). A 10 km rupture length on the IAF should produce a ~0.5 m offset and a 38 km rupture of the integrated IAF-FMF would generate a 1.8 m offset. (B) Moment magnitude of earthquakes (M) as a function of surface rupture length (km). Exposed IAF scarp is 1 km and would equate to a ~4.9 Mw. Inferred IAF rupture length of 8.5 to 10 km would yield ~6.2 Mw. Light gray dots are strike-slip faults. Gray squares are reverse faults. Gray hexagons represent normal faults. Modified from Wells and Coppersmith (1994).
Figure 21. Generalized Cenozoic stratigraphy of the western Lake Mead area. Modified from Duebendorfer and Simpson (1994).
Determination of strike

\[ \Delta y = Y_{\text{high}} - Y_{\text{low}} \]

\[ \Delta x = 100 \]

\[ \theta = \text{invTan}(\Delta y / \Delta x) \]

\[ \theta = 22^\circ \]

Determination of dip

Figure 22. Three-point structure contouring schematic. In the figure above, a hypothetical geologic bed (gray fill) dips moderately to the right (down hill). Dashed strike-lines (or structure contour lines) connect points of equal elevation \( Y_{\text{high}} \) and \( Y_{\text{low}} \) along a contact. The change of elevation \( \Delta y \) is difference between \( Y_{\text{high}} \) and \( Y_{\text{low}} \) elevations. Horizontal map distance \( \Delta x \) is the perpendicular distance between the contour elevation lines. The magnitude of dip is the inverse tangent of \( \Delta y / \Delta x \).
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LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

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1. Geologic Map of t
the Western River Map

By

William M. Rittase

2007

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Mountains, Clark County

Map Unit Description

Alluvium (Quaternary) - Surface is devoid of minor grasses. Desert pavement and varnish consist of eolian silts to coarse grained sands and clasts vary in composition depending upon surrounding lithologies.

Young alluvium (Quaternary) - Poorly to unsorted wash channels and on fan surfaces. Vegetation consists of grasses, bushes and creosote up to 2 m high desert pavement with little to no varnished silts to coarse grained sands and clasts vary in composition depending upon surrounding lithologies.

Alluvium of the Las Vegas Wash (Quaternary) - Well sorted and well bedded alluvium in areas of the Las Vegas Wash. Bedding is generally planar with minor cross-bedding. 3-7 cm thick with 1-2 cm diameter limestones occur throughout an otherwise fine-grained cm thick bedsets. Qalv is slightly indurated of the wash.

Intermediate alluvium south of water treatment plant. Alluvium surface has a well developed pavement. 60% of Tpd clasts. Av horizon extends 1 inch thick are 0.5-3 cm with remainder 5-20 cm in diameter and make up 95% of surface area with a light lime crust. Creosote bushes are small, < 0.5 m, and are 0.5-3 m (1-4 feet) above active wash channel. Desert pavement is solidated.

Slightly older alluvium south of water treatment plant. Alluvium surface on alluvial fan near Equestrian Road. Surface displays a moderately sorted Tpd clasts and 20% matrix of light tan to gray sand and silt. 30% of surface clasts are varnished and sit on top of older alluvium. Qa4 is older than Qa3 but less varnished.
Map Unit Descriptions

Qa

Alluvium (Quaternary) – Surface is devoid of vegetation with the exception of minor grasses. Desert pavement and varnish is generally nonexistent. Matrix consists of eolian silts to coarse grained sands and pebbles, clasts may be > 1 m. Clast composition depends upon surrounding lithologies.

Qa2

Young alluvium (Quaternary) – Poorly to unsorted fluvial deposits in inactive wash channels and on fan surfaces. Vegetation is abundant and consists of grasses, bushes and creosote up to 2 m high. Poorly to moderately developed desert pavement with little to no varnished clasts. Matrix consists of eolian silts to coarse grained sands and clasts vary in size from 1-20 cm. Clast composition depends upon surrounding lithologies.

Qalv

Alluvium of the Las Vegas Wash (Quaternary) – 1-3 meter thick deposits of well sorted and well bedded alluvium in and adjacent to the Las Vegas Wash. Bedding is generally planar with minor cross-stratification. Gravel beds are 3-7 cm thick with 1-2 cm diameter limestone, sandstone, and dacite clasts that occur throughout an otherwise fine-grained silt and sand deposit with 4-12 cm thick bedsets. Qalv is slightly indurated with steep breaks along the banks of the wash.

Qa3

Intermediate alluvium south of water treatment facility (Quaternary) – Alluvium surface has a well developed pavement with moderate varnish on 60% of Tpd clasts. Av horizon extends 1 inch into substratum. 80% of clasts are 0.5-3 cm with remainder 5-20 cm in diameter. Most clasts are touching and make up 95% of surface area with a light tan, silty matrix in between. Creosote bushes are small, < 0.5 m, and are widely spaced. Surface sits 0.3-1.3 m (1-4 feet) above active wash channel. Deposit is poorly sorted and unconsolidated.

Qa4

Slightly older alluvium south of water treatment facility (Quaternary) – Oldest surface on alluvial fan near Equestrian Road sits 1.3-2 m (4-6 feet) higher than active wash. Surface displays a moderately developed pavement with 80% Tpd clasts and 20% matrix of light tan to gray, fine-grained sand and silt. 40% of surface clasts are varnished and sit on top of a 0.5 inch Av horizon. Surface is older than, and sits higher than Qa3, but has a less well developed surface.
Undifferentiated, older Basalt flows of the River Mountains (Tertiary) - Multi-
textured, multi-compositional, vesiculated, basalt flows with auto-brecciated
margins. One set of basalt flows is fine- to medium-grained, olivine-rich and
weathering to iddingsite (1-2 % modal abundance), with large pyroxenes
0.2-0.4 cm long. Plagioclase phenocrysts in these flows are small (<1 mm) and
are less common than in the other flows. A second group of basalt flows is
strongly porphyritic, vesiculated, contains large (1-1.5 cm long) pyroxenes (3-5
% modal abundance), and has 0.1-0.3 cm sized olivine phenocrysts weathered
to iddingsite. Small, needle-like plagioclase vitrophereis, from 1-5 mm
long, have a modal abundance between 3-7 %. Upward-fining, coarse-grained
sandstone beds are locally interbedded in and cap some Tpb2 flows north of
Lake Mead Parkway.

Bitter Ridge Limestone Member of the Horse Spring Formation (Tertiary) -
White to light gray weathered limestone with interbedded calcareous
siltstone and mudstone. Chert is rare to absent. Occasional rip-up clasts and
disturbed bedding occur throughout the section and appear as poorly sorted,
angular clasts of limestone in a calcareous mud and sand slurry. Base of unit
consists of 1-2 meters of auto-brecciated Tta basalt flows capped with a
coarse-grained, carbonate and quartz sandstone that grades upward into a
deposit of ripped-up, angular clasts of Thb in a similar matrix of carbonate and
quartz sandstone.

Tuffaceous & Pyroclastic rocks of Powerline Road (Tertiary) - Localized airfall
and surge deposits in the northern River Mountains. Tps has a distinctively
bright-white, fine-grained matrix containing quartz, feldspar, welded glass
shards, and pumice fragments. Biotite and hornblende phenocrysts have a
modal abundance of < 3% and are 1-4 mm in size. Tps appears to have a
sharp basal contact with Tpd. However, lateral contacts with Tpd flows are
locally gradational and may indicate an upper stratigraphic position within
Tpd. Tps shares a similar stratigraphic level to Tpdv. Tps is commonly capped
by Tpb2 flows. Clast sizes in Tps range from 1-5 cm across generally with rare
clasts up to 20 cm in diameter. Reworked, epiclastic sandstones and conglo-
merate deposits are interbedded at the base and top of Tps and weathers to a
rosy-pink to yellow-orange color. Conglomerates are angular and sub-angular
and have bedding thicknesses from 5-30 cm. Fluvially reworked sandstones
and conglomerates are, arkosic, moderately- to well-bedded and well-sorted
medium- to coarse-grained quartz sandstone with average bedding thick-
nesses of 1-5 cm. Tps weathers easily and is a slope former.
Slightly older alluvium south of water treatment facility (Quaternary) – Oldest surface on alluvial fan near Equestrian Road sits 1.3-2 m (4-6 feet) higher than active wash. Surface displays a moderately developed pavement with 80% Tpd clasts and 20% matrix of light tan to gray, fine-grained sand and silt. 40% of surface clasts are varnished and sit on top of a 0.5 inch Av horizon. Surface is older than, and sits higher than Qa3, but has a less well developed surface due to young stream incisions giving Qa4 a nonplanar morphology. Deposit is a poorly sorted, poorly bedded, and unconsolidated.

In-situ surface colluvium and soil (Quaternary) – Clast composition is heavily dependent upon proximal lithologies, but almost always is dacite. Dacite clasts are sub-angular to sub-rounded, vary in size from 1-50 cm, and display variable stages of desert pavement and varnish development following deposition. Matrix is comprised of variable amounts of clay, silt, and sand totaling 40-60% of deposit. Matrix color is typically light tan to buff, but may vary to a medium brownish-red.

Colluvium of moderate slopes (Quaternary) – Unsorted clast- and matrix-supported debris formed on moderate to gentle slopes and saddles. Surfaces are vegetated with young creosote and grasses. Desert pavement and Av horizons are nonexistent to poorly developed. Angular to subangular clasts with composition dependent upon surrounding lithologies, but is generally Tpd.

Talus (Quaternary) – Unsorted scree slopes of angular lithic fragments. Very young morphological surface; soils and vegetation are not present. Qt typically forms on steep (>50°) slopes of Tpd. Individual scree slopes often are both heavily- and non-varnished and may indicate pre-depositional varnishing and/or cyclic surface exposure of clasts.

Young fanglomerate (Quaternary) – Very poorly sorted and unconsolidated fanglomerate deposit of Tpd clasts in a light tan to white silty matrix. Qfa deposits are matrix supported, with 20-30% subangular to subrounded clasts 1-8 cm in diameter. Surface has moderate desert pavement development with Tpd clasts touching. Most surface clasts are 1-8 cm across with <5% 20-80 cm across. Av horizon is approximately 1 inch thick.

Intermediate fanglomerate of Ithaca Road (Quaternary) – Poorly sorted and un lithified alluvium deposited on Trc and Trs north of Ithaca Road. Lithologically similar to Qfc but is less indurated and is deposited in younger paleo-stream channels. Surface displays bar and swell topography and is deeply incised with Qtb benches in ravine bottoms.

Older Fanglomerate of Ithaca Road (Quaternary) – Poorly sorted, poorly to moderately indurated, slope forming fanglomerate capping the Red Sandstone Unit east of Ithaca Road. Deposit consists of 40-50% Tpd clasts and 50-60% light tan to gray silt and fine sand matrix. Clast sizes vary from 0.5 cm to 40 cm across with most being < 3 cm. Larger boulders of Tpd on the Qfc surface are well rounded and highly varnished. Near horizontal exposures have well developed desert pavements with clasts touching and well varnished.

Fanglomerate of the southeastern Interior Valley (Quaternary) – Very poorly sorted and unconsolidated alluvium capping Trc in the southeastern corner of the Interior Valley. Deposit is supported by a matrix of light tan-brown silt and clay. Clasts are sub-angular to sub-rounded and are composed of 80% TdIV and 20% Tdrm in outcrop. Qfse surface displays bar and swell topography.

Fanglomerate of the southwestern Interior Valley (Quaternary) – 712 foot thick deposit of unsorted and unconsolidated volcanic lithic clasts and silt. TdIV and Tdrm make up 80-100% of clasts with minor Tpd. Majority of clasts are 1-3 cm across and sub-angular. Surface of Qfsw shows distinct bar and swell topography with poor to moderate pavement development and little varnish generally. Surface Av horizon is 0.5-inch thick.

Young stream terrace deposits of the River Mountains (Quaternary) – Characteristically the youngest and lowermost terrace deposit in stream valleys with...
Volcaniclastic sandstone in Tpdvc (Tertiary) – Well bedded, parallel, and well sorted volcaniclastic sandstone and tuffaceous deposit interbedded in Tpdvc west of the Interior Valley. Tpdvc appears to be fluviually reworked Tpdvc and not a surge deposit because climbing ripples and gradational margins were not observed. Tpdvc thickness ranges from 1-2 m. Hydrothermal alteration preferentially weathers out pumice fragments and precipitates silica in the matrix, giving deposit a vesiculated and vitric texture. Quartz and plagioclase phenocrysts vary in size from 1-5 mm. Biotites are also small, 1-4 mm, and make up < 2% of phenocrysts. Other exposures of Tpdvc are present to the in "mini-Interior Valley" north of the Interior Valley but mere not of mapable scale. Some were only lightly-altered and were light-tan to gray colored, while more heavily altered deposits had strong yellow-green hues.

Volcaniclastic block and ash deposit (or) dacite flow with large blocks with interbedded debris flows (Tertiary) – Poorly to unsorted volcanic breccia containing clasts of Tpd and pumice. Clasts are subrounded to angular and vary in size from 0.5 cm to > 1 meter in diameter. Matrix is a medium brown to light gray, moderately altered ash and mud in varying proportions. Bedding is parallel, generally very thick to massive (>1 m), and most notable from a distance. North of the Interior Valley, Tpdvc is matrix-supported and contains a light-gray ash or heavily-weathered dacite matrix with small, 1-2 mm sized biotite phenocrysts. West of the Interior Valley, 1-2 m thick, matrix-supported mudflows containing 1-5 cm sized Tpd clasts and silt are interbedded in a very thickly bedded, clast-supported breccia. Weathered surfaces are typically a brownish-orange due to higher mud and silt contents in the matrix. West and northwest of the Interior Valley, Tpdvc is a cliff and ridge-former and is strongly varnished. North of the Interior Valley, deposit is a low bluff to slope former and is less varnished.

Rhyolite flows of Powerline Road (Tertiary) – Vitrophic flows of pale blue to white-gray rhyolite near Ithaca Road along the western mountain front. Tpr is less resistant than Tpd, crumbles readily into 0.5-1 cm sized angular clasts, and forms low rounded hills and valleys between taller Tpd ridges. Because of poorer resistance, Tpr is not varnished. Rhyolite is almost entirely quartz and plagioclase with small, 1-2 mm sized biotites < 3% modal abundance. Flows appear to be highly zeolitized by hydrothermal fluids.

Andesite flows in northern Interior Valley (Tertiary) – Dark gray to gray-blue vitrophic andesite flows interbedded in Tpdvc. Biotite phenocrysts, 1-3 mm in size, are present in 3-4% modal abundance. Tpa is less resistant than capping Tpdvc and is a slope and saddle former.

Red dacite with basalt and andesite enclaves (Tertiary) – Fresh specimens are dark gray to purple, porphoritic dacite containing well-rounded basalt-andesite enclaves weathered to lavender and very dark gray. Dacite is highly vitric with abundant (~ 30%) phenocrysts of quartz 1-3 mm across and traces of biotite 1 mm long. and are lavender to very dark gray on weathered and fresh surfaces. Weathered Tpdm has a distinct brown to black surface that stands apart from weathered gray Tpd flows and is more resistant to erosion (i.e. cliff and ledge former) than Tpd. Contact with Tpd is sharp where faulted, but may be gradational with andesitic-basalt enclaves extending into adjacent dacite flows locally.

Red dacite with basalt/andesite enclaves west of Interior Valley (Tertiary) – Highly porphoritic, red dacite west of the Interior Valley. Large plagioclase phenocrysts, 2-5 mm, make up 5-10% of groundmass in hand specimen. Numerous andesitic and basalt enclaves, 2-8 cm in diameter distinguish Tpda from surrounding Tpd. Tpda is similar to Tpdm in the north River Mountains but has a more vitrophic and lighter red matrix.
and Tdrm make up 80-100 1-3 cm across and sub-an
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Young stream terrace dep
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Surface is moderately inci

Older stream terrace depo
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well developed desert pavi
Tpd clasts. Most clasts are
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Alluvium (Quaternary-Terti
with sub-rounded clasts of
size. Granite and schists cla
Thumb Member. 90% of all
60-70% of QTa is fine-grain
colored. Large secondary g
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Conglomerate of the Las Ve
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Wash. Conglomerate is clas
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Red Sandstone Unit congl
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Conglomerate is mostly ma
near basin margins through
fine-grained, angular to sub
m make up 80-100% of clasts with minor Tpd. Majority of clasts are across and sub-angular. Surface of Qfsw shows distinct bar and swell apathy with poor to moderate pavement development and little varnish. Surface Av horizon is 0.5-inch thick.

Stream terrace deposits of the River Mountains (Quaternary) - Characteristically the youngest and lowest terrace deposit in stream valleys with terrace banks. Qta terrace elevations range 0.5-2 m above active wash channels. Unit has poor to moderate desert pavement with non-touched clasts of sub-angular Tpd. Clasts are not touching, poorly sorted, from 1-7 cm diameter, and make up 60-70% of surface. Matrix is light gray, silty-sandy composition. Measured Av horizons were less than 1 cm thick.

Stream terrace deposits of the River Mountains (Quaternary) - The highest terrace deposit in stream valleys with multiple terrace Qtc terrace elevations range 1-3 m above active wash channels. Very developed desert pavement with moderate to well-developed varnish on its surface. Most clasts are touching and make up 90% of surface. Matrix is own silt and contains a 2-inch Av horizon.

Redaceous of the Interior Valley (Quaternary-Tertiary) - A poorly sorted, bedded, moderately indurated conglomerate unconformably overlying the northeastern and southern sections of the Interior Valley. Conglomerate is clast-supported with a minor matrix component of coarse sand to silt. Tpd clasts dominate in the northern section of the Interior Valley with Tdsm and TdIV in the southern half. Clasts range in size from 1-3 cm across. Small cross stratification is in an otherwise planar and parallel bedded unit with angular to subangular clasts. Surface has a well-developed pavement with the majority being moderately varnished. Surface clasts are touching and make up 90% of surface area with the remaining 2% a light tan, silty matrix with a 1-inch Av horizon. Original surface has sparse vegetation consisting of a light tan, silty matrix with a 2-inch Av horizon.

Volcaniclastic sandstone and interstratified flows (Quaternary-Tertiary) - Poorly sorted, gypsum-rich alluvial deposits of the Las Vegas Wash (Quaternary-Tertiary) - 1-2 meter thick volcaniclastic sandstone (Qfsv) atop clast-supported. Qfsv adjacent to the Las Vegas Wash conglomerate is clast-supported with angular clasts of Tdhb and Tdsm primarily. Qfsv is crudely bedded with parallel and cross-stratification. Deposit is strongly lithified and form bluffs where well exposed.

Red dacite with basalt/andesitic enclave. Highly porphyritic, red dacitic phenocrysts, 2-5 mm, make up 60-70% of surface and are mostly touching. Interclast matrix is light gray to tan silt and sand with a 1-2 inch Av horizon.

River Mountains dacite of Qtb is defined as any intermediate stream terrace(s) with three or more terrace banks and/or where singular terraces correlate with Qta and Qtc. Qtb elevations range from 1-3 m above wash channels. Desert pavement development on surfaces is light to moderate with slight varnishing of Tpd clasts. Tpd clasts ranging from 0.5-8 cm diameter comprise 60-80% of surface and are mostly touching. Interclast matrix is light gray to tan silt and sand with a 1-2 inch Av horizon. Is moderately incised by younger streams.

Qtfx is fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon.

Dark gray dacite with basaltic andesite enclaves in a fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon.

Dark gray dacite with basaltic andesite enclaves in a fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon.

Red Sandstone Unit and deposits of the River Mountains dacite of Qtb are mostly sheet bedded with thickness from 3-10 cm. Clasts are clast-supported with a light tan, thin silt and sand matrix with a 1-inch Av horizon. Very light gray, fine-grained matrix with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon. Fine-grained, moderately indurated matrix, light gray to tan, with a 2-inch Av horizon.
Red dacite with basalt/andesite enclaves west of Interior Valley (Tertiary) – Highly porphoritic, red dacite west of the Interior Valley. Large plagioclase phenocrysts, 2-5 mm, make up 5-10% of groundmass in hand specimen. Numerous andesitic and basalt enclaves, 2-8 cm in diameter distinguish Tpda from surrounding Tpd. Tpda is similar to Tpdm in the north River Mountains but has a more vitropheric and lighter red matrix.

The Lower Tertiary rocks include:

- **Volcaniclastic sandstone and conglomerate (Tertiary)** – A very small and localized outcropping of volcaniclastic sandstone and conglomerate interstratified in Tpd northwest of the Interior Valley. Tpds is older than the Red Sandstone Unit and does not appear to be a distal facies of Tpdc/Tpdcv. Tpds is mostly sheet bedded with minor cross beds locally. Bedsets range in thickness from 3-10 cm. Clasts are angular to subangular Tpd and range in size from 3-10 cm across.

- **River Mountains dacite of Powerline road (Tertiary)** – Extensive flows of heterogeneous, light gray to purplish-maroon dacites throughout much of the River Mountains study area. Dacite flows are banded and commonly display large amplitude flow folds up to 60 m high and 30-60 m long (Bell and Smith, 1980). Vitropheric zones are common throughout Tpd and typically have a bluish-gray color. Plagioclase, biotite, and hornblende are the dominant phenocrysts and vary in size from 0.1 to 0.5 cm across. Tops, bottoms, and the more distal portions of flows are heavily auto-breciated; especially north of Lake Mead Parkway where sub-rounded to well-rounded breccia clasts of Tpd range from 10-30 cm in diameter and make up 80% of outcrop. Zeolitized flows of Tpd are white to light gray, crumbly, and are slope and saddle formers among the more resistant maroon and medium gray dacites. Fractures and faults in Tpd locally contain jasperoid indicating the presence of shallow hydrothermal fluid alterations. Epiclastic sandstone and conglomerate beds occur throughout the section and are reliable indicators of fault block attitudes.

- **Volcaniclastic sandstone in Tdiv (Tertiary)** – Coarse-grained, angular and sub-angular, volcaniclastic sandstone and conglomerate deposits south of the Interior Valley. Sandstone grains and larger clasts are composed of Tpd, Tdiv and Taiv. Tsv sandstone is moderately to well sorted and well-stratified with bedding 3-15 cm thick. Medium-bedded conglomerates (20-30 cm thick) are poorly sorted, moderately-stratified and planar bedded with only local low-angle cross stratification. Fresh surfaces are light gray to tan. Weathered surfaces are strongly oxidized and have a purplish-gray coloration. Tsv is very resistant and is a cliff-former.

- **Dark gray dacite south of Interior Valley (Tertiary)** – Fresh exposures of dark gray, porphoritic dacite and andesite flows with increasing concentrations of basalt and andesite enclaves towards the eastern interior portions. The contact between Tda and Tpd is gradational and has been defined here (this study) as the first occurrence of basaltic-andesite dikes and enclaves. Tda becomes highly porphoritic to the east where 1-3 mm sized plagioclase and biotite phenocrysts are present in an aphanetic matrix.

- **Volcaniclastic sandstone in Tdiv (Tertiary)** – Coarse-grained, angular and sub-angular, volcaniclastic sandstone and conglomerate deposits south of the Interior Valley. Sandstone grains and larger clasts are composed of Tpd, Tdiv and Taiv. Tsv sandstone is moderately to well sorted and well-stratified with bedding 3-15 cm thick. Medium-bedded conglomerates (20-30 cm thick) are poorly sorted, moderately-stratified and planar bedded with only local low-angle cross stratification. Fresh surfaces are light gray to tan. Weathered surfaces are strongly oxidized and have a purplish-gray coloration. Tsv is very resistant and is a cliff-former.

- **Dark gray dacite and andesite south of the Interior Valley (Tertiary)** – Fresh exposures of dark gray, porphoritic dacite and andesite flows contain 1-2 mm plagioclase phenocrysts in a purplish-blue to gray aphanetic matrix. Most flows are heavily oxidized and varnished giving the gray unit a strong orange and red hue locally. Flow banding and and folding are common and are of similar size as in Tpd. Td1 is a cliff and ledge former.

- **Dark gray andesite in Tdiv (Tertiary)** – Dark gray andesite flows at the base of Td1. The contact between Taiv and Td1 is defined at a pronounced change in porphoritic texture with larger, 1-3 mm plagioclase phenocrysts, and a slightly darker matrix signifying Td1.

- **Heavily altered dacite south of Interior Valley (Tertiary)** – Td1r is readily distinguished from other units by its extreme hydrothermal alteration causing unit to display an exterior tie-dyed appearance of white, gray, yellow and red coloration.
Stratigraphic contact. Dashed where approximately located.

Normal fault. Dashed where approximately located, dotted where concealed. Ball and bar on downthrown block, slip direction unknown.

Normal fault with scarp. Bar on downthrown block (hangingwall).

Fault. Dashed where approximately located, dotted where concealed. Tick marks show dip direction and magnitude. Arrow shows trend and plunge of lineation on fault surface.

SCALE 1:12,000

CONTOUR INTERVALS 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

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**SYMBOLS**

- **Stratigraphic contact.** Dashed where approximately located.
- **Normal fault.** Dashed where approximately located, dotted where concealed. Ball and bar on downthrown block, slip direction unknown.
- **Normal fault with scarp.** Bar on downthrown block (hangingwall).
- **Fault.** Dashed where approximately located, dotted where concealed. Tick marks show dip direction and magnitude. Arrow shows trend and plunge of lineation on fault surface.

**SCALE 1:12,000**

- 1 MILE
- 2000 3000 4000 5000 6000 7000 FEET
- 0 0.5 1 KILOMETER

**CONTOUR INTERVALS 40 FEET**

ONAL GEODETIC VERTICAL DATUM OF 1929

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Young Basalt flow by Lake Las Vegas (Tertiary) - 10-15 m thick flows of basaltic composition are prevalent in the Interior Valley. These flows are characterized by a high concentration of tuffaceous material in the matrix and the appearance of dark gray to black, 0.01-2 m thick bands of fine-grained, arkosic sandstone and siltstone. These bands are well rounded and make up approximately 80% of all clasts and are sub-angular to angular. Clast composition is predominantly Tpd and Tpdb with some reworked Trc in the northwestern River Mountains. Basalt clasts are rare except near the base of unit immediately adjacent to Tp2b flows. Provenance in the Interior Valley is Tpd, Tpdb, Tda, and TdIv, in addition to reworked Trc. Bedding is predominantly parallel with local cross beds and imbricated clasts, suggesting high energy deposition during sheet flow on alluvial fan surfaces. Bedding is normally graded with thicknesses of 3-50 cm generally but locally exceeds 1 meter. Cut and fill channels are rare. Flame structures and other soft sediment deformation structures are common throughout Trc. Trc is well indurated and forms resistant ledges next to Trs but is generally a slope former on Tpd. Distal ash-fall layers 5-50 cm thick or more are preserved throughout Trc. A 50-100 m basal section of exposed Trc near Ithaca Road is a matrix- to clast-supported, volcaniclastic breccia with extensive hydrothermal alteration. This basal breccia forms a prominent ledge to the south against Tpr and is nearly identical to other Trc except for the absence of cherty and manganese veins, similar to Trs, to up 3 cm thick between bedding. Ash fall layers are silver to white and are common throughout the section with thicknesses from 0.2-1 m in the northwestern River Mountains and up to 3 m in the northern Interior Valley.

Red Sandstone Unit intermediate facies (Tertiary) - A sandy facies that lies stratigraphically between Trc and Trs. Deposit is well-sorted, fine- to medium-grained, arkosic sandstone and siltstone. Grain provenance is primarily Tpd and grains are well rounded to sub-rounded. Unit is light tan, with strong orange and yellow hues locally. Bedding is dominantly parallel with 1-15 cm thick beds. Sandy beds are moderately resistant to erosion and are slope and saddle formers between Trc outcrops. Conglomerate interbeds, 5-20 cm thick, occur locally and form more resistant ledges in Ttr. Conglomerate beds are normally graded, have depositional to scoured bases, and contain sub-angular to sub-rounded Tpd, Tpdb, and Tpdb2 clasts 0.5-5 cm across in the northwestern River Mountains. In the Interior Valley, Ttr is tuffaceous with small clasts (<0.5 cm) of Tpd in laminae (1-2 mm) to thin (<4 cm) bedsets.

Red Sandstone Unit siltstone and mudstone (Tertiary) - Thinly bedded to laminated (<1 cm) siltstone and mudstone interbeds that occur in at least 2 stratigraphic levels within Trc and have significant primary and secondary gypsum. Bedding is planar and continuous where not gypsiferous, but becomes discontinuous with increasing levels of secondary gypsum deposits. Unit is either light pink to deep tan/orange, or white to light gray where gypsum dominates. Trs is not exposed in the Interior Valley.

Tuffaceous, gypsiferous, and manganiferous rocks of the Red Sandstone Unit in the Three Kids Mines (Tertiary) - Highly variable sedimentary deposits of tuffaceous rocks, clastics, and evaporates. Tuffaceous rocks are interbedded with coarse-grained clastics in the bottom and middle sections, with evaporates dominating the upper stratigraphic section. Tuffaceous rocks are parallel bedded, continuous, and are moderately to well welded. Biotite phenocrysts are small 1-3 mm and have a low modal distribution, < 1% in hand specimen. Conglomeratic beds 5-40 cm thick are normally graded with angular to sub-angular Tpd clasts 1-4 cm in size. Cross bedding is rare in the conglomeratic facies. Trs closely resembles Muddy Creek Formation strata, but is distinguishable by the dull-gray to light-tan color of the clastic and tuffaceous facies as well as the appearance of dark gray to black, 0.01-2 mm thick bands of manganese oxides parallel to bedding. The upper 10-20 m of Trs is a reddish-brown, gypsiferous mudstone similar to Trs, but is readily distinguished by a high concentration of tuffaceous material in the matrix and the presence of manganese seams.

Young Basalt flow by Lake Las Vegas (Tertiary) - 10-15 m thick flows of rusty-brown to dark gray weathered basalt. Fresh surfaces are dark green to gray and contain tiny phenocrysts (1-2 mm) of pyroxene and biotite. Pyroxene is commonly weathered to iddingsite. Some of the flows are aphanetic and most do not contain no visible plagioclase phenocrysts like Tpd. Tpdb depositionally parallel to Tpd and these interlayer with Tpdb.

References:
Bohannon, R.G. 1984. Nonmarine...
resembles a quartzite with no biotite and little feldspar. Original structures and flow features are not present and quartz and feldspar grains appear fused. Thdrm has a low resistance to weathering and is a slope and saddle former. No fresh rock specimens were apparent.

Thumb Member andesite/basalt of the Horse Spring Formation (Tertiary) - 10-20 meter thick package of basalt flows separating Thumb and Bitter Ridge Limestone members of the Horse Spring Formation in the River Mountains. Very small (1-2 mm) pyroxene and biotite phenocrysts are rare in hand specimen. Plagioclase crystals small (< 2 mm) and are rounded unlike Tpb2. Thtb has a sharp depositional contact at its base with Th and contains 1-2 meters of basalt breccia with a coarse-grained, calcereous and quartz-sand matrix at its upper contact with Thb.

Thumb Member brecciated dacite flows of the Horse Spring Formation (Tertiary) - Interstratified, 3-5 m thick flow of auto-brecciated dacite near the top of the Th section above Thtx and below Th. Breccia clasts range in size from 5-25 cm across and are sub-angular. Deposit is light gray and forms a small ridge in the more easily eroded Th. Plagioclase, biotite, and hornblende make up the common phenocrysts.

Thumb Member siltstone and mudstone of the Horse Spring Formation (Tertiary) - Pinkish-brown, gypsiferous mudstone and siltstone facies of the Thumb Member. Gypsum is both primary and secondary with the latter forming numerous veins of gypsum (2-5 cm wide) cutting though and parallel to bedding planes. Composition is immature with a matrix of 50-60% very fined-grained, sub-angular quartz sand and 40-50% silt-sized feldspar. Heavily weathered and zeolitized volcanic sandstones and tuffs are also common and have distinctive greenish hues. Contains a 2-3 meter thick auto-brecciated dacite flow above Ttb near the top of the section. Capped by Thtb. Th is a saddle and slope former.

Thumb Member mega-breccia with Proterozoic detritus of the Horse Spring Formation (Tertiary) - Large slide deposits of porphyritic granite and banded gneiss with garnet. All exposures of Thtx north of the River Mountains and south of the Las Vegas Wash are contained within un-metamorphosed Th. Thtxs source is interpreted to from the Gold Butte metamorphic core complex (cf., Rowland et al., 1990; Fryxell and Duebendorfer, 2005).

Thumb Member sandstone facies of the Horse Spring Formation (Tertiary) - Fine-grained, well-sorted, and interbedded sandstone, siltstone, and mudstone. Thts underlies Th and Thtb and is characteristically more resistant and lithified than Th. Thts is well-bedded, with beds 5-7 cm thick and mostly planar bedding. Unit also contains local ripple cross-bedding 1-2 cm high. Matrix is highly gypsiferous in mudstone interbeds and secondary gypsum is common throughout deposit.

Rainbow Gardens-Thumb Member evaporite (Tertiary) - Massive to thickly-bedded gypsum and anhydrite diapir east of the Calico Hills neighborhood north of Lake Mead Parkway. Bedding is domal. Thrte locally contains inclusions of Tpb2. Exposed Thrte suggests a minimum thickness of 75 m (120 ft). Evaporite is estimated to have originated from either a gypsiferous lithofacies of the Rainbow Gardens Member as described by Bohannon (1984) or a more gypsiferous facies of the Thumb Member than was exposed in the study area. Thrte shares a fault contact with Thb and Tpd to the west and Thb2 to the south. Recent grading for a new residential subdivision to the east has obscured the contact with Thrte. No halokinesis structures were documented in adjacent sediments, but salt appears to followed pre-existing fault lines (see Plate 3).

References:
AREA OF MAP

CONTACTS

Stratigraphic contact. Dashed where approximately located.

Normal fault. Dashed where approximately located, dotted where concealed. On downthrown block, slip direction unknown.

Normal fault with scarp. Bar on downthrown block (hangingwall).

Fault. Dashed where approximately located, dotted where concealed. Tick marks indicate dip direction and magnitude. Arrow indicates trend and plunge of lineation on fault.

SCALE 1:12,000

CONTOUR INTERVALS 40 FEET
NATIONAL GEODETIC VERTICAL DATUM

Supplement to:
Rittase, W.M., 200
Mountain, south

APPROXIMATE MEAN DECLINATION

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SYMBOLS

- Dashed where approximately located, dotted where concealed. Ball and bar, slip direction.
- Bar on downthrown side. Tick marks shows magnitude. Arrow shows orientation on fault surface.
- Strike and dip of bedding.
- Syncline. Trend and plunge of the axial surface. Dashed where approximately located, dotted where concealed.
- Anticline. Trend and plunge of the axial surface. Dashed where approximately located, dotted where concealed.
- Tie lines linking stratigraphic units and fault kinematic data.

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the presence of chert between bedding. As out the section with the Mountains and up to

Red Sandstone Unit is stratigraphically between gravel, arkosic sands and grains are well red orange and yellow hues in thick beds. Sandy bed saddle formers between occur locally and form normally graded, have to sub-rounded Tpd, Eastern River Mountains. It (<0.5 cm) of Tpd in lam

Red Sandstone Unit is laminated (< 1 cm) silic stratigraphic levels with gypsum. Bedding is present becomes absent to discontinuous deposits. Unit is either where gypsum is dominant

Tuffaceous, gypsiferous in the Three Kids Mine, tuffaceous rocks, clasts with coarse-grained clasts dominating the bedded, continuous, are small 1-3 mm and Conglomeratic beds are sub-angular Tpd clast atic facies. Trs closely distinguishable by the facies as well as the appearance of manganese oxides reddish-brown, gypsiferous by a high content presence of manganese

Young Basalt flow by rusty-brown to dark gray and contain tiny eis commonly we most do not containionally overlies Tpt a

Tuffaceous sandstone separating Tpb above (<1%). Clasts of Tpb and bedding is very calcite and reacts vi
the presence of cherty and manganese veins, similar to Tst, up to 3 cm thick between bedding. Ash fall layers are silver to white and are common throughout the section with thicknesses from 0.2-1 m in the northwestern River Mountains and up to 3 m in the northern Interior Valley.

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Tuffaceous sandstone (Tertiary) - Reworked, fine-grained ash-fall deposit separating Tpb above and Tpb2 below. Biotites are small (<3 mm) and rare (<1%). Clasts of Tpb2 or Tpd were not found. Unit thickness varies from 2-7 m and bedding is very thin to medium (1-20 cm). Tpt matrix is cemented with calcite and reacts vigorously with acid.

References:
Bohannon, R.G., 19 region, southern N. Mountain B. Rowland, S.M., Parr logic and st the French: B.P., eds., Ex Society of A

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Thdb (Tertiary) – Interglacial, 3-5 m thick flow of auto-brecciated dacite near the top of the Tht section above Thtx and below Thtb. Breccia clasts range in size from 5-25 cm across and are sub-angular. Deposit is light gray and forms a small ridge in the more easily eroded Tht. Plagioclase, biotite, and hornblende make up the common phenocrysts.

Thumb Member siltstone and mudstone of the Horse Spring Formation (Tertiary) – Pinkish-brown, gypsiferous mudstone and siltstone facies of the Thumb Member. Gypsum is both primary and secondary with the latter forming numerous veins of gypsum (2-5 cm wide) cutting through and parallel to bedding planes. Composition is immature with a matrix of 50-60% very fined-grained, sub-angular quartz sand and 40-50% silt-sized feldspar. Heavily weathered and zeolitized volcanic sandstones and tuffs are also common and have distinctive greenish hues. Contains a 2-3 meter thick auto-brecciated dacite flow above Ttb near the top of the section. Capped by Thtb. Tht is a saddle and slope former.

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References:
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### Plate 2. Geologic Map of Frenchman Mountain

#### Map Unit Descriptions

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Qa</strong></td>
<td>Active washes (Quaternary) – Little to no vegetation, no desert pavement, unsorted clasts of dolomite and limestone, no AV horizon.</td>
</tr>
<tr>
<td><strong>Qc</strong></td>
<td>Colluvium of moderate slopes (Quaternary) – Unsorted clast- and matrix-supported debris, sparse creosote and grasses, formed on moderately-steep hillsides, no desert pavement, angular clasts of limestone and dolostone, no AV horizon.</td>
</tr>
<tr>
<td><strong>Qa2</strong></td>
<td>Youngest abandoned wash channels (Quaternary) – ~0.5 m higher than active channels, sparse creosote and grasses, slight pavement development, 20% clasts (not touching), 80% light tan matrix of silt and sand, no in-situ varnish, no AV horizon.</td>
</tr>
<tr>
<td><strong>Qf</strong></td>
<td>Youngest fanglomerate surface (Quaternary) – Slight desert pavement, 40% clasts, 60% light tan silty matrix, small creosote and grasses, no AV horizon.</td>
</tr>
<tr>
<td><strong>Qf2</strong></td>
<td>Young-intermediate fanglomerate surface (Quaternary) – Moderately developed desert pavement, 50% clasts, 50% matrix, small creosote and grasses, 0.5&quot; AV horizon, some in situ varnish on carbonate clasts.</td>
</tr>
<tr>
<td><strong>Qf3</strong></td>
<td>Intermediate fanglomerate surface (Quaternary) – Well-developed desert pavement, 80% clasts, 20% silt and sand matrix of light tan color, 90% of clasts are carbonates, 8% sandstone, and 2% chert, 1&quot; AV horizon, some in situ varnish on clasts, deposit is unconsolidated.</td>
</tr>
<tr>
<td><strong>Qa3</strong></td>
<td>Highest bluffs (Quaternary) – Fanglomerate deposit at base of Frenchman Mountain, light silty-tan matrix, contains sub-rounded clasts of carbonate and sandstone 3-7 cm across, well developed desert pavement (90% clast, 10% matrix) with clasts touching, 1&quot; AV horizon, large creosote, sparse grasses, deposit is strongly indurated.</td>
</tr>
<tr>
<td><strong>QTf</strong></td>
<td>Older conglomerate (Pliocene-Miocene) – Poorly sorted, poorly bedded, well lithified conglomerate, light tan/orange matrix of coarse carbonate sands with gray dolostone and limestone clasts, 5-13 cm thick beds, normally graded, clasts subrounded to subangular, clasts 2-4 cm across. Found locally in a small wash channel, unit resembles Red Sandstone Unit in the River Mountains but with different provenance.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Pc</strong></td>
<td>Calville Limestone</td>
</tr>
<tr>
<td><strong>Mmc</strong></td>
<td>Monte Cristo Formation</td>
</tr>
<tr>
<td><strong>Dsi</strong></td>
<td>Crystal Pass Member - Sultan Formation</td>
</tr>
<tr>
<td><strong>Dsvl</strong></td>
<td>Valentine and Ironside Members - Sultan Formation</td>
</tr>
<tr>
<td><strong>Cn</strong></td>
<td>Nopah Formation</td>
</tr>
</tbody>
</table>

Late Cambrian to early Pennsylvanian limestone and dolostone rocks of Frenchman Mountain in the footwall of main normal fault.
Frenchman Mountain Study Area

- Matrix-likely steep slope, no outcrop.
- More than active contact, 20% situ varnish, no weathering.
- 40% horizon.
- Intensively developed grasses, vegetation.
- Sand desert
- 10% of clasts in situ
- Frenchman carbonate and last, 10% grasses, sandstone, well
- Red, well sorted sands normally
- Peddled, well sorted sands normally
- Carbonate and sandstone, well
- Sylvanian
- Fault of Moun
- Large fault.

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Intermediate fanglomerate surface (Quaternary) – Well-developed desert pavement, 80% clasts, 20% silt and sand matrix of light tan color, 90% of clasts are carbonates, 8% sandstone, and 2% chert. 1° AV horizon, some in situ varnish on clasts, deposit is unconsolidated.

Highest bluffs (Quaternary) – Fanglomerate deposit at base of Frenchman Mountain, light silty-tan matrix, contains sub-rounded clasts of carbonate and sandstone 3-7 cm across, well developed desert pavement (90% clast, 10% matrix) with clasts touching, 1° AV horizon, large creosote, sparse grasses, deposit is strongly indurated.

Older conglomerate (Pliocene-Miocene) – Poorly sorted, poorly bedded, well lithofied conglomerate, light tan/orange matrix of course carbonate sands with gray dolostone and limestone clasts, 5-13 cm thick beds, normally graded, clasts subrounded to subangular, clasts 2-4 cm across. Found locally in a small wash channel, unit resembles Red Sandstone Unit in the River Mountains but with different provenance.

Callville Limestone
Monte Cristo Formation
Crystal Pass Member - Sultan Formation
Valentine and Ironside Members - Sultan Formation
Nopah Formation

Late Cambrian to early Pennsylvanian limestone and dolostone rocks of Frenchman Mountain in the footwall of main normal fault.

CONTACTS

Stratigraphic contact. Dashed where approximately located.

Normal fault with scarp. Dashed where approximately located, dotted where concealed. Bar on downthrown (hangingwall) block.

AREA OF MAP

1000 0 1000

APPROXIMATE MEAN DECLINATION

13.3°

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Map Legend

SYMBOLES

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Tie lines linking stratigraphic units and fault kinematic data.</td>
<td></td>
</tr>
</tbody>
</table>

Scale: 1:12,000

Contour Intervals: 40 Feet

National Geodetic Vertical Datum of 1929

Supplement to:

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UMI®
Plate 3. River Mountains Geologic Cross Section


West

A

2710' (834 m)

1710' (526 m)

710' (218 m)

-290' (89 m)

-1290' (-397 m)

(A) A-A' Geologic cross section. See Plate 1 for cross section location, unit names, and descriptions. No vertical scale.

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ic Cross Sections A-D

er Mountains and Frenchman Mountain, University of Nevada, 183 p.

s. No vertical exaggeration.
(B) B-B’ Geologic cross section. See Plate 1 for cross section location, unit n...
The diagram shows a section with various geological units labeled with 'Trs', 'Tpd', 'Tpdm', 'Thb', 'Tpd', and 'Tht'. Each unit is represented with specific symbols and annotations. No vertical exaggeration is applied to the section.

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(A) A-A' Geologic cross section. See Plate 1 for cross section location, unit names, and descriptions. No vertical exa

(C) C-C' Geologic cross section. See Plate 1 for cross section location, unit names, and descriptions. No vertical exa
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(B) B-B’ Geologic cross section. See Plate 1 for cross section.

(D) D-D’ Geologic cross section. See Plate 1 for cross section.
Plate 1 for cross section location, unit names, and descriptions. No vertical exaggeration.
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Plate 4. Trench Profile of the French

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Frenchman Mountain Fault
Fault
Trench Unit Descriptions

**Hps** Pedogenic layer (Holocene) - Deposit is moderately indurated and reverse graded with 1-2 cm size clasts of subangular carbonate and chert overlying a 5-10 cm thick section of laminated eolian sand and silt in a highly vesicular matrix of gypsum and carbonate. Hps unconformably overlies Qcw1, Qfg, and Qg, and is distinguished by a sharp increase in matrix cementation and clast to matrix ratio.

**Qcw1** Youngest colluvial wedge (Quaternary) - Unsorted; matrix-supported; contains 60% angular to sub-angular carbonate and chert clasts and 40% yellow to light-tan/orange colored, very fine silt matrix. Clasts size varies from 0.5-1 cm across (80%) 1-5 cm across (20%). Deposit is mostly unbedded, except at the base most proximal to the fault where a 1-2 cm thick, laminated silt layer is exposed; poorly indurated; and contains abundant root traces. Qcw1 may be the distal part of a larger colluvial wedge that has been degraded.

**Qcw2** Intermediate colluvial wedge (Quaternary) - Unsorted; clast-supported; contains 80% sub-angular carbonate and minor chert clasts 1-5 cm across, and 20% light-tan, moderately indurated silt matrix. Qcw2's matrix is more strongly calcified and gypsiferous than Qcw1. Bedding is poor, 3-5 cm thick dips westward 20-25° and shows a moderate angular discordance with Qcw1 and Qcw3.

**Qcw3** and unsorted carbonate and calcite clasts, 2-4 cm across coherent, surrounded by carbonate rinds containing calcite.

**Qcw4** clast-supported; contains light tan carbonates and rinds common matrix with the remainder and chert clasts no taper with the possibility of the

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Qcw3 Intermediate colluvial wedge (Quaternary) - Strongly indurated and unsorted deposit of clast- and matrix-supported colluvium. Matrix is carbonate and chert silt cemented with mostly gypsum and some calcite, with calcite mostly present as rinds on clasts. Qcw3 has 80% sub-angular clasts, 2-4 cm across with rare clasts up to 10-20 cm across. Wedge may contain coherent blocks of Qfg that appear as poorly bedded conglomerate surrounded by white, gypsiferous soil. No consistent bedding is present.

Qcw4 Oldest colluvial wedge (Quaternary) - Moderately indurated, clast-supported colluvial wedge exposed at the bottom of the trench. Matrix is light tan and contains noticeably less gypsum than Qcw3. Clasts lack calcite rinds common in Qcw3 and are unsorted, sub-angular to sub-rounded carbonates 5-7 cm across.

Qfg Fault gouge (Quaternary) - Unsorted, moderately indurated, matrix supported soil and rock. Deposit is less indurated than Qcw2, Qcw3, Qcw4, Qfl, and Qfg but more than Hps and Qcw1. 70% of deposit is a silt matrix with thick rinds of sparpy gypsum creating a botryoidal texture with the remainder of the unit composed of angular and sub-angular carbonate and chert clasts 1-4 cm across. Qfg is determined to be fault gouge because no taper with depth occurs and slumped blocks are not present, precluding the possibility of a fissure fill. 10% of clasts are rotated parallel to the fault.
Gravel layer (Quaternary) - >1 m thick conglomerate layer with a base scoured into Qfl. Deposit is moderately indurated and contains extensive secondary gypsum precipitated on clasts and fine carbonate silt and fine sand, disrupting bedding and making Qg matrix-supported. 35% of matrix is open pore space. Carbonate clasts and minor chert clasts are sub-angular to rounded and vary in size from 1-4 cm across. Calcite rinds on clasts are rare.

Fine-grained lacustrine rocks (Quaternary) - Mostly a fine-grained gypsum and carbonate sandy silt deposit. Secondary gypsum is sparry and occurs as overgrowths on other gypsum and carbonate grains. Cobble beds are rare (0-5%) and have thin, lenticular geometries of small channels (20 X 8 cm). Gypsiferous unit is highly indurated and is a light tan to white color.

Fine-grained lacustrine and fluvial rocks with gravel beds (Quaternary) - Similar to Qfl but contains 20-25% carbonate and chert clasts 2-10 cm in diameter. Unit is highly indurated and is light tan to white colored. Clasts in the conglomerate beds are unsorted and sub-angular. Conglomerates are clast-supported, lenticular shaped (40 X 15 cm), and commonly have scoured bases.
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Plate 5. Fault Kinematics

Mountains

By

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AREA OF MAP

FAULT KINEMATICS

- Normal fault. Dotted where concealed.
- Oblique (sinistral) fault. Dotted where concealed.
- Oblique (dextral) fault. Dotted where concealed.
- Strike-slip fault. Dotted where concealed.
- Oblique & unknown kinematics where concealed.
- Multiple slip senses fault. Dotted where concealed.

SCALE 1:12,000

CONTOUR INTERVALS 40
NATIONAL GEODETIC VERTICAL D

Supplement
Rittase, W
Mountain

APPROXIMATE MEAN DECLINATION

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Supplement to:
