Paleoseismology of the Black Hills Fault, southern Nevada, and implications for regional tectonics

Eric Fossett

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ABSTRACT

Paleoseismology of the Black Hills Fault, Southern Nevada, and Implications for Regional Tectonics

by

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The Black Hills fault (BHF) is a Holocene fault located in Eldorado Valley, ~ 7 km from Boulder City, southern Nevada. The importance of this study is to determine the seismic hazards the BHF poses to Boulder City and the greater Las Vegas metropolitan area and to determine the mechanisms driving the young deformation in the Lake Mead region. The BHF is a multistranded fault that had five surface rupturing paleoearthquake events in the past ~ 25 ka. Paleoseismic fault offsets indicate that the BHF is capable of generating a $M_w = 6.4 - 6.9$ earthquake. Slip rates calculated for the BHF are 0.33 – 0.55 mm yr$^{-1}$, which is significantly higher than the 0.01 – 0.1 mm yr$^{-1}$ slip rates estimated for most of the faults in this region. The high slip rates on the BHF, and several other young faults in the Lake Mead tectonic domain (LMTD) may relate to deformation in the Death Valley area. Active dextral and transtensional faulting in the Death Valley region accommodates northwestward translation of the Sierra Nevada block, and thus creates strain accommodation space, which may drive extension to the east in the LMTD.
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CHAPTER 1

INTRODUCTION

The Black Hills fault (BHF) is a part of a system of Miocene – Quaternary faults here called the Lake Mead tectonic domain (LMTD) within the central Basin and Range province (CBR) (Figs. 1 and 2). The BHF lies along the western margin of Eldorado Valley and the topographic base of the pluton of the Black Hills in the northern McCullough Range approximately 8 km west of Boulder City, 12 km southeast of Henderson, and 30 km southeast of Las Vegas (Fig. 2).

The initial work on the BHF occurred in 1980 as an unpublished study by the Bureau of Reclamation and had later supplemental work by the Seismotectonic Section of the Bureau of Reclamation (Anderson, 1986; Anderson and O’Connell; 1993). Prior to this study, the only published indication of this fault was on the Boulder City 15’ geologic map (Anderson, 1977), where the BHF was mapped as a concealed fault bounding the east margin of the Black Hills. Informally, the BHF also had been referred to as the Railroad Pass fault and the Eldorado Valley fault (e.g., Werle and Knight, 1992). Anderson and O’Connell (1993) are credited with naming the fault the “Black Hills fault” as a result of the discrepancy between the Werle and Knight’s (1992) Eldorado Valley fault and Weber and Smith’s (1987) use of the name Eldorado Valley fault, for an alluvium covered, west-dipping fault along the west side of the Eldorado Mountains that they interpreted to be the southern extension of the Saddle Island detachment (Fig. 2).
The purpose of this thesis is twofold and is separated into two sections that each reflect a single main goal. Chapter two describes the paleoseismic history and seismic hazards of the BHF using geologic mapping, scarp profiles, paleoseismic trenching, \(^{14}\text{C}\) dating, and published regression models. Chapter three places the BHF in the neotectonic development of the CBR by synthesizing the mid-Miocene to present tectonic development of the CBR and placing the Quaternary faults of the LMTD (including the BHF) into the current deformational patterns.

This study of the BHF is important for several reasons. The late Quaternary paleoseismic development of the BHF is important because of its proximity to Boulder City and the greater Las Vegas metropolitan area. The BHF had been recognized as an active fault with large displacement. The large displacement suggests that the fault is capable of generating a large magnitude earthquake, which could cause significant damage to Boulder City, and possibly the Las Vegas area. It is also important to place the BHF and other active faults within the LMTD into the regional deformation patterns to gain a better understanding of the effects of regional strain patterns on the local neotectonic deformation. Most recent studies in the CBR focus on the locus of deformation along the eastern Sierra Nevada with no mention of deformation to the east in the LMTD. However, active deformation in the LMTD may be related to active deformation along the eastern Sierra. This study will suggest a direct relationship between LMTD and eastern Sierra Nevada deformation, and thus Pacific-North American plate motions.
CHAPTER 2

PALEOSEISMOLOGY OF THE BLACK HILLS FAULT, SOUTHERN NEVADA

2.1 Introduction

The Lake Mead tectonic domain (LMTD) is used here to indicate a complex series of Tertiary and Quaternary strike-slip and normal faults in the central Basin and Range Province (Figs. 1 and 2). Despite the proximity of the LMTD to the nation’s fastest growing metropolitan area and Nevada’s largest population center, few paleoseismic studies are published on the Quaternary faults (e.g., Slemmons et al., 2001; Taylor et al., 2001; Bidgoli et al., 2003). This study documents and analyzes the latest Quaternary to Holocene paleoseismology of the Black Hills fault (Fig. 2). The BHF is a late Tertiary(?) - Holocene normal fault that is located near the southern boundary of the LMTD (Fig. 2). The BHF lies along the western margin of Eldorado Valley and bounds the eastern mountain front of the Black Hills ~ 7 km southwest of Boulder City, Nevada (Fig. 2). Previous studies of the BHF document the fault as a single, continuous strand that extends 10 – 14 km along the entire length of the Black Hills, although the surface rupture length is only ~ 4.5 km (Fig. 3) (Anderson and O’Connell, 1993; Werle and Knight, 1998). Anderson and O’Connell (1993) suggest that the length of the BHF may be as long as 29 km if the fault extends south along the southeastern boundary of the McCullough Range, but propose that the southern edge of the Black Hills provides a logical segment boundary because of a 2 km step-back between the Black Hills and the
McCullough Range (Fig. 2). Another proposed interpretation that increases the length of the BHF makes it part of the left-lateral LMFS, more precisely, connects it to the Mead Slope fault (MSF) (Fig. 2) (Slemmons et al., 2001).

In addition to fault length, scarp height data can be used to evaluate paleoseismicity. Maximum scarp heights were previously measured to be 1.8 – 2.8 m (Anderson and O'Connell, 1993; Werle and Knight, 1998). Anderson and O’Connell (1993) stated that no obvious bevels were observed and concluded that the scarps were the result of a single large earthquake. Werle and Knight (1998) compared these scarp to regression models of scarp degradation derived-ages of known fault scarps and reported ages of 8.4 – 5.5 ka for last surface rupture, although they did introduce the possibility that the BHF scarp was a composite scarp, which negates the scarp degradation model-derived age.

Despite previous studies, many questions remain unanswered regarding the BHF. The purpose of this study is to: (1) document the geometry and kinematics of the BHF; (2) determine the late Quaternary and Holocene history of the fault; and (3) assess the seismic hazard potential the BHF poses to the Las Vegas area. To document the geometry and kinematics, geologic mapping at the 1:12,000 scale, topographic profiling, and paleoseismic trenching were undertaken. To determine the fault history, paleoseismic trench data and inorganic radiogenic carbon dates were analyzed. Seismic hazards were evaluated by calculating slip rates and comparing measured displacement to other faults with known earthquake magnitudes.

It is important to study the BHF because the rapid growth of the Las Vegas metropolitan area now places people and structures near the fault, and the possibility of seismicity (Fig. 4). The lack of studies conducted on Quaternary faults in the area along
with an absence of any large historic earthquakes in the region sets the potentially
dangerous precedent that the LMTD is tectonically inactive and unable to produce large
magnitude earthquakes. However, Slemmons et al. (2001) have indicated that
Quaternary faults in the LMTD are capable of generating M 7.0+ earthquakes, but the age
of last surface rupture and slip-rates have not been determined. Thus, assessment of
seismic hazards associated with Quaternary faults in the LMTD is greatly needed. Based
on the geomorphic expression of the BHF, it is probable that it is the youngest and most
active fault in the region, so it provides a great opportunity to study recent seismicity and
to assess the greatest seismic hazards to the area.

2.2 Data

Map Units

New detailed geologic mapping, at the 1:12,000 scale, shows that the BHF cuts
Quaternary alluvial fans deposited along the eastern margin of a ~ 13.8 Ma quartz
monzonite pluton (Appendix I) exposed in the Black Hills of the northern McCullough
Range (Figs. 3 and 5; Plate 1). Quaternary fanglomerate units consist exclusively of sand
to boulder size sediment derived from the pluton and silt from eolian sources. Four
Quaternary fanglomerate units were identified based on geomorphic characteristics. The
oldest fan unit (Qn) is distinguished by a well-developed desert pavement surface with
varnished very-coarse pebble gravel to fine cobble gravel clasts that are sub-angular to
sub-rounded and represent ~ 90% of the surface (Fig. 6; Plate 1) (Appendix II.1). The
second oldest geomorphic unit (Qt2) is the most aerially extensive and is characterized by
coarse pebble gravel to boulder gravel on the surface where clasts represent ~ 78% of the
surface (Fig. 7; Plate 1) (Appendix II.1). This unit also exhibits grussification of ~35% of the clasts. The next youngest fan unit (Qb) comprises large desert varnished and unvarnished boulders that lack matrix (Fig. 8; Plate 1). The youngest unit (Qc) consists of active washes and fans that are cut into the older fan units (Fig. 9; Plate 1). The BHF offsets all fan units except Qc.

**Geometry**

This study documents 14 east-dipping fault strands by scarps that range in length from ~ 75 m to ~ 4.5 km (Fig. 5; Plate 1). These scarps were recognized by abrupt changes in topography and/or lineaments. The scarps are approximately parallel to the range front and cut across fan surfaces. Herein, the longest, most continuous strand will be referred to as the "main trace" of the BHF (Fig. 5; Plate 1). The shorter scarps are more linear and have an average strike of ~N10E, whereas the longer fault scarps tend to be sinuous and have an average strike of ~N25E (Fig. 5; Plate 1). The longer strands continue from near the south end of exposures of the pluton in the Black Hills and into section 15 (Fig. 5; Plate 1). The scarps with relatively shorter rupture lengths are observed all along the length of the pluton in the Black Hills, but are more abundant at the northern mapped extent of the BHF (section 15) (Fig. 5; Plate 1).

The scarp height of individual strands varies from centimeters to ~3.5 m, with the largest measured scarp occurring near the center of the main trace. Near the southern end of the pluton of the Black Hills, hereafter informally called the Black Hills pluton, the main trace has a maximum scarp height of ~2.75 m where it is truncated by an active alluvial fan originating in the gap between the pluton and volcanic rocks exposed in the southern Black Hills (northern McCullough Range) (Fig. 5; Plate 1). To the north, this
strand has a maximum scarp height of ~ 0.3 m where it bends to the east and is concealed by anthropomorphic disturbance (Fig. 5; Plate 1).

The shorter scarps have lengths of ~ 100 m and heights that range from ~ 0.5 m to ~ 3.0 m. These shorter scarps are (1) most prevalent at northern end of the fault zone, (2) closer to the range front than the longer strands at the northern terminus of the BHF, and (3) overlap in a left-stepping pattern near the northern boundary of surface faulting (Fig. 5; Plate 2). In addition, the axis of the mountain ridge deflects to the east, and the height of the range decreases drastically where the shorter strands become more prevalent (Fig. 5; Plate 1).

2.3 Data and Interpretations

Topographic Profiles

Topographic profiles were measured to: (1) determine fan slope, scarp slope, and scarp heights; (2) document multiple strands; and (3) use in combination with scarp diffusion models (Figs. 10a-c; Appendix III.I – X). All profile data were collected using a TPS 1100 total station. Alluvial fan profiles were measured as close to the axis of the fans as possible. Scarp profiles were measured orthogonal to fault strike to measure the maximum scarp height and scarp slope angle. Profiles were not taken on the northernmost fans because the coarse boulder deposits were not conducive to producing accurate profiles. The profiles show that the alluvial fans have slopes of ~ 9° - 15° with an average of 12° (Fig. 10a). In addition, these profiles document multiple fault strands (Fig. 10a).
Fault strands were recognized in profile by abrupt changes in elevation and/or changes in fan slopes (Fig. 10a). The maximum measured scarp height of 3.49 m was measured across the main trace of the BHF (Fig. 10a). The maximum scarp height of the main trace decreases to 2.96 m at the trench location (Fig. 10b). The profile across the main trace indicates an average scarp slope of ~25° at the trench site (Fig. 10b) (Appendix III.I-X).

The presence of three discrete bevels on the main trace scarp surface indicates that it is a composite scarp (Fig. 10c). Bevels on a scarp are created when successive faulting events along the same fault occur and there is adequate time for erosion and scarp degradation between rupture events. The observation of bevels invalidates the basic assumption that a scarp must be the product of a single rupture event for diffusion modeling to estimate scarp formation age to apply, thus the ages derived from diffusion models are not reported (e.g., Hanks et al., 1984).

**Slip Sense**

To determine if any lateral motion occurred along the BHF, drainage patterns were analyzed. Lateral motion on the fault would cause lateral offset or deflection of drainages across the fault. This method was deemed appropriate because drainages in the study area are relatively linear, so abrupt changes in the drainage patterns are easily documented. The analysis was conducted using a digital orthophoto quadrangle and defining all large drainages with particular attention given where drainages cross the main trace (Fig. 11). Data were collected by projecting a straight line down active drainage channels and documenting the apparent lateral deflection or offset of the two line segments (Fig. 11). No lateral offsets were observed, so all data collected are
drainage deflections. This method documents apparent right lateral deflection of ~ 44% of deflections measured and apparent left lateral deflection of ~ 56%. This data suggests that the BHF is dip-slip, not strike-slip.

**Mountain Front Sinuosity and Valley Depth : Valley Width**

In addition to topographic profiles and drainage geomorphology, range front sinuosity and valley depth – valley width ratios were also measured. Range front sinuosity and valley depth – valley width ratios can provide a first order estimate of slip rates. The basic principle of range front sinuosity is that recent uplift creates a more linear range front while valley depth - valley width ratios are based on the shape of the valley; the narrower the valley, the more recent the uplift.

This study used the Boulder City NW 7.5' DOQ and ArcGIS 8.2 to measure range front sinuosity and valley depth - valley width. Range front sinuosity is calculated by dividing the measured distance of the bedrock-piedmont interface along the range front by the measured straight-line distance (Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996). The closer the calculated value is to 1, the more linear the mountain front is, and thus, the inferred uplift rate of the mountain block is higher (Table 1) (Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996). The mountain front sinuosity values measured in this study range between 1.12 and 1.29 (Table 1). Mountain front sinuosity values between 1.1 – 1.3 are interpreted to infer uplift rates of the mountain block of 0.5 mm yr⁻¹ or higher (Table 1) (Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996).

Valley depth – valley width ratios were calculated by measuring the distance from ridge to ridge across a drainage 0.5 km up gradient from the bedrock/piedmont interface.
Table 1. Classification of relative tectonic activity of normal fault-block mountain. Inferred uplift rates are for semi-arid climates only (adapted from Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996).

<table>
<thead>
<tr>
<th>Classes of relative activity</th>
<th>Piedmont landforms</th>
<th>Mountain-block landforms</th>
<th>Range-front sinuosity</th>
<th>Valley depth/valley width ratio</th>
<th>Inferred uplift rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Maximal</td>
<td>Unentrenched alluvial fan</td>
<td>V-shaped valley in bedrock, U-shaped valley in alluvium or soft bedrock</td>
<td></td>
<td></td>
<td>1.0 - 5.0</td>
</tr>
<tr>
<td>2- Rapid</td>
<td>Entrenched alluvial fan</td>
<td>V-shaped valley</td>
<td>1.1 - 1.3</td>
<td>0.06 - 0.53</td>
<td>0.5</td>
</tr>
<tr>
<td>3- Slow</td>
<td>Entrenched alluvial fan</td>
<td>U-shaped valley</td>
<td>1.6 - 2.3</td>
<td>0.2 - 3.5</td>
<td>0.05</td>
</tr>
<tr>
<td>4- Minimal</td>
<td>Entrenched alluvial fan</td>
<td>Embayed mountain front</td>
<td>≥ 5.2</td>
<td>0.4 - 3.8</td>
<td>0.005</td>
</tr>
<tr>
<td>5- Inactive</td>
<td>Dissected piedmont</td>
<td>Piedmont embayment</td>
<td>2.6 - 4.0</td>
<td>0.9 - 39.4</td>
<td>≤ 0.005</td>
</tr>
</tbody>
</table>

BHF

| 2- Rapid | Entrenched alluvial fan | V-shaped valley | 1.12 - 1.29 | 0.10 - 0.27 | 0.33 - 0.55 |


The ridge to ridge distance is then divided into the measured valley depth at the same location (Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996). Typically, measured values below ~ 0.5 have high inferred slip rates (Table 1) (Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996). Values between 0.10 and 0.27 were measured for valleys in the Black Hills (Table 1). Valley depth – valley width ratio values between 0.06 – 0.53 are interpreted to infer uplift rates of 0.5 mm yr\(^{-1}\) or higher (Table 1) (Bull and McFadden, 1977; Bull, 1984, 1987; McCalpin, 1996).

### Paleoseismic Trench

A 75 m long trench was excavated across the main trace and a smaller strand of the BHF near the southern termination of the main trace to determine the kinematics and history of the fault (Figs. 3, 5 and 12; Plates 1 and 2). The trench ranged from 1 m deep in the upper (west) portion to 3.5 m depth in the lower (east) part. Stratigraphic units in the trench are dominantly fanglomerates that have clasts ranging in size from gravel to boulder with some stratigraphic units containing arid soils (Fig. 12; see Plate 2 for complete descriptions). A total of 38 fault strands were identified in the trench and are identified by alignment of clasts along the fault surface, disruption of materials, and/or by observed displacement of stratigraphic units across faults (Figs. 13 and 14). Observed vertical displacement (throw) across faults ranges from 5.1 cm to 1.98 m (Table 2). Cumulatively, vertical displacement across all faults exposed in the trench totals 12.965 m (Table 2). The predominant strikes of fault strands are between N02E and N35E, while dips of the faults vary from 50° to 86° (Table 2).

A stage I-II CaCO\(_3\) soil provides a marker horizon that is useful for determining the kinematics and history of the most recent earthquake events. In addition to this marker...
horizon, two additional CaCO₃ soil horizons that sit near the surface were dated. One near-surface horizon is in the hanging wall and the other is a young fan deposit in the upper trench (footwall), thus providing three CaCO₃ soil horizons that were dated using radiogenic ¹⁴C from inorganic carbon (Fig. 12; Plate 2).

Inorganic carbon samples were collected from four locations (2 in the footwall, 3 in the hanging wall) in the trench and submitted to Beta Analytic, Inc. for inorganic ¹⁴C dating (Fig. 12; Plate 2; Appendix IV). Sample selection was based on identifying horizons that provided the best opportunity to constrain movement history on the fault, had suitable material for dating, and satisfied the criteria set above. The youngest age of 9,230 ± 80 BP (10,580 – 10,220 cal BP 2σ) is from the stage I CaCO₃ soil of the uppermost fan in the footwall (Fig. 5; Plate 2; Appendix IV). The next youngest age of 10,870 ± 70 BP (12,650 - 12,740 cal BP 2σ) came from the uppermost CaCO₃ soil (stage I) in the hanging wall (Fig. 12; Plate 2; Appendix IV). The buried marker horizon (stage I – II) in the hanging wall yielded ages of 19,290 ± 120 BP (22,260 – 23,540 cal BP 2σ) and 21,550 ± 130 BP (Fig. 12; Plate 2; Appendix IV). An age of 16,650 ± 90 BP (19,330 – 20,360 cal BP 2σ) was determined from the correlative marker horizon in the footwall (Fig. 12; Plate 2; Appendix IV). The apparent age discrepancy is explained by the footwall sample having a longer exposure near the surface, and thus the cumulative average effect had a greater influence, yielding a younger age. Again, all ¹⁴C dates are considered minimum ages because of the cumulative average effect inherent in ¹⁴C measured from pedogenic carbonate, but the dates calculated seem to agree well with estimated ages of pedogenic carbonate development (Gile et al., 1981; Machette, 1985; Reheis et al., 1992; Buck and Monger, 1999).
The radiogenic inorganic carbon method was selected because: (1) no organic carbon was present in the trench; (2) material was too coarse for luminescence methods; and (3) U-series dating was deemed unreliable without age control from other dating methods for corroboration (Paces et al., 1995). The use of pedogenic carbon for dating is useful with the recognition that ages determined will be minimum ages because development of pedogenic carbonate is time transgressive, thus the material being dated is a cumulative average (Buck and Monger, 1999). Despite the recognition that the \( ^{14} \text{C} \) dates are a cumulative average, the use of pedogenic carbonate for radiocarbon dates was considered acceptable and samples were collected based on the following criteria: (1) contamination from older organic matter was considered minimal to non-existent based on the arid environment and the lack of organic material in the sediments (Buck and Monger, 1999); (2) material sampled was stage I and stage II calcic soils (coated clast rinds where possible), so the cumulative average effect could be kept to a minimum; (3) samples were collected from the lowest possible location in the horizons to minimize younger contamination from depth of wetting and illuviation effects; and (4) parent material is non-calcareous so detrital carbonate is minimal to non-existent (Buck and Monger, 1999).

2.4 Discussion

Surface Rupture History

Interpretation of the faulting history of the BHF is complicated by several factors. The depositional units observed in the trench have a relatively homogenous clast size, are from the same source, and were deposited in the same depositional environment. Despite
the similarity of the strata, units were differentiable by thin gravel beds underlying/overlying units and slight matrix differences within individual stratigraphic units. The recognition of these detailed sedimentological features was key to documenting the offset of the faults exposed in the trench.

Another difficulty encountered was that many faults recognized in the trench were observed to cut only part way into an overlying layer (ie., most of the faults associated with the oldest faulting event). Several explanations for this observation are possible. One explanation is that the faulting event ruptured the surface, and the overlying unit was deposited soon enough after the event so that no individual colluvial wedges had time to form and the unit itself acts as the colluvial wedge. Another possibility is that the faults actually ruptured through the unit, but subsequent CaCO₃ soil development overprints the fault trace. A third possibility is that the faults did not rupture to the surface. Regardless, any of these interpretations suggest that the faulting event is nearly time correlative with the deposition of the overlying unit and becomes a fundamental assumption for interpretation of the faulting history.

Based on different strata in the upper and lower portions of the trench, it is impossible to directly relate faults younger than Q₁₅ in the upper and lower portions of the trench. Trench unit Q₁₅ is the most laterally continuous stratigraphic unit exposed within the trench, and thus, is used as a marker bed to aid in the determination of the number, and amount of offset, of faulting events (Fig. 12; Plate 2). This marker unit is the uppermost unit in the footwall that is cut by the main trace. This unit is buried by younger depositional units upslope (e.g., Q₆ and Q₇) that do not directly correlate to units in the lower part of the trench (Fig. 12; Plate 2). Therefore, the event associations reported in
Table 2 have been separated into events in the upper portion (i.e., event association 1u, where 1 represents the most recent event) of the trench and events in the lower portion (i.e., event association 11, where 1 represents the most recent event). The upper trench is defined here as all strata and faults upslope, or west of the main trace.

Based on the observation of displaced units and colluvial wedges, a total of three surface rupturing events are recognized in the upper trench. The oldest event recognized in the upper trench (event association 3u) is illustrated by faults k-x (Fig. 12; Plate 2) and accounts for a total of ~3.1 m displacement (Fig. 12; Plate 2; Table 2). These faults either cut into, or are overlain by unit Q_{15}, but they do not cut through the entire unit (Fig. 12; Plate 2). The exact relationship between the faults and unit Q_{15} is ambiguous (as discussed earlier), but these faults are interpreted to be older than the rupture of the other faults.

The next youngest event in the upper trench (event association 2u) is most easily illustrated by faults f-h (Fig. 12; Plate 2). These faults cut through unit Q_{16}, but do not displace unit Q_{17} like faults from the next youngest event, thus making this event younger than 3u (Fig. 12; Plate 2). Faults i1 - i3 are also interpreted to have ruptured during this event, although these faults may have ruptured during multiple events. Rupture of these faults (i1 - i3) is thought to have occurred during the second event based on the deposition and stratigraphic position of unit Q_{c1}, a colluvial wedge (Fig. 12; Plate 2). Total displacement for this event is ~1.1 m (Fig. 12; Plate 2; Table 2). Faults i1 - i3 also offsets unit Q_{r7}, which indicates movement along these faults during a younger earthquake event (Fig. 12; Plate 2).
Table 2. Geometry and kinematics of faults observed in the trench

<table>
<thead>
<tr>
<th>Fault ID</th>
<th>Strike and Dip</th>
<th>Vertical Displacement</th>
<th>Event Association</th>
<th>Age</th>
</tr>
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<tbody>
<tr>
<td>a</td>
<td>005 74E</td>
<td>&gt; 8 cm</td>
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<td></td>
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<tr>
<td>b</td>
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<td>23 cm</td>
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<tr>
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</tr>
<tr>
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<tr>
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<td>Vertical Displacement</td>
<td>Event Association</td>
<td>Age</td>
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<tr>
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<tr>
<td>bb</td>
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<td>cc</td>
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</table>
The youngest event documented in the upper trench (event association 1u) is interpreted to be the largest event exposed in this portion of the trench. Faults a – e, j, and i1 – i3 all appear to have ruptured during this event (Fig. 12; Plate 2). This interpretation is based on the observation that all of these faults offset unit Qf7. Faults a – e have associated colluvial wedges overlying unit Qf7 (e.g., Qc2 – Qc5) (Fig. 12; Plate 2). Faults i1 – i3 shows less offset of Qf7 than Qf5, which suggests that they were active during both the 1u and 2u events (Fig. 12; Plate 2). The largest measured displacement along these faults occurs on fault j, with 1.12 m of measured vertical displacement. Total displacement across all faults associated with event 1u is 1.75 m (Fig. 12; Plate 2; Table 2).

The lower trench is defined as all faults and strata downslope, or east of, and including the main trace (faults z – mm) (Fig. 12; Plate 2). Based on displaced units and colluvial wedges, a total of four or five surface rupturing events are delineated in the lower trench.

The oldest definite event documented in the lower trench (event association 4l) is best demonstrated by faults bb and mm (Fig. 12; Plate 2). Although the throw across fault bb cannot be determined, the associated colluvial wedge (Qc6) is the stratigraphically lowest colluvial wedge exposed in the lower trench (Fig. 12; Plate 2). In addition, fault bb is overlain by two younger units (Qc9 and Qc10), which constrains the upper time of motion (Fig. 12; Plate 2). The 93 cm minimum vertical displacement across this fault (Table 2) is inferred from the measured thickness of colluvial wedge Qc9 (Fig. 12; Plate 2). This displacement is considered a reliable minimum estimate because it assumes that the
colluvial wedge was deposited to the top of the scarp and other colluvial wedges show the same relationship to other faults (Fig. 12; Plate 2).

Fault mm is also associated with event 41 (Fig. 5; Plate 2). Fault mm cuts unit QfS and has an associated colluvial wedge (Qc7) that is covered by a younger unit (Qcs) (Fig. 12; Plate 2). Vertical displacement across this fault is measured at ~74 cm (Fig. 12; Plate 2).

Fault II also appears to be related to this event because it offsets unit QfS by 23 cm and is overlain by Qcs (Fig. 12; Plate 2). This fault dips upslope and is interpreted to represent a buttress for the Qcs unit that is the colluvial wedge from event 41, but material from its footwall may also have contributed to the colluvial wedge (Fig. 12; Plate 2).

Faults ee – gg are also interpreted have moved during this event because they offset unit QfS by a total of ~79 cm (Fig. 12; Plate 2). This interpretation is uncertain because these faults appear to offset, by a few centimeters, the lowest part of colluvial wedge Qcs that is attributed to event 41 (Fig. 12; Plate 2). However, no separate colluvial wedges are associated with these faults. It appears that colluvial wedge development from these faults was close enough in time to deposition of colluvial wedge Qcs that subsequent Bk soil development overprints any distinguishing characteristics of separate colluvial wedges, if any existed (Fig. 12; Plate 2).

The next youngest paleoearthquake interpreted in the lower trench (event association 31) has fewer faults associated with it, but significant total throw of ~1.45 m accumulated on the faults that ruptured during this event (Fig. 12; Plate 2; Table 2). Faults hh and ii are the only faults exposed in the trench that indicate rupture during this event (Fig. 12; Plate 2). A colluvial wedge (Qcs) is interpreted to have formed as a result of this faulting.
Unit Q_{cs} overlies units Q_{c6} and Q_{c7}. Thus, Q_{cs} is younger than the event that created those units (Fig. 12; Plate 2). Unit Q_{cs} is in turn overlain by unit Q_{c9} (Fig. 12; Plate 2).

Unit Q_{c9} is interpreted to be a colluvial wedge that resulted from the next youngest faulting event documented in the lower trench (event association 2l) (Fig. 12; Plate 2). Faults aa1 – aa2 are part of the main fault zone and account for 1.98 m vertical displacement along the main trace (Fig. 12; Plate 2). The vertical displacement for this fault was calculated by subtracting the measured throw of faults z (0.51 m), bb (0.93 m), and cc (0.98 m?) from the total measured throw of unit Q_{c5} (Fig. 12; Plate 2). In addition to the amount of displacement, these faults exhibit a higher abundance of shear matrix, or fault rock, and clasts aligned along the fault plane than the other faults observed in the trench.

The youngest, or most recent event (MRE) in the lower trench (event association 1l) accounts for ~ 1.5 m throw on fault z and the antithetic fault cc (Fig. 12; Plate 2). These faults form a graben that bounds faults aa1 – aa2 and bb; together these faults all form the main trace (Fig. 12; Plate 2). A thin layer of unconsolidated colluvial material (Q_{c10}) originates at fault z and terminates at fault cc (Fig. 12; Plate 2). This colluvial material is also observed to cover fault aa1 – aa2 and overlie unit Q_{c9} (Fig. 12; Plate 2).

Previously it was stated that “it is impossible to directly relate faults younger than Q_{c5} in the upper and lower portions of the trench.” Although this statement is fundamentally correct, inferences can be made that allow a loosely constrained correlation of events between the upper and lower portions of the trench. Faults jj and kk in the lower trench portion were not considered a separate event because of the lack of exposure, the lack of definitive properties of a fault, and offset too small to be considered a surface rupturing
Although they do rupture into unit Q\textsubscript{15} (Fig. 12; Plate 2). These faults were considered active during a younger event that failed to propagate through the sediment, or as just a fracture. However, an apparent correlation exists between these faults (jj and kk) and faults related to the oldest event in the upper part of the trench (faults k – x) because all these faults are observed to displace unit Q\textsubscript{15}, but not cut all the way through the unit (Fig. 12; Plate 2). While this relationship is not definite, it is logical, so another event must be added to the lower trench (event association 51). This brings the total number of events observed in the lower trench to 5 events.

Although it is possible to correlate this oldest observed event in the lower and upper trench directly, the other events cannot be correlated directly. The preferred interpretation is that the MRE determined in the upper and lower portions of the trench are equivalent. This interpretation is based on the recognition that the MRE in the lower trench occurred after 10,870 ± 70 BP (12,650 – 12,740 cal BP 2σ) and the MRE in the upper trench is younger than 9,230 ± 80 BP (10,580 – 10,220 cal BP 2σ). The close temporal relationship between the dated horizons and the recognition of offsets of these units suggests that the rupture of the faults occurred during the same paleoearthquake event. The faults that ruptured during the second event in the upper trench (faults f – i) cannot be correlated to faults in the lower trench. The only correlation that can be made is to suggest that the faults that resulted from the second event in the upper trench occurred with one of the second, third, or fourth events delineated in the lower trench.

**Surface Rupture Chronology**

Fault correlations and event associations allow approximate ages to be assigned to paleoearthquakes (ie., PE1) using the radiocarbon dates determined for units Q\textsubscript{15}, Q\textsubscript{07}, and
Q9 (Fig. 12; Plate 2). Based on the spatial relationships between faults k – x, jj, and kk and unit Q15 it is possible to estimate an age for PE5 (event associations 51 and 3u). Unit Q15 has a radiocarbon date of 19,290 ± 120 BP (22.26 – 23.54 cal BP 2σ) in the lower trench. Although there are three radiocarbon dates for this unit, this age is considered the most reliable because this unit was buried, subsequently isolating it from further input of younger material, unlike the 16,650 ± 90 BP age. The oldest observed deformation from event PE5 caused displacement of unit Q15, but the unit is not completely cut through (Fig. 12; Plate 2). This relationship suggests that this earthquake event occurred coeval with deposition of this unit, therefore the radiocarbon age of 19,290 ± 120 BP (22,260 – 23,540 cal BP 2σ) is considered a close approximation to the age of this paleoearthquake event.

The PE4 (event association 41 and 2u?) is loosely constrained between 19,290 ± 120 BP (22,260 – 23,540 cal BP 2σ) and PE3 based on the observation that faults related to this paleoearthquake event displace unit Q15, caused the formation of colluvial wedge Q6, and are covered by unit Q9 (Fig. 12; Plate 2). The timing of PE3 (event association 31 and 2u?) is constrained to between PE4 and 10,870 ± 70 BP (12,650 – 12,740 cal BP 2σ) because faults hh and ii cut unit Q6, the colluvial wedge formed as a result of PE4, and are overlain by unit Q9 (Fig. 12; Plate 2). The largest paleoearthquake (PE2) is interpreted to have occurred ~ 10,870 ± 70 BP (12,650 – 12,740 cal BP 2σ) because the dated unit Q9 is interpreted to be the colluvial wedge associated with this event. The only constraint that can be placed on the MRE (PE1) is that it occurred more recently than 9,230 ± 80 BP (10,580 – 10,220 cal BP 2σ).
An exact retrodeformation of stratigraphic units observed in the trench was not possible due to several factors. First, the depositional environment for some units is unclear (i.e., Qc9). For instance, unit Qc9 may have been deposited by a migrating drainage, may be an inset fan deposited in the topographic low created by faulting, or alternatively may in fact be a colluvial wedge. Second, given the depositional environment (alluvial fan), it is not possible to assume lateral continuity of depositional units. Third, the downslope extent of units is unknown. If the full length of units overlying Qrs in the upper trench was known, the volume of material missing could be estimated and used to infer material moved downslope. As it is, it is unclear whether these units are eroded, or represent their original extent. Lastly, the true maximum thickness of some units is unclear. Alluvial fan units are observed to be thicker between the shoulder and backslope, but erosion and/or deflation/inflation of the surface does not allow the true thickness to be known. Without the true maximum thickness of units (i.e., Qrs), it is impossible to calculate the volume of material removed and transported downslope. Given these possibilities, and the recognition of multiple events that increases the fan slope and mountain front height, it is possible to account for sediment volume without requiring material to be derived from directly upslope by colluvial wedge processes.

**Slip Rates**

The fault displacement and rupture age data allow calculation of a slip rate for the BHF. The slip rates are calculated using the oldest radiocarbon age of 23,540 cal BP and the total throw measured in the trench. For the longest-term slip rate, the 12.965 m total throw measured in the trench was divided by the oldest age of 23,540 cal BP to yield a
slip rate of 0.55 mm/yr. It should be noted that this slip rate is considered the maximum slip rate because the radiocarbon age is a minimum age and there is no lower age constraint. This slip rate also assumes that the events observed in the upper trench are correlated correctly to events in the lower trench.

To provide a lower constraint on the slip rate with no need for assumptions, the total amount of displacement measured in the lower trench (7.59 m) was divided by the 23,540 cal BP age. This yielded a slip rate of 0.33 mm/yr, which is the slowest possible slip rate determined for the BHF. The most conservative slip rate estimate was calculated by adding all measured displacement in the trench (12.965 m), subtracting measured offset of faults from the oldest and youngest events (12.965 m - 5.905 m = 7.06 m), and dividing this total by the time between the oldest and youngest possible paleoearthquakes (23,540 - 9,230 = 14,310 yrs). This closed-interval method yields an estimated slip rate of 0.49 mm/yr, which is very close to the 0.5 mm/yr slip rate inferred from the mountain-front sinuosity and valley-depth to valley-width method (Table 2). Regardless, the 0.33 - 0.55 mm/yr slip rates estimated in this study are significantly higher than the 0.01 - 0.10 mm/yr slip rates previously estimated for faults in this region (dePolo, 1998).

Earthquake Magnitude

Using displacements measured in the trench it is possible to estimate the moment magnitude for each earthquake event by plotting the displacement measurements on regression plots derived from known earthquakes from around the world. Based on data from known earthquakes, moment magnitudes for the BHF are estimated using Wells and Coppersmith’s (1994) regression plots. The maximum displacement for each earthquake event observed in the trench is plotted on the moment magnitude vs maximum
displacement regression plot to determine the maximum credible earthquake. The maximum displacement used for each estimate is the largest measured displacement on a single fault for each earthquake event. For PE5, a $M_w = 6.6$ is estimated from the maximum observed displacement of 0.71 m (Fig. 15). PE4 is estimated to have a $M_w = 6.6$ based on the 0.74 m measured maximum displacement (Fig. 15). The third event (PE3) has 0.95 m maximum displacement which suggests $M_w = 6.7$ (Fig. 15). For the penultimate event (PE2), $M_w = 6.9$ is estimated from the 1.96 m of maximum displacement (Fig. 15). The MRE (PE1) has 1.12 m maximum displacement which indicates $M_w = 6.7$ (Fig. 15).

Moment magnitude may also be estimated based on average displacement (Wells and Coppersmith, 1994). Because it is not possible to measure the average displacement, the average displacement is taken as $0.33 \pm 0.9$ of the maximum displacement (Wells and Coppersmith, 1994; McCalpin and Slemmons, 1998). The average displacement for PE5 is estimated to be 0.23 m which suggests $M_w = 6.4$ (Fig. 16). PE4 is interpreted to have been $M_w = 6.4$ based on the estimated 0.24 m average displacement (Fig. 16). The average displacement of 0.31 m estimated for PE3 indicated $M_w = 6.5$ (Fig. 16). The average displacement for the PE2 is estimated to be 0.65 m, which suggests $M_w = 6.8$ (Fig. 16). The MRE (PE1) has $M_w = 6.6$ based on the 0.37 m average displacement estimate (Fig. 16).

All moment magnitude estimates are considered minima because it's possible that the maximum displacements measured may not be the true maximum displacements. The displacement measurements are not considered true maxima because they were measured in the trench, which lies near the southern end of the BHF (Fig. 5; Plate 2). The largest
measured scarp height lies ~ 1 km north of the trench and is considered the best location to measure true maximum displacements, but was inaccessible for trench excavation.

Another problem that arises regarding the moment magnitude estimates using SRL indicate that the SRL is too short to generate the large magnitude earthquakes suggested by the regression models.

**Surface Rupture Length**

In addition to using displacement to estimate moment magnitude, surface rupture length may also be used to estimate paleoearthquake magnitudes. The ~ 4.5 km SRL determined for the BHF was plotted on the moment magnitude vs. SRL regression plot and yielded $M_w = 5.8$ (Fig. 17). This magnitude estimate poses a problem in that it has been reported that normal faults with earthquakes less than $M_w \sim 6.0$ are generally unlikely to create a surface rupture (e.g., Pezzopane and Dawson, 1996). In fact, to generate the $M_w \sim 6.4 - 6.9$ earthquakes estimated from the regressions, the SRL of the BHF would have to be 13.7 - 37.1 km (Figs. 15 - 17).

The maximum displacement vs. surface rupture length regression plot are also useful in illustrating the short SRL issue. Using the observed SRL of ~ 4.5 km, the maximum displacement estimated is 0.22 m (Fig. 18), which contrasts greatly with the maximum throws of 0.71 - 1.96 m measured in the trench. Conversely, using the maximum displacements measured, the regressions indicate the SRL should be 14.8 - 41.4 km (Fig. 18). This apparent discrepancy demands evaluation.

One possible explanation is that the mapped SRL of ~ 4.5 km is a minimum. To the south, the scarp along the main trace is ~ 2.8 m where it is truncated by an active drainage originating in the gap between the pluton of the Black Hills and volcanic rocks
of the southern Black Hills (Fig. 5; Plate 1). South of the active drainage is a large alluvial fan (Q2m) that is interpreted to be equivalent in age to geomorphic map unit Qa2, although it is possible that these fans are younger if the geomorphic surface development is enhanced by their location (i.e., different soil forming factors) (Fig. 5; Plate 1). Even if these fans are younger than the main trace, no scarps are located along the base of the volcanic rocks of the southern Black Hills so the SRL could only have been ~ 1.5 km longer. This does not provide the necessary length to satisfy the regression estimates.

While it is possible to hypothetically extend the surface rupture of the BHF slightly to the south, it is not possible to increase the surface rupture to the north for two reasons. The first reason is that the surface trace is observed to gradually decrease in height along strike to the north to the extent that the scarp is less than 0.3 m where it is truncated by an anthropogenically-disturbed area (Fig. 5; Plate 1). The highest measured scarp height occurs on the main trace and coincides with the greatest topographic relief between the pluton and basin floor (~ 690 m). The scarp height and range elevations decrease towards the tip of the fault in a classic “bow and arrow” type pattern. The observation of the decreased scarp height and the ‘bow and arrow’ vector displacement pattern suggests that additional surface rupture to the north is unlikely.

Another reason that the surface rupture cannot be continued to the north is the lack of displaced Quaternary sediment north and/or east of the mapped trace. During the time of this study, two trenches were excavated perpendicular to the strike of the BHF for engineering purposes. One trench (trench BCWP) was excavated between Henderson and Boulder City for a 36” water pipe and was 2 - 4 m deep (Fig. 5; Plate 2). No faults were observed to displace Quaternary sediment, but several ~ N-S striking faults cut
bedrock exposed in the trench. It is possible that the Quaternary sediment exposed in this trench post-date the MRE on the BHF, but the bedrock that was cut by the faults was planed off, suggesting that these faults are significantly older than the BHF surface rupturing events. The other trench (trench BHTL) was excavated near the northern extent of the mapped trace for telephone lines and was 1.5 – 2.0 m deep (Fig. 5; Plate 2). No faults displaced units in this trench. Based on geomorphic expression of units near BHTL trench exposures, the lithologic units observed in this trench are interpreted to be equivalent in age to the Qa1 map unit. The lack of displacement of sediment similar in age to those displaced by the fault elsewhere indicates that the surface rupture of the BHF does not continue to the north.

Another possible explanation for the unexpectedly short SRL is that deformation occurred in a short, but relatively wide zone of faulting. This hypothesis is viable based on the recognition of multiple fault scarps along the Black Hills (Fig. 5; Plate 1). Cumulatively, all strands along the Black Hills total ~ 24 km of surface displacement. This significantly raises the SRL measurement, although it is known that not all of these strands ruptured during the same event. While this hypothesis could aid in resolving the short SRL discrepancy, it is beyond the scope of this project to quantify this relationship. In addition, using the cumulative length would not yield proper results as estimates of SRL from regressions are based of single strand lengths.

An additional hypothesis that has been proposed that would increase the SRL of the BHF is that the BHF is linked to the MSF (Slemmons et al., 2001) (Fig. 2). While late Quaternary – Holocene scarps are recognized on both faults, no scarps are observed between the two faults. In addition, trenches BCWP and BHTL show no evidence of
faulting where the BHF would have to cross to be linked to the MSF (Fig. 5; Plate 1). Whereas no evidence suggests a link between these faults that would increase the SRL of the BHF, a link at depth cannot be ruled out.

The preferred interpretation for resolving the short SRL is to consider the apparent discrepancy to be a result of the intersection of the fault rupture patch and the topographic surface. When a fault moves, the initial motion is from a point source, the hypocenter or focus (Fig. 19). From the focus of the earthquake, the motion propagates outward along the fault surface. The propagating motion along the fault plane is the spreading dislocation surface (Fig. 19). The dislocation surface, or rupture patch, may not spread uniformly, causing displacement to concentrate along a certain course within the patch as opposed to being distributed entirely along the entire fault plane. This may be the case along the BHF (Fig. 20).

This rupture patch model allows for a short SRL with a longer rupture length in the subsurface. When the spreading dislocation surface is concentrated along a narrow course within the patch, the displacement at the surface may be contained to a shorter length. Although the highest amount of motion is restricted to a narrow zone, some motion is still distributed along the length of the rupture patch. This distribution of deformation is interpreted to represent the style of deformation observed along the BHF. The short SRL is interpreted to represent the surface expression of a relatively low concentration of deformation along the spreading dislocation surface. The motion along the spreading dislocation surface that is in the higher motion zone is distributed along a course within the rupture patch at depth along the fault. This could greatly increase the rupture length of the fault, to the extent that the discrepancy indicated by the regression
models becomes minimal. The discrepancy is considered minimal with this model because the geomorphic expression of the Black Hills suggests that the rupture patch length of the fault would be at least 15 km. While this rupture length is still significantly shorter than the ~ 40 km suggested by regressions for a $M_w = 6.9$, it begins to approach the lower rupture length estimates of the regressions ($\sim 14$ km rupture length with a $M_w = 6.4$).

One uncertainty in this interpretation related to the BHF, is how lithology affects this model, or more specifically, whether the spreading dislocation surface is controlled by lithology. The surface rupture length of the BHF is observed to be constrained to the length of the pluton of the Black Hills, with no indication of surface rupture along the volcanic rocks of the southern Black Hills (Fig. 5; Plate 2). It is unclear whether the plutonic rock focused the motion along a narrow spreading dislocation surface, or if this relationship is just coincidental. Regardless, this model provides a plausible explanation that accounts for the large displacements with a short SRL.

2.5 Seismic Hazards

The term 'active fault' has several definitions that depend on the intention and context in which the fault is being studied. For the purpose of seismic hazard assessment, an active fault is defined by Boschi et al. (1996) as “a structure that has an established record of activity in the late Pleistocene (ie., in the past 125 ka) and a demonstrable or inferable capability of generating major earthquakes.” Geotechnical studies generally consider a fault active or ‘capable’ if evidence exists for multiple earthquake events in the past 500 ka, or one event in the past 35 ka (e.g., Slemmons, 1981). Based on the
recognition of 4 – 5 surface rupturing earthquakes in the past ~ 23 ka, the BHF is classified as an active fault by all definitions.

It is important to recognize the BHF as an active fault because of the fault's location near a growing metropolitan area. This study estimates that the BHF is capable of generating a $M_w \sim 6.9$ earthquake and has a relatively high slip rate of $0.33 - 0.55$ mm/yr. The magnitude estimates and calculated slip rates have been used to estimate a model-derived recurrence interval (RI) of $\sim 1 - 3$ ky (Fig. 21) (Slemmons, 1977). The average RI estimated from trench data is 4.7 ky with exact calculation indicating a variable RI ranging between $3.6 - 10.2$ ky. The lower 3.6 ky RI is calculated for the earthquake events older than $9,230 \pm 80$ BP ($10,580 - 10,220$ cal BP $2\sigma$). The 10.2 ky RI is estimated for one event since $10,220$ cal BP, thus is uncertain. This uncertainty poses a problem in that the MRE could have occurred $\sim 8$ ka, making the BHF highly likely to rupture in the near future, or the MRE could have happened $\sim 1$ ka, indicating that another earthquake event in the near future is unlikely. Nevertheless, the possibility of a large magnitude ($M_w \geq 6.0$) earthquake on this fault in the future is considered likely, which could pose a concern for the people and structures located near the fault.

Structures located in close proximity to the BHF that could be at risk include an ammunition manufacturing plant ($\leq 100$ m along strike), three gravel quarries ($\leq 1$ km), a natural gas pipe ($\sim 1 - 2$ km), a power plant ($\sim 5$ km), Boulder City ($\sim 7$ km), Henderson ($\sim 12$ km), and Las Vegas ($\sim 30$ km).
2.5 Conclusions

This study has determined that the BHF is a multistranded normal fault that has a composite history. A total of 14 strands have been documented with the maximum single-strand SRL of ~ 4.5 km occurring on the main trace. The main trace records the largest measured scarp height of 3.49 m, which has discrete bevels that indicate a three-event composite history. The composite history inferred from scarp bevels is verified with trench data, which indicates three scarp forming events along the main trace.

Paleoseismic trench data and radiogenic carbon dating indicate that at least five surface rupturing earthquake events have occurred since the latest Pleistocene. The oldest event is interpreted to have occurred ~ 19,290 ± 120 BP. The best estimates for the following two events are between 19,290 ± 120 BP and 10,870 ± 70 BP. The fourth (penultimate) event is has a rupture age of ~10,870 ± 70 BP. The MRE is loosely constrained to < 9,230 BP. All ages determined are considered minimum ages because of cumulative average effect inherent in radiocarbon dates using pedogenic carbonate.

Estimated slip rates range from 0.33 – 0.55 mm/yr, based on the 12.965 m of throw measured for all faults in the trench and the oldest reported age of 23,540 cal BP. These rates are considered maxima because the radiocarbon ages are minima. Vertical displacement on individual faults ranges between 0.05 – 1.98 m. The relatively high calculated slip rates are supported by range-front sinuosity values of 1.12 – 1.29 and valley depth – valley width values of 0.10 – 0.27, both of which suggest slip rates of ~ 0.5 mm yr⁻¹.

Paleoearthquake magnitudes were estimated using the maximum and average displacements per event and plotting these on regression models. The regressions for
smallest average displacement (0.23 m) and the largest maximum displacement (1.96 m) indicate that the BHF is capable of generating $M_w \sim 6.4 - 6.9$, respectively. These estimates are considered minima because true maximum and average displacements were not measured. These magnitude estimates conflict with magnitude estimates calculated using SRL.

Magnitude estimates from the regression using SRL indicate $M_w = 5.8$ is expected for a fault, like the BHF, with a SRL of $\sim 4.5$ km, whereas a SRL of $\sim 39$ km is expected for a fault that experiences a $M_w = 6.9$ earthquake. This problem is also observed when using the SRL vs. maximum displacement regression. The SRL of $\sim 4.5$ km is estimated to have maximum displacement values of 0.22 m, while the observed maximum displacement of 1.96 m should have a SRL of $\sim 41$ km according to this regression model. This discrepancy is interpreted to be a result of incomplete rupture of an entire fault plane, a narrow spreading dislocation surface such that only part of the rupture patch reaches the surface, and/or a deep hypocenter. It is unclear whether this phenomenon is controlled by lithologic differences or other factors.

Using the estimated earthquake magnitudes and calculated slip rates, the estimated recurrence interval for activity on this fault should be $\sim 1 - 3$ ky. However, using the five determined earthquake events since $\sim 19,290 \pm 120$ BP ($22,260 - 23,540$ cal BP 2σ), the recurrence interval is more likely in the $3.6 - 10.2$ ky range for the latest Pleistocene. Based on the relatively short RI, high slip rates, and high earthquake magnitude estimates, the BHF should be considered to pose a significant hazard to Boulder City and the Las Vegas metropolitan area.
CHAPTER 3

QUATERNARY FAULTING IN THE LAKE MEAD TECTONIC DOMAIN, SOUTHERN NEVADA: IMPLICATIONS FOR ACTIVE CENTRAL BASIN AND RANGE DEFORMATION

3.1 Introduction

The central Basin and Range province (CBR) in the southwestern U.S. has been the subject of numerous studies in the past ~25 years. The foci of these studies vary among the magnitude, amount, and timing of extension (e.g., Wernicke et al., 1988); Miocene to present reconstructions (e.g., Wernicke et al., 1988; Wernicke and Snow, 1998; Snow and Wernicke, 2000); and plate boundary and lithospheric forces driving extension in this region (e.g., Atwater, 1970; Atwater and Stock, 1998; Sonder and Jones, 1999). In addition, ~25% of the motion between the Pacific and North American plates is accommodated in the CBR (e.g., Minister and Jordan, 1987), predominantly along the western margin in the Walker Lane belt (WLB) and eastern California shear zone (ECSZ), and this motion has prompted numerous recent geodetic studies (e.g., Dixon et al., 1995, 2000; Bennett et al., 1997; Hearn and Humphreys, 1998; Bennett et al., 2003). This study synthesizes previous work of the deformation to provide a possible model that fits Pleistocene to Holocene deformation in the Lake Mead tectonic domain (LMTD) (this study) into the temporal and spatial tectonic relationships interpreted for the western United States.
The CBR is defined by Wernicke (1992) as the highly extended terrain bounded on the west by the Sierra Nevada, the east by the Colorado Plateau, the north (~ 37° N) by the northern Basin and Range, and the south (~ 35° N) by the southern Basin and Range (Fig. 1). The WLB, Death Valley fault system (DVFS), ECSZ, and LMTD (Lake Mead extended domain of Wernicke, 1992) are sub-provinces that are generally discussed separately, but are included within the CBR based on timing and style of deformation (Fig. 1). Although the WLB extends along most of the length of the Sierra Nevada, only the southern end is included within the CBR (Fig. 1). Likewise, only the northern extent of the Eastern California shear zone (ECSZ) is included within the CBR (Fig. 1).

The ECSZ is defined by Dokka and Travis (1990) as a complex series of mid-Cenozoic strike-slip and normal faults related to Basin and Range extension and late Miocene to Holocene strike-slip, normal, and reverse faults related to the transfer of motion from the San Andreas fault system to the WLB. For clarity, this paper adopts the terminology of Miller and Yount (2002) where the youngest strike-slip faults in the ECSZ related to strain transfer from the San Andreas fault system are termed the "Mojave strike-slip province" (MSSP). This terminology excludes faults of the ECSZ related to mid-Cenozoic extension that pre-dates extension in the CBR, and refers exclusively to faults in the ECSZ that are late Cenozoic in age and are related to recent and current deformation resulting from Pacific – North American plate motions (Fig. 1).

The WLB consists of nine structural domains that form a ~ 100 km wide zone that extends from the northern Sierra Nevada to the Garlock fault (Fig. 1) (Stewart, 1988). The nine domains are differentiated by changes in fault strikes and/or slip sense, although the predominant trend of the WLB is northwest-striking dextral and normal faults.
Mid- to late-Miocene deformation in the southern WLB was dominated by large-scale extension accommodated on high- and low-angle normal faults of the DVFS (area of overlap between the ECSZ and WLB on Fig. 1) (e.g., Wright and Troxel, 1973; Wernicke et al., 1988). Late Miocene marked a westward migration of extensional faulting and the onset of significant dextral faulting in the Death Valley region (Wernicke et al., 1988; Wernicke and Snow, 1998; Snow and Wernicke, 2000). The westward migration of tectonism is not only documented in the DVFS, but is recorded throughout the entire CBR, originating in the LMTD (Wernicke et al., 1988; Wernicke, 1992; Atwater and Stock, 1998; Wernicke and Snow, 1998; Sonder and Jones, 1999; Snow and Wernicke, 2000).

The LMTD is the highly extended region between the Colorado Plateau and the Spring Mountains that is dominated by the right-lateral Las Vegas Valley shear zone (LVVSZ), the left-lateral Lake Mead fault system (LMFS), and numerous predominantly SW-directed high- and low-angle normal faults that are kinematically linked to the strike-slip faults (Fig. 2) (Anderson, 1973; Bohannon, 1979, 1984; Wernicke et al., 1988; Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992; Duebendorfer et al., 1998). The NW-striking LVVSZ and NE-striking LMFS are interpreted to represent conjugate intracontinental transform faults separating areas of differentially extended terrains while accommodating N-S compression and E-W extension (Anderson, 1973; Bohannon, 1983; Wernicke et al., 1988; Cakir, 1990; Cakir and Aydin, 1990; Wernicke, 1992; Anderson et al., 1994; Duebendorfer et al., 1998). Extensional deformation in the LMTD is believed to have initiated ~ 15 Ma (Anderson, 1971; Anderson et al., 1972) and continued until at least 8.4 Ma (Campagna and Aydin, 1994; Duebendorfer et al., 1998).
with deformation migrating to the west through time (Wernicke et al., 1988; Wernicke, 1992; Atwater and Stock, 1998; Wernicke and Snow, 1998; Sonder and Jones, 1999; Snow and Wernicke, 2000). In addition, Pliocene(?)-Holocene normal faults have been documented in this region (e.g., Bingler, 1977; Bell and Smith, 1980; Matti and Bachhuber, 1985; Matti et al., 1987; Anderson and O’Connell, 1993; dePolo, 1998; Werle and Knight, 1998; Matti et al., 1999; Slemmons et al., 2001; Taylor et al., 2001; Bidgoli et al., 2003; Fossett, Chapter 2).

Despite the recognition of young faults within the LMTD, few studies have discussed their role in the active deformation in the CBR. Perhaps the slow geodetic rates determined for this area (e.g., Nevada Association of Land Surveyors, Southern Nevada GPS Subcommittee, 1999) suggests a negligible role in the regional deformation. This study contends that Pliocene(?)-Holocene deformation in the LMTD plays a significant role in the regional strain budget, but is poorly understood due to lack of study. That is not to say that the active deformation in the LMTD approaches rates observed along the eastern Sierra Nevada, but that rates could be substantially higher than recognized. This study uses a synthesis of previous works to provide a plausible framework that allows for a change in extension direction of the young normal faults in the LMTD compared to older faults, and relates current deformation observed in the LMTD to deformation along the eastern Sierra Nevada, and thus plate motions.

3.2 Timing of Central Basin and Range Extension

The following section provides a brief overview of the timing and westward migration of extension in the CBR and MSSP (Fig. 22). Prior to ~16 Ma, the CBR was a
relatively unextended region within the Great Basin. At ~ 16 Ma, large-magnitude E-W extension begin to widely affect the CBR region. Plate motion reconstructions (e.g., Atwater and Stock, 1998) indicate an increase in plate motion velocity at ~ 12 Ma, and a change in plate motion directions at ~ 8 Ma. Other authors (e.g., Cox and Engebreston, 1985; Pollitz, 1986; Dixon et al., 1995) have suggested an additional change in plate motions at ~ 5 – 3 Ma, although Atwater and Stock (1998) could not resolve these changes in Pliocene plate motions. However, a noticeable change in tectonic deformation style in the western CBR and MSSP does occur at ~ 5 – 4 Ma.

Prior to ~ 16 Ma, extension was localized mainly within the northern and southern Basin and Range provinces, although some major extensional deformation occurred within the CBR. Some normal faulting occurred in the Death Valley region prior to 16 Ma, most notably along the western edge of the Titus Canyon basin and in the Ubehebe basin (Fig. 23) (Snow, 1990; Snow and White, 1990; Snow and Lux; 1999; Snow and Wernicke, 2000). Faulting along the Kingston Range detachment initiated at about 16 Ma (Fig. 23) (Snow and Wernicke, 2000).

In addition to relatively minor extension in the Death Valley region, the Mojave block and northern Colorado River extensional corridor exhibited widespread extension prior to ~ 16 Ma (Figs. 1 and 23) (e.g., Glazner and Supplee, 1982; Faulds et al., 2001). Extension spread from the westernmost Mojave region to east of the Whipple Mountains (Glazner and Bartley, 1984; Glazner, 1990; Glazner et al, 2002). In the northern Colorado River extensional corridor, extension and magmatism initiated ~ 22 Ma at ~ 35° N latitude and swept northward where it ceased in the LMID at ~ 12 Ma (Fig. 23)
Glazner and Bartley, 1984; Gans et al., 1989; Faulds et al., 1994; Smith and Faulds, 1994; Faulds et al., 1999, 2001).

The time between 16 and 12 Ma marked the onset of widespread extension within the CBR (Fig. 24). Large-magnitude extension was concentrated in the LMTD and Nevada Test Site regions at this time and shows a general westward progression of deformation through time (Figs. 1 and 24).

Deformation in the LMTD is interpreted to have been largely controlled by two separate strike-slip fault systems, the LVVSZ and LMFS, and have both an opposite sense of slip and strike directions. The ~ 15 – 8.5 Ma LVVSZ (Longwell, 1960; Bohannon, 1979, 1984; Rowland et al., 1990; Duebendorfer and Black, 1992; Duebendorfer et al., 1998) is interpreted to be a transfer fault separating middle Miocene deformation in the Nevada Test Site area (northern Death Valley) from younger extension in the LMTD (Fig. 24) (Fleck, 1970b; Davis and Burchfiel, 1973; Wernicke et al., 1988; Duebendorfer and Black, 1992; Duebendorfer et al., 1998). The LMFS is a series of left-lateral and kinematically linked normal faults that are interpreted to accommodate most of the extension in the LMTD from ~ 12.5 to 8 Ma (Figs. 2 and 24) (Wernicke and Snow, 1998; Duebendorfer et al., 1998). The LMFS and Saddle Island detachment (SID) are largely responsible for the southwestward translation of Frenchman Mountain from the Gold Butte area to its present location (Figs. 2 and 24) (e.g., Rowland et al., 1990).

Northwest of the LMTD, in the Nevada Test Site region (north Death Valley region), rotations in the Specter Range suggest initiation of large-magnitude extension at ~ 16 – 15 Ma (Fig. 24) (Snow et al., 1993, Snow and Prave, 1994; Snow and Lux, 1999). The
clockwise rotation documented in the Specter Range forms an oroflexure in map view that is the product of dextral shear on the LVVSZ (e.g., Burchfiel, 1965). The Sheep Range detachment, the controlling structure for much of the extension transferred to the LVVSZ, is interpreted to have initiated ~ 13 Ma (Fig. 24) (Guth, 1981, 1990; Guth et al., 1988; Wernicke et al., 1988).

In the central Death Valley region, the inception of detachment faulting occurred ~ 13 Ma along the western flank of the Spring Mountains (Fig. 24) (Snow and Lux, 1999; Snow and Wernicke, 2000). Although the LVVSZ forms the southern boundary of the Sheep Range detachment, Snow and Wernicke (2000) suggest that it extended across the LVVSZ as the Point of Rocks fault and was later offset (Fig. 24).

During the 12 – 8 Ma time period, extensional deformation continued in the LMTD and progressed westward into the Death Valley region (Fig. 25). Extension in the LMTD and Nevada Test Site regions was in its waning stages between 10 and 8 Ma (Duebendorfer and Simpson, 1994; Duebendorfer et al., 1998). In the Nevada Test Site region, extension migrated west from the Specter Range to the Bare Mountain, Bullfrog Hills, and Boundary Canyon areas from ~ 12 – 8 Ma (Fig. 25) (Reynolds et al., 1986; Carr, 1990; Hoeisch et al., 1997; Fridrich, 1999).

South of the Nevada Test Site in the central Death Valley region, extension continued to migrate west from the Spring Mountains. The locus of deformation west of the Spring Mountains migrated from the Point of Rocks fault towards the Black Mountains area ~ 9 Ma (Fig. 25) (Holm et al., 1992). In the eastern Black Mountains, the Amargosa detachment initiated ~ 8 – 7 Ma, and shows a northwestward progression of deformation (Fig. 25) (Holm et al., 1992; Holm and Dokka, 1993; Holm, 1995).
In addition to initiation of detachment faulting, strike-slip faulting also initiated in the central Death Valley region during this time. The southern Death Valley fault zone initiated dextral simple shear at ~10 Ma and the Furnace Creek fault zone initiated dextral movement ~9 Ma (Fig. 25) (Butler et al., 1988; Snow and Lux, 1999; Snow and Wernicke, 2000; Niemi et al., 2001). East of the northern Avawatz Mountains, several strands of the southern Death Valley fault system are truncated by the sinistral Garlock fault, which is interpreted as an intracontinental transform that separates the highly extended Death Valley region from the relatively unextended Mojave block (Davis and Burchfiel, 1973; Wernicke et al., 1988; Spencer, 1990) (Fig. 25).

In the 8–4 Ma timeframe, no significant changes occurred in the locus of deformation until ~6 Ma. Extension migrated west from Bare Mountain and the Bullfrog Hills at ~7.6 Ma and from the west flank of the Spring Mountains to the west side of the Panamint Range at ~7–6 Ma (Fig. 26) (Weiss et al., 1993; Snow and Lux, 1999; Niemi et al., 2001). The west side of the Panamint Range was exposed by the Emigrant fault system at ~6 Ma and separated the Panamints from the southern Cottonwood Mountains (Fig. 26) (Hodges et al., 1989). The Cottonwood Mountains were also separated from the Grapevine Mountains at this time (Fig. 26) (Snow and Lux, 1999; Snow and Wernicke, 2000). In addition to detachment faults, oblique-slip and strike-slip faults began to play a significant role in the tectonic development of this region at ~5 Ma.

The first of the pull-apart basins to open formed in the present Deep Springs Valley at ~6–7 Ma (Reheis and Sawyer, 1997) and Fish Lake Valley at ~5 Ma (Fig. 26) (Reheis,
1993; Reheis and Sawyer, 1997). In addition to strike-slip faults becoming dominant in the Death Valley area, strike-slip faults were also becoming prevalent in the MSSP.

After 5 Ma, the strain field in the Death Valley – MSSP region was dominated by right-lateral shear and transtension (Snow and Wernicke, 2000). The Hunter Mountain fault opened Saline Valley after ~ 2.8 Ma (Burchfiel et al., 1987; Conrad et al., 1994). The Emigrant fault system continued to separate the Cottonwood Mountains from the Panamint Range between ~ 6 and 3 Ma (Fig. 27) (Hodges et al., 1989; Snow and Lux, 1999). The northern Death Valley – Furnace Creek fault system continued motion and opened the northern Death Valley pull apart basin (Fig. 27) (Brogan et al., 1991). The opening of Owens Valley began ~ 3.4 – 2.3 Ma (Fig. 27) (e.g., Bachman, 1978).

Lee et al. (2001) describe a dynamic kinematic model that suggests a transfer of slip from the MSSP and southern Death Valley fault zone to the Owens Valley and Hunter Mountain faults and then to the northern Death Valley – Furnace Creek – Fish Lake Valley fault systems through the Deep Springs, Eureka Valley, and Emigrant normal fault systems (Fig. 27). The transfer of slip from northwest-striking dextral faults through northeast-striking, northwest-dipping normal faults accommodates the northwestward translation of the Sierra Nevada block.

The LMTD also underwent a rejuvenation of extensional deformation during this time period. Numerous Quaternary normal faults are documented in and around the Las Vegas basin (Figs. 2 and 27) (e.g., Bingler, 1977; Bell and Smith, 1980; Matti and Bachuber, 1985; Matti et al., 1987; Anderson and O'Connell, 1993; dePolo, 1998; Werle and Knight, 1998; Matti et al., 1999; Slemmons et al., 2001; Taylor et al., 2001; Bidgoli et al., 2003; Fossett, Chapter 2). The Quaternary faults in the LMTD with the largest
offset or highest slip rates are the Frenchman Mountain fault (FMF), the Eglington – Decatur fault (EDF), the California Wash fault (CWF), and the Black Hills fault (BHF) (Figs. 2 and 27). The faults north of the LVVSZ have a N-NE strike and dip W, whereas faults within the Las Vegas basin strike N and have an E dip, except for the FMF which dips W. Although many faults in the LMTD have geomorphic expressions indicating Quaternary movement, insufficient data exist to constrain the time of initiation for these faults.

The most-studied Quaternary fault in the LMTD is the BHF (Figs. 2 and 27) (e.g., Anderson and O’Connell, 1993; Werle and Knight, 1998; Fossett, Chapter 2). The BHF is a multi-stranded normal fault that underwent five surface rupturing earthquake events in the past ~ 25 ka (Fossett, Chapter 2). The Quaternary fault scarp strikes ~ N25°E and dips steeply to the SE (Fossett, Chapter 2). Along the northern end of the Black Hills, an older set of NW-striking, NE-dipping faults are interpreted to have accommodated SE–NW extension during the mid-Miocene deformation event.

Recent studies in the CBR have focused on the current rate of deformation using geodetic data (i.e., Dixon et al., 1995; Bennett et al., 2003). Velocity estimates in the MSSP south of the Garlock fault range between ~ 8 – 12 mm yr\(^{-1}\) in a N-NW direction (Savage et al., 1990; Ma et al., 1994; Sauber et al., 1994; Dixon et al., 1995). In the Death Valley – northern MSSP – southern WLB part of the CBR, geodetically based studies indicate NW-directed velocity estimates that range from ~ 9 - 13 mm yr\(^{-1}\) (Dixon et al., 1995; Hearn and Humphreys, 1998; Dixon et al., 2000; McClusky et al., 2001; Miller et al., 2001; Bennett et al., 2003). In the Nevada Test Site region, WNW directed velocity estimates do not exceed ~ 2 mm yr\(^{-1}\), and are closer to ~ 1 mm yr\(^{-1}\) (Bennett et
al., 1997; Wernicke et al., 1998; Savage et al., 1999; Dixon et al., 2000). In the Las Vegas basin area of the LMTD, the apparent velocity estimate is $\sim 1 \text{ mm yr}^{-1}$ oriented S$\,65^\circ$E, although the reference frame for this estimate is not provided (Nevada Association of Land Surveyors, Southern Chapter, Southern Nevada G.P.S. Subcommittee, 1999).

3.3 Discussion

The changes in extension locations and patterns in the CBR over the past $\sim 16 \text{ Ma}$ (Wernicke et al., 1988; Wernicke and Snow, 1998) correspond well with observed changes in relative plate motions (e.g., Atwater and Stock, 1998). Using a reference point on the Pacific plate near the Mendocino Triple Junction relative to a stable North America, Atwater and Stock (1998) estimated a rate of $\sim 33 \text{ mm yr}^{-1}$ directed $\sim N60^\circ W$ between 30 and 12 Ma for that point. From $\sim 12 \sim 8 \text{ Ma}$ the point was displaced along the same azimuth, but at a rate of $\sim 52 \text{ mm yr}^{-1}$ (Atwater and Stock, 1998). At $\sim 8 \text{ Ma}$, the direction of displacement changed to $\sim N37^\circ W$ with the rate staying about the same at $\sim 52 \text{ mm yr}^{-1}$ (Atwater and Stock, 1998). These changes in relative plate motions are manifested within the CBR as a rapid westward progression of extensional deformation from $\sim 12 \sim 9 \sim 8 \text{ Ma}$, and an increase of northwest-directed strike-slip faults at $9 \sim 7 \text{ Ma}$ (Wernicke et al., 1988; Atwater and Stock, 1998; Snow and Wernicke, 2000). These changes are also consistent with the directions of extension documented through time (e.g., Wernicke et al., 1988).

When extension was prominent in the LMTD ($\sim 15 \sim 8 \text{ Ma}$), the dominant extension direction was WSW to E $\sim W$ (Wernicke et al., 1998). Once the plate motions changed to
a more northerly displacement path (~ 8 Ma), the extension direction was mostly WNW to NW in the Death Valley region (Wernicke et al., 1988). Wernicke et al. (1998) contend that the lack of NW-directed faults in the LMTD indicates that extension in the LMTD was near completion at ~ 8 Ma when the principle extension direction changed in response to plate motions. Although this interpretation is fundamentally correct for the mid-Miocene development of the LMTD, it does not account for the E-W to WNW extension direction along Quaternary faults in the LMTD (Figs. 2 and 27).

Despite the recognition of Quaternary faults in the LMTD, models describing this current deformation remain limited. Initiation of early deformation in this region was attributed to buoyancy forces (Wernicke and Axen, 1988; Sonder and Jones, 1999) and the rolling hinge model that was driven by changes in plate motions (Wernicke et al., 1988; Hamilton, 1988; Snow and Wernicke, 2000), but no models have been provided to explain Quaternary deformation. This study presents a possible model that is based on the northwest translation of the Sierra Nevada block that creates a ‘strain accommodation space,’ thus causing extension to the east in the LMTD.

The San Andreas fault system accommodates ~ 75% of the motion between the Pacific and North American plates with most of the remaining motion being transferred to the MSSP and northward to the MSSP – WLB overlap zone (e.g., Minster and Jordan, 1987; Dokka and Travis, 1990; Argus and Gordon, 1991). The transferred motion is mainly dextral shear in the MSSP south of the Garlock fault (e.g., Dokka and Travis, 1990) and dextral strike-slip and transtensional deformation north of the Garlock fault along the eastern Sierra Nevada (Fig. 1) (e.g., Snow and Wernicke, 2000; Monastero et al., 2002). Peltzer et al. (2001) contend that ~ 50% of the right-lateral motion in the
MSSP is concentrated along the Blackwater-Little Lake fault system (Fig. 27) and that strain from the northern end of the 1992 Landers earthquake may connect with strain along the southern end of the Owens Valley fault, resulting in a strain accumulation between the MSSP and WLB. This observation indicates a possible transfer of strain from the southern MSSP to the MSSP – WLB in the Death Valley region.

The transfer of dextral shear is also suggested north of the Garlock fault. Lee et al. (2001) indicate that right-lateral shear is transferred from the southern Death Valley fault system to the Owens Valley fault and then the dextral motion on the Owens Valley, Hunter Mountain, and Panamint Valley faults systems is transferred back to the northern Death Valley – Furnace Creek – Fish Lake Valley fault systems (Fig. 27). Their model indicates that the slip is transferred on the NE-striking, NW-dipping Deep Springs, Eureka Valley, and Towne Pass – Emigrant normal fault systems (Fig. 28). The model provided by Lee et al. (2001) accommodates the northwest translation of the Sierra Nevada block (Fig. 28).

The motion transferred from the Blackwater – Little Lake and southern Death Valley fault zones to the Owens Valley fault indicates a westward transfer of motion (Fig. 28). The transfer of motion from the Owen Valley and Hunter Mountain faults indicate an eastward migration of slip (Fig. 28). The west- and east-directed transfers of slip, in combination with northwestward directed normal faults could possibly create an area of ‘accommodation space’ at ~ 36° N latitude that is here suggested to cause extension to the east in the LMTD (Fig. 28). This model could further be facilitated by left-lateral motion on the Garlock fault (Fig. 28).
As the Sierran block translates northwestward, strain accommodation space is created along its southeastern boundary in its wake (Fig. 28). It is possible that the active normal faults in the Death Valley region satisfy the space problem, although given their location at the northern end of the Death Valley portion of the MSSP – WLB, it is more likely that these faults are accommodating the northwest translation of the Sierra Nevada, thus creating the ‘accommodation space,’ rather than filling it (Fig. 28). This accommodation space model is further supported by the recognition that the faults in the LMTD are at the same range of latitudes as the ‘accommodation space’ (Fig. 28). While this recognition is not in, and of, itself corroborative of the accommodation space, the lack of Quaternary faults south of this latitude in the LMTD indicates a driving mechanism at this latitude and presents at least one possible explanation for the young deformation observed in the LMTD (Fig. 28).

An alternative to this hypothesis is that a change in boundary forces drove this rejuvenated extension in the LMTD. At ~ 5 Ma, older traces of the San Andreas fault system were abandoned (i.e., the San Gabriel fault) and the main trace was initiated to the east (Crowell, 1982; Crowell, 1992). The reorientation of the San Andreas fault system could have caused changes in the boundary conditions that were sufficient enough to reactivate extension in the LMTD. This model is considered unlikely because of the before mentioned lack of documented Quaternary faults directly south of the LMTD.

One last possibility is that the Quaternary deformation observed in the LMTD is the result of the residual plate motions. Geodetic measurement indicate ~2 – 3 mm yr\(^{-1}\) motion distributed to the east of the MSSP – WLB (e.g., Dixon et al., 1995; Bennett et
al., 2003). However, the concentration of Quaternary deformation solely within the LMTD and not to the north or south makes this interpretation improbable.

3.4 Conclusions

The initiation and westward progression of extensional deformation since mid-Miocene time is well documented within the CBR. Extension initiated along the eastern margin of the CBR at ~16 Ma and progressed westward through time. Current deformation is focused along the eastern margin of the Sierra Nevada. Restorations by Wernicke et al. (1988) indicate that the Sierra Nevada microplate has been translated ~250 – 300 km along a path oriented ~N73°W (Wernicke et al., 1988). From ~16 – 12 Ma the displacement was oriented WSW to E–W, from ~12 – 9 Ma extension was oriented about the same but at a faster rate, and from 9 – 8 Ma to present, the extension direction changed to WNW to NW (Wernicke et al., 1988). These observed changes in rate and extension directions correlate closely with documented changes in relative plate motions (Atwater and Stock, 1998).

At ~5 Ma, the MSSP – WLB region changed deformation patterns to accommodate dextral shear and transtensional deformation. Several authors (e.g., Cox and Engebreston, 1985; Pollitz, 1986; Dixon et al., 1995) have proposed a change in plate motions somewhere between 5 and 3 Ma, although Atwater and Stock (1998) cannot resolve these changes in their data. The change in deformation patterns along the eastern Sierra is interpreted to accommodate the NW translation of the Sierra Nevada block with the northward migration of the Mendocino Triple Junction. The deformation along the
southeastern Sierra Nevada is also proposed to provide the necessary kinematics to drive modern extension in the LMTD.

Geodetic studies indicate that the MSSP – WLB accommodates ~ 8 – 12 mm yr\(^{-1}\) deformation (e.g., Hearn and Humphreys, 1998) with 2 – 3 mm yr\(^{-1}\) distributed to the east through the Basin and Range province (e.g., Dixon et al., 1995; Bennett et al., 2003).

Within the CBR, the LMTD contains numerous Quaternary faults, although no Quaternary faults are recognized directly north or south of this area. This study suggests that the proposed transfer of slip from the eastern and central Mojave block to the Owens Valley fault and the transfer of slip back to the northern Death Valley – Furnace Creek – Fish Lake Valley faults through NW-directed normal fault creates an ‘accommodation space’ which drives Quaternary deformation in the LMTD.

Although a lack of data currently exists to further evaluate this hypothesis, this proposed model honors all current data. The model proposed in this chapter is by no means a complete solution, but is intended to spur and facilitate further study related to the driving forces of Quaternary deformation observed in the LMTD. Possible studies that could be integrated to confirm/negate this model include detailed gravity studies in the location of the proposed ‘accommodation space’ and more tectonic studies in the area of the MSSP-WLB transfer zone.
CHAPTER 4

SUMMARY AND CONCLUSIONS

Extensional deformation initiated at ~ 16 Ma in the CBR. Prior to ~ 16 Ma, extension was widespread to the north and south of the CBR. At ~ 16 Ma extension began along the eastern side of the CBR, in the LMTD and eastern Nevada Test Site region. Extension in the LMTD was mostly accommodated on the right-lateral LVVSZ, the left-lateral LMFS, and kinematically linked normal faults. North of the LVVSZ and LMFS, extension occurred mostly on detachment faults. At ~ 12 Ma, extension began to migrate west from the LMTD and Nevada Test Site areas. Wernicke et al. (1988) ascribe the westward migration of extensional deformation to the rolling hinge model.

Beginning at ~ 9 – 8 Ma, northwest-striking dextral faults began to form in the Death Valley region. At ~ 5 – 4 Ma, detachment faulting started to give way to transtension as the predominant mode of deformation along the eastern Sierra Nevada.

The westward migration of extension and the changes in deformation patterns through time have been attributed to changes in plate motions (e.g., Atwater and Stock, 1998; Wernicke and Snow, 1998). From ~ 30 – 12 Ma, a point on the Pacific plate moved in a N60°W direction at ~ 33 mm yr⁻¹ (Atwater and Stock, 1998). Between 12 – 8 Ma, that point was displaced in the same direction, but at the faster rate of ~ 52 mm yr⁻¹ (Atwater and Stock, 1998). At ~ 8 Ma, the direction of the plate motion changed to ~ N37°W, but the rate remained constant at ~ 52 mm yr⁻¹, which is the current direction and
rate (Atwater and Stock, 1998). The intracontinental deformation patterns observed in the CBR correspond well to the documented changes in plate motions.

Currently, the San Andreas fault system accommodates ~75% of the motion between the Pacific and North American plates (e.g., Minister and Jordan, 1987; Argus and Gordon, 1991). The remaining ~25% of the motion is distributed to the east, mostly in the WLB and ECSZ/MSSP (e.g., Dokka and Travis, 1990; Argus and Gordon, 1991). Geodetic-based studies verify this estimate by indicating ~8 – 13 mm yr\(^{-1}\) slip rates through the ECSZ/MSSP and along the southeastern Sierra Nevada (Savage et al., 1990; Ma et al., 1994; Sauber et al., 1994; Dixon et al., 1995, 2000; Hearn and Humphreys, 1998; McClusky et al., 2001; Miller et al., 2001; Bennett et al., 2003). The motion along the faults of the WLB and ECSZ/MSSP accommodates the northwestward translation of the Sierra Nevada block with the northward migration of the Mendocino triple junction.

Lee et al. (2001) present a model that accommodates the translation of the Sierra Nevada on northwest-striking dextral and kinematically linked northeast-striking, northwest-dipping normal faults. Their model suggests that motion is transferred from the dextral southern Death Valley fault zone to the Owens Valley fault. The northwest-directed Deep Springs Valley, Fish Lake Valley, and Towne Pass – Emigrant normal faults transfer slip from the Owens Valley and Hunter Mountain – Panamint Valley strike-slip faults to the northern Death Valley – Furnace Creek and Fish Lake Valley faults. This model is further supported by Peltzer et al. (2001), who indicate that there is an interaction of strain between the Blackwater – Little Lake fault system and the Owens Valley fault system.
The transfer of slip from the east to the west, and then back to the east, in combination with northwest-directed extension creates a ‘strain accommodation space’ in the southeast part of the WLB – ECSZ – MSSP at about the latitude of the slip transfer (~36° - 37° N). The accommodation space provides the necessary mechanism to drive extension to the east in the LMTD. No Quaternary deformation is observed directly south of the LMTD, which suggests a driving mechanism at this latitude.

The LMTD consists of mid-Miocene strike-slip and kinematically linked normal faults. Extension greatly affected this area between ~16 – 8 Ma, with relative quiescence following the main period of extension. A rejuvenation of extension in the LMTD occurred sometime in Pliocene(?) or Quaternary time as the ‘strain accommodation space’ was generated. The young faults in the LMTD accommodate E – W to WNW – ESE directed extension. The faults in the LMTD with the most displacement or that are most studied are the CWF, EDF, FMF, and BHF.

The BHF is the southernmost Quaternary fault in the LMTD and is located along the western margin of Eldorado Valley, ~7 km west of Boulder City. The BHF has 14 strands that cut Quaternary alluvial fans and range in length from ~100 m to ~4.5 km. Measured scarp heights range from centimeters to a maximum of 3.49 m. Bevels on the main trace of the BHF and paleoseismic trench data indicate that it is a composite scarp resulting from three paleoearthquake events.

A ~75 m paleoseismic trench was excavated across the main trace near the southern extent of the BHF. Trench data and 14C dates from soil units indicate five paleoearthquakes in the past ~25 ka. Maximum vertical displacements measured for individual events range from 0.71 m to 1.96 m. Using the measured displacement of the
faults in the trench and radiocarbon ages, slip rates are estimated to be $0.33 - 0.55 \text{ mm yr}^{-1}$. Although these rates are considered maxima because they rely on the inorganic $^{14}$C determined ages, which are considered minima, they correlate well with slip rate estimates determined for mountain front sinuosity ($0.5 \text{ mm yr}^{-1}$) and valley-depth to valley-width ratios ($0.5 \text{ mm yr}^{-1}$).

Using maximum displacement, average displacement can be estimated, both of which can be used to estimate paleoearthquake magnitudes. Using regressions derived from earthquakes with known magnitude and displacement, maximum displacement measurements from the BHF indicate that the fault is capable of generating a $M_w = 6.7 - 6.9$ earthquake, while average displacement measurements suggest a $M_w = 6.4 - 6.8$ earthquakes are possible on the BHF. While these estimates are in close agreement with one another, they vary greatly from magnitude estimates derived using SRL.

Regressions using the $\sim 4.5 \text{ km}$ SRL indicate that the BHF should only be able to generate a $M_w = 5.8$. However, the maximum displacement regressions indicate that a $M_w = 5.8$ should have a maximum displacement of $0.22 \text{ m}$, which is significantly smaller than the $0.71 - 1.96 \text{ m}$ maximum displacement measured in the trench. In order to generate the $M_w = 6.4 - 6.9$ earthquakes, the regressions indicate that the SRL should be $\sim 14 - 37 \text{ km}$. This discrepancy is also observed using the SRL vs. maximum displacement regression, which suggests that the SRL should be $\sim 15 - 41 \text{ km}$ based on the $0.71 - 1.96 \text{ m}$ maximum displacement. The $\sim 4.5 \text{ km}$ SRL suggests a maximum displacement of $0.22 \text{ m}$.

The apparent discrepancy between displacement, SRL, and magnitude estimates can be explained by a rupture patch with asymmetrical slip along it. The surface rupture
patch is the area on the fault plane that accommodates the displacement. The rupture
patch may rupture as an irregular shape focusing displacement along a certain course. If
the displacement is focused along a narrow course in a vertical direction as opposed to a
wide zone in a horizontal direction, displacement at the surface will be constrained to a
short SRL, although displacement in the subsurface could be significantly longer. This
appears to be the case along the BHF.

Based on the recognition that the BHF is capable of generating a large magnitude
earthquake, the determination of five surface rupturing earthquake events in the past ~ 25
ka, and the proximity of the fault to Boulder City and the greater Las Vegas metropolitan
area, the BHF is a greater seismic risk than previously estimated. Recurrence interval
estimates range from ~ 1 – 10 ky, although ~ 5 ky seems the most reliable estimate.

Based on the trench data, one earthquake occurred in the past 9,230 ± 80 BP (10,580 –
10,220 cal BP 2σ), suggesting that the BHF could rupture in the near future if it continues
to follow the same patterns that have determined for the past ~ 25 ka.
Figure 1. Regional map showing approximate locations of tectonic provinces in the southwestern U.S. CBR- Central Basin and Range Province (Wernicke, 1992); CNSB- Central Nevada seismic belt (Wallace, 1984); CP- Colorado Plateau; ECSZ- Eastern California shear zone (Dokka and Travis, 1990); IMSB- Intermountain seismic belt (Smith and Sbar, 1974); LMTD- Lake Mead tectonic domain; MSSP- Mojave strike-slip province (Miller and Yount, 2002); NCREC- northern Colorado River extensional corridor; WLB- Walker Lane belt (Stewart, 1988). The light blue box indicates the location of the LMTD (Fig. 2).
Figure 2. Shaded relief map showing the Miocene to Holocene faults of the LMTD. Red lines indicate faults that are interpreted to have been active in the Quaternary. Blue lines denote faults that are believed to have late Tertiary (Miocene) aged motion. Red box indicates BHF study area (Fig. 5). ACF- Arrow Canyon fault; BHF- Black Hills fault; BRF- Bitter Ridge fault; BSVF- Bitter Spring Valley fault; CCF- Cabin Canyon fault; CWF- California Wash fault; CWMF- Cashman-Whitney Mesa fault; DLF- Dry Lake fault; EDF- Eglington-Decatur fault; EVF- Eldorado Valley fault (after Weber and Smith, 1987); FMF- Frenchman Mountain fault; FRF- Frenchman River fault; GBF- Gold Butte fault; GWF- Grand Wash fault; HBF- Hamblin Bay fault; HSF- Hen Springs fault; HVF- Hungry Valley fault; LRF- Lime Ridge fault; LMF- Lakeside Mine fault; LVVSZ- Las Vegas Valley shear zone; MR- McCullough Range; MSF- Mead Slope fault; NMR- northern McCullough Range; PF- Piedmont fault; RSF- Rogers Spring fault; SID- Saddle Island detachment; VV- Valley View fault; WCF- West Charleston fault; WF- Wheeler Ridge fault (fault locations from Langenheim and Schmidt, 1996; Duebendorfer et al., 1998; Langenheim et al., 1998, 2001; Slemmons et al., 2001).
Figure 3. Oblique air photo mosaic of the northern Black Hills and Black Hills fault looking west. Blue arrows (a) indicate the extent of the main trace, yellow arrow (b) shows location of the highest measured scarp height (3.49 m), the green arrow (c) represents the location where the scarp height significantly decreases and deflects to the east, the orange arrow (d) indicates the gap between the quartz monzonite pluton in the north Black Hills and the volcanic rocks of the southern Black Hills that marks the location where fault scarps end in the south, and the red arrow (e) indicates the trench location.
Figure 4. Map of Lake Mead tectonic domain showing faults and seismicity between 1892 and 1998. Small circles indicate $M = 2 - 3$, medium circles show $M = 3 - 4$, and large circles indicate $M \geq 4$. Note amount of seismicity near Boulder City. Much of this abundant seismicity is attributed to loading following the filling of Lake Mead. BHF-Black Hills fault, LMFS- Lake Mead fault system, LVVSZ- Las Vegas Valley shear zone, MSF- Mead Slope fault (modified from dePolo and dePolo, 1999).
Figure 5. Geologic map of the Black Hills fault study area. (See Plate 1 for complete unit descriptions). Box indicates approximate location of Figure 11.
Figure 6. Photo of geomorphic map unit Qm1. This unit has a well-developed desert pavement surface with clasts representing \( \sim 90\% \) of the surface.

Figure 7. Photo of geomorphic map unit Qm2. This unit has a poorly-developed desert pavement surface where clasts are \( \sim 78\% \) of the surface.
Figure 8. Photo showing geomorphic map unit $Q_{a3}$. This unit consists of large boulders and has no matrix or soil development.

Fig. 9. Photo representing geomorphic map unit $Q_{a4}$. This unit is active alluvial deposits that are not cemented and unconsolidated.
Figure 10a. Topographic profiles of alluvial fans and fault scarps along the Black Hills. Profiles were measured in straight line segments as close to the axis of fans as possible while remaining perpendicular to fault scarps. Fault scarps are observed in profiles as abrupt changes in elevation and/or changes in slope angles. Red arrows delineate location of the main trace on the profiles. Blue arrows show other fault strands. Profile locations are shown on Figure 5 and Plate 2 and correspond to profile labels. Figures 10b and 10c are located near profile BHFP1.
Figure 10b. Topographic profile across the main trace at the trench location. This profile shows scarp height, scarp angle, and fan slope angle. This profile indicates a maximum scarp height of 2.96 m, an average scarp slope of 25°, and a fan slope angle of 12°.

Figure 10c. Topographic profile of the main trace illustrating discrete bevels of the scarp slope.
Fig. 11. Digital orthophoto quadrangle showing drainage deflection method. Changes in drainage flow direction were documented by offset line segments (blue lines) across faults (yellow lines). Drainage deflections were verified by field observations. Notice split between left-lateral deflections and right-lateral deflections across fault strands and origination of active fans across the main trace (lowest fault pictured). Figure location shown on Figure 5.
Figure 12. Paleoseismic trench log across the BHF. The trench was excavated near the southern end of the pluton of the Black Hills across a ~3 m scarp and a smaller scarp (Fig. 5). The trench reveals five paleoearthquake events since ~23 ka. See Plate 2 for complete unit descriptions.
Figure 13. Photo showing clast alignment along the main trace of the fault.

Figure 14. Photo showing pendant development that has been rotated along a fault.
Figure 15. Regression plot of maximum displacement versus moment magnitude from known earthquakes. Stars indicate where measured maximum displacements from the BHF plot on the regression. Dashed lines show moment magnitude estimates from the measured data. Moment magnitude estimates range between $M_w = 6.9 - 6.6$ (modified from Wells and Coppersmith, 1994).

Figure 16. Regression plot of average displacement versus moment magnitude from known earthquake data. Average displacement is reported as one-third of maximum displacement (McCalpin and Slemmons, 1998). Stars are plotted on the regression based on average displacement values. Dashed lines shows moment magnitude estimates derived from average displacement. Estimated moment magnitudes range between $M_w = 6.8 - 6.4$ (modified from Wells and Coppersmith, 1994).
Figure 17. Regression plot showing surface rupture length versus moment magnitude. Stars indicate where data plots on the regression line. Dashed lines represent inferred values from plotted data. The 4.5 km SRL measured has an estimated $M_w = 5.8$, while the $M_w = 6.9 - 6.3$ estimated from Figures 15 and 16 indicate that the SRL should be $\sim 15 - 39$ km (modified from Wells and Coppersmith, 1994).

Figure 18. Regression plot of surface rupture length versus maximum displacement. Stars indicate where BHF data and inferred data plot on the regression. Dashed lines show inferred values from measured data. The $\sim 4.5$ km measured SRL suggests max. displacement should be 22 cm, while max. displacement measured in the trench suggest the SRL should be $\sim 15 - 41$ km (modified from Wells and Coppersmith, 1994).
Figure 19. Conceptual diagram illustrating a surface rupture patch. An earthquake originates at the focus and the motion propagates outward in an irregular pattern. The orange area indicates areas of highest displacement. Yellow indicates less displacement. The arrows show relative direction of displacement propagation.
Figure 20. Conceptual model relating the surface rupture patch model to the BHF. The apparent surface rupture discrepancy observed by regression models can be explained an irregular surface rupture patch that fails to rupture along the entire length of the fault.
Figure 21. Diagram relating earthquake magnitude and slip rates to infer recurrence interval. Using $M_w = 6.9 - 6.4$ and 0.33 – 0.55 mm/yr slip rates, this model suggests an average recurrence interval of ~ 1-3 ky (modified from Slemmons, 1977).
Figure 23. Shade relief map of CBR showing extensional deformation that initiated between ~30 – 16 Ma. Geographic locations are labeled on Figure 22. KRD- Kingston Range detachment, TCF- Titus Canyon fault, TWF- Tucki Wash fault, UBF- Ubehebe Basin fault.
Figure 24. Shade relief map of CBR showing extensional deformation that initiated between 16 and 12 Ma. Geographic locations are labeled on Figure 22. Red faults indicate initiation during this time period. Blue faults indicate continued motion during this time frame. Black faults indicate faults that are no longer active. BDD- Beaver Dam detachment, EVF- Eldorado Valley fault, GVF- Grapevine fault, GWF- Grand Wash fault, KRD- Kingston Range detachment, LMF- Lakeside Mine fault, LMFS- Lake Mead fault system, LVVSZ- Las Vegas Valley shear zone, MPD- Mormon Peak detachment, PRF- Point of Rocks fault, RVF- Rock Valley fault, SID- Saddle Island detachment, SRD- Sheep Range detachment, TCF- Titus Canyon fault, TSD- Tule Springs detachment, TWF- Tucki Wash fault, UBF- Ubehebe Basin fault.
Figure 25. Shade relief map of CBR showing extensional deformation that initiated between 12 and 8 Ma. Geographic locations are labeled on Figure 22. Red faults indicate initiation during this time period. Blue faults indicate continued motion during this time frame. Black faults indicate faults that are no longer active. BCD- Boundary Canyon detachment, BDD- Beaver Dam detachment, BMD- Black Mountain detachment, EVF- Eldorado Valley fault, FCFZ- Furnace Creek fault zone, GF- Garlock fault, GVF- Grapevine fault, GWF- Grand Wash fault, KRD- Kingston Range detachment, LMF- Lakeside Mine fault, LMFS- Lake Mead fault system, LVVSZ- Las Vegas Valley shear zone, MPD- Mormon Peak detachment, PRF- Point of Rocks fault, RVF- Rock Valley fault, SDFZ- southern Death Valley fault zone, SID- Saddle Island detachment, SRD- Sheep Range detachment, SVF- Stewart Valley fault, TCF- Titus Canyon fault, TSD- Tule Springs detachment, TWF- Tucki Wash fault, UBF- Ubehebe Basin fault.
Figure 26. Shade relief map of CBR showing extensional deformation that initiated between 8 and 4 Ma. Geographic locations are labeled on Figure 22. Red faults indicate initiation during this time period. Blue faults indicate continued motion during this time frame. Black faults indicate faults that are no longer active. BCD- Boundary Canyon detachment, BDD- Beaver Dam detachment, BF- Blackwater fault, BMD- Black Mountain detachment, DSVF- Deep Springs Valley fault, ETPF- Emigrant - Towne Pass fault, EVF- Eldorado Valley fault, FCFZ- Furnace Creek fault zone, FLVFS- Fish Lake Valley fault system, GF- Garlock fault, GVVF- Grapevine fault, GWF- Grand Wash fault, HMF- Hunter Mountain fault, KRD- Kingston Range detachment, LMF- Lakeside Mine fault, LMFS- Lake Mead fault system, LVVSZ- Las Vegas Valley shear zone, MPD- Mormon Peak detachment, NDVFZ- northern Death Valley fault zone, PRF- Point of Rocks fault, PVF- Panamint Valley fault, RVF- Rock Valley fault, SDFZ- southern Death Valley fault zone, SID- Saddle Island detachment, SRD- Sheep Range detachment, SVF- Stewart Valley fault, SVFS- Saline Valley fault system, TCF- Titus Canyon fault, TSD- Tule Springs detachment, TWF- Tucki Wash fault, UBF- Ubehebe Basin fault.
Figure 27. Shade relief map of CBR showing extensional deformation that initiated between 4 Ma and present. Geographic locations are labeled on Figure 22. Red faults indicate initiation during this time period. Blue faults indicate continued motion during this time frame. Black faults indicate faults that are no longer active. ACF- Arrow Canyon fault, AFF- Argus Frontal fault, BCD- Boundary Canyon detachment, BDD- Beaver Dam detachment, BF- Blackwater fault, BHF- Black Hills fault, BMD- Black Mountain detachment, CWF- California Wash fault, DLF- Dry Lake fault, DSVF- Deep Springs Valley fault, EDF- Eglington – Decatur fault, ETPF- Emigrant – Towne Pass fault, EVF- Eldorado Valley fault, FCFZ- Furnace Creek fault zone, FLVFS- Fish Lake Valley fault system, FMF- Frenchman Mountain fault, GF- Garlock fault, GVF- Grapevine fault, GWF- Grand Wash fault, HMF- Hunter Mountain fault, IF- Independence fault, KRD- Kingston Range detachment, LLFZ- Little Lake fault zone, LMF- Lakeside Mine fault, LMFS- Lake Mead fault system, LVVSZ- Las Vegas Valley shear zone, MPD- Mormon Peak detachment, NDVFZ- northern Death Valley fault zone, OVF- Owens Valley fault, PRF- Point of Rocks fault, PVF- Panamint Valley fault, RVF- Rock Valley fault, SDFZ- southern Death Valley fault zone, SFF- Sierran Frontal fault, SID- Saddle Island detachment, SRD- Sheep Range detachment, SVF- Stewart Valley fault, SVFS- Saline Valley fault system, TCF- Titus Canyon fault, TSD- Tule Springs detachment, TWF- Tucki Wash fault, UBF- Ubehebe Basin fault, VV- Valley View fault, WMFZ- White Mountains fault zone.
Figure 28. Map showing generalized locations of active faults in the CBR that relate to the strain accommodation space model. Blue arrows (smaller) indicate direction of the slip transfer between faults. Red arrows (larger) show extension directions. The extension directions are generalized based on orientation of the faults, but agree well with velocity estimates from geodetic studies. ACF- Arrow Canyon fault, AFF- Argus Frontal fault, BF- Blackwater fault, BHF- Black Hills fault, CWF- California Wash fault, CWMF- Cashman - Whitney Mesa fault, DLF- Dry Lake fault, DSF- Deep Springs Valley fault, DVFCFZ- Death Valley - Furnace Creek fault zone, EDF- Eglington - Decatur fault, ETF- Emigrant - Towne Pass fault, FLVFZ- Fish Lake Valley fault zone, FMF- Frenchman Mountain fault, GF- Garlock fault, HMF- Hunter Mountain fault, LLF- Little Lake fault, OVF- Owens Valley fault, PVF- Panamint Valley fault, SDFZ- southern Death Valley fault zone, SFF- Sierran Frontal fault.
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