EVALUATION OF THE SIERRA NEVADA FRONTAL FAULT SYSTEM AT BAIRS CREEK IN THE VICINITY OF MANZANAR, CALIFORNIA

An Undergraduate Thesis
Presented to
The Faculty of
California State University, Fullerton
Department of Geological Sciences

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Science
in Geology

By
Garrett Mottle
2015

Phil Armstrong, Faculty Advisor
Evaluation of the Sierra Nevada Frontal Fault System at Bairs Creek in the Vicinity of Manzanar, California

Garrett Mottle
Advisor: Dr. Phil Armstrong
I ABSTRACT

The Sierra Nevada Frontal Fault System (SNFFS) includes a series of east-dipping normal faults along the eastern front of the Sierra Nevada Mountains in eastern California. Most researchers assumed that faults there ~60° east. Late Pleistocene to Holocene horizontal extension rates based on this ~60° dipping fault system are estimated to be 0.2-0.3 mm/yr. Recent studies on the SNFFS near Bishop, CA reveal less steep dips of 29-46°. Another recent study near Independence, CA reveal dips of 29-34° east. My study was conducted farther south on normal fault exposures near Manzanar National Historic Site, CA. To calculate fault orientation, 60 data points were collected using differential GPS along the bottom cusp of fault exposures in offset Quaternary surfaces. Elevations range from ~1780m to ~1890m over the ~2000m of fault exposure. An Excel program was used to model the fault dip assuming a planar fault, and these data resulted in a 21°-23° east dip. Due to this low-angle normal fault geometry, horizontal extension rates based on a steeply dipping normal fault system need to be re-evaluated, as extension rates could be increased by as much as a factor of four.
II INTRODUCTION

Problem

This project addresses the orientation of the Sierra Nevada Frontal Fault System (SNFFS) in eastern California, which generally is assumed to dip ~60° east (e.g., Le et al., 2007). The SNFFS is a range-bounding fault system along the western side of Owens Valley that partly accommodates uplift of the Sierra Nevada Mountains in eastern California with a vertical fault slip rate of 1.73 mm/yr as calculated by Le et al. (2007). The horizontal extension rates based on this 1.73 mm/yr vertical slip rate are based on a ~60° east-dipping normal fault. However, the dips found in several field areas along the eastern Sierran front are far less than the assumed 60° (Phillips and Majkowski, 2011; Gadbois et al., 2014). This is important because horizontal extension rates for Owens Valley based on this vertical slip rate calculated from a 60° degree dipping normal fault system will need to be re-evaluated to comply with a potentially lower angle normal fault system as suggested by other studies. Based on previous studies and reconnaissance mapping, I hypothesize that the faults near Manzanar National Historic Site dip significantly less than the assumed 60°, which would suggest that horizontal extension rates are higher than previously assumed.

Location

The SNFFS study area for this analysis is located at the base of the Sierra Nevada range in eastern California between George and Bairs creeks (figure 1). The field site is directly west of Manzanar National Historic Site between the towns of
Independence to the north and Lone Pine to the south. The SNFFS is at the western margin of the Basin and Range Province and the western margin of the Eastern California Shear Zone (ECSZ).

Previous work on the SNFFS has shown that many normal faults in the SNFFS dip much more shallowly than the assumed 60° (figure 2). Phillips and Majkowski (2011) found that faults typically dip less than 50° along the northern part of the SNFFS near Bishop, CA. More recent work found that faults dip 29-34° east near Independence (Shagam, 2011). Gadbois (2014) found that faults cutting through bedrock near Tuttle Creek by Lone Pine, CA dip 35° east (Figure 3).
Figure 2: Map from Phillips and Majkowski (2011) of fault orientations in northern Owens Valley near Bishop, CA. The Sierra Nevada Mountains are located on the western side of the map, the White Mountains are located on the northeastern corner, and the colored contours represent basin depth of northern Owens Valley. The yellow arrows represent dip direction. The numbers indicate dip.
Figure 3: Google Earth image showing locations of recent undergraduate thesis studies on the Sierra Nevada Frontal Fault System near Lone Pine and Independence, CA. Black dashed line represents the approximate location of the SNFFS along the range front. Shagam (2011) found 34° east dipping normal faults at Shepherd Creek and a 29° east dipping normal fault at Independence Creek. Gadbois (2014) found a 35° east dipping normal fault at Tuttle Creek. At Bairs Creek I found 21°-23° east dipping normal faults.
Goals

The goals of this study are to evaluate the geology surrounding and orientation of the Sierra Nevada Frontal Fault System between George Creek and Bairs; initial work will be based on the observations of Le et al. (2007). Basic field mapping was conducted to confirm and/or expand on the work of Le et al. (2007), then the main fault through Bairs Creek area was surveyed using differential GPS (figure 4). This analysis will help us better understand extension rates in Owens Valley based on fault dips, as well as gain a better understanding of normal fault dips in general.

Figure 4: Field photo looking west at range front near Bairs Creek from distance. Black solid line represents the approximate location of the main SNFFS fault scarp used for analysis.
III: GEOLOGIC BACKGROUND

Geologic History and Setting of SNFFS

The Sierra Nevada Mountains are a west-tilted normal fault block that forms the western boundary of the basin and range province, which is an extensional margin forming a system of normal faults (Le et al. 2007). The fault block strikes north-northwest to southeast. The range is approximately 644 kilometers long and 100-125 kilometers wide (Argus and Gordon, 1991; Phillips and Majkowski 2011). The western side of the Sierra Nevada rises above the Central Valley floor with a gentle slope, while the eastern side of the range rises steeply, forming an eastern escarpment. This escarpment is caused by a system of normal faults (SNFFS) associated with extension of the basin and range province. The mountains also form the western boundary of the Eastern California Shear Zone, which results in the Owens Valley region having NW striking dextral faults, NE striking normal faults, and NW striking range-bounding normal faults in which some are associated with the SNFFS. This fault activity is caused by a combination of extensional and dextral shear in eastern California (Le et al., 2007). Fault activity in the Basin and Range Province is concentrated mostly on the eastern and western boundaries, with the western boundary being particularly active (Phillips and Majkowski, 2011).

The Sierra Nevada Mountains were uplifted mainly as a result of the extension of the Basin and Range province, which extends east of the Sierra Nevada to the state of Utah. Prior to extensional forces causing uplift of the Sierra, the region was a volcanic arc with magma forming beneath the crust due to subduction during the Mesozoic. This led to the formation of the Sierra Nevada batholith, which is
Jurassic-Cretaceous in age. Subduction-related deformation, uplift, and erosion ended in the early Cenozoic (Wakabayashi and Sawyer, 2001). Crustal extension in the Basin and Range province began approximately 35 Ma, but the main tilting of the Sierra Nevada and east-down normal faulting along the SNFFS dominantly began about 5 Ma (Wakabayashi and Sawyer, 2001). As a result of crustal extension in the Basin and Range province, there is a series of mountain ranges and valleys much like a horst and graben landscape (Wakabayashi and Sawyer, 2001). Most of these valleys and ranges trend north-south. Sediment flowing down from the ranges fills the valleys, adding pressure to the extensional cracks already created, and further helping extension of the margin (Sauber et al, 1994). Further helping extension in the Basin and Range province is that subduction caused over-thickening of the crust, which was then thinned by the migration of the Mendocino Triple Junction and the transition of the region from a subduction zone to an extensional margin (Phillips and Majkowski, 2011). This dextral translational motion caused by the migration of two triple-junctions caused the faulting to trend northwest to southeast.

Sierra Rock Types

The Sierra Nevada Mountains consist of mostly plutonic rocks, but also consist of metamorphic, volcanic, and sedimentary rocks. The plutonic rocks are mostly granite, but they also consist of diorite, gabbro, porphyry, periodotite, and pegmatites (Hill 2006). Along with plutonic rocks, the Sierra Nevada also consists of volcanic, sedimentary, and metamorphic rocks. California was adjacent to a subduction zone during the Mesozoic (Saleeby, 1999) when the plutonic rocks were
emplaced. These plutonic rocks intrude mostly Paleozoic metamorphic rocks such as gneiss, hornfels, chert, greenstone, schist, calcareous rocks, phyllite, quartzite, serpentine, and slate. Lava flows, lahars, volcanic ash falls, and remnants of extinct volcanoes indicate that volcanism was common throughout much of the Cenozoic. Volcanic rocks consist of basalt, andesite, rhyolite, tuff, obsidian, cinder, and pumice. Sedimentary rocks due to glaciation can be found in the Sierra and along western Owens Valley, such as conglomerates and glacial till.

**Quaternary Alluvial Deposits**

The majority of surficial deposits found in the area are comprised of Quaternary alluvial deposits aging from ~124 ka to 3-4 ka (Le et al., 2007). There are a total of seven different Quaternary deposits found in the area, and they vary from glacial deposits to non-glacial alluvial deposits, giving them different geomorphological characteristics (Le et al., 2007). These alluvial deposits were dated using model CRN Beryllium-10 exposure age dating on quartz from exposed boulders. They were recalculated using an erosion rate of 0.3 cm/k.y. on boulder surfaces (Small et al., 1995). The following descriptions of Quaternary deposits along the eastern Sierran front are modified from Le et al. (2007). The mapping of Le et al (2007) was evaluated and modified where appropriate within the field area (figure 5). Contacts between alluvial surfaces were mapped by using Google Earth images and by basic field mapping with a handheld GPS (figure 6).

**Qf1**

Qf1 is the oldest of the alluvial fan deposits, with an approximate mean age of 123.7 +/- 16.6 ka. They appear as 30-100 meter high mounds and are orange to
Figure 5: Geologic map of the SNFFS near Bairs Creek. Map is modified from Le et al. (2007). This geologic map shows the contacts between Quaternary alluvial surfaces in the Bairs Creek area and SNFFS fault scarps.
orange-tan in the field (Le et al 2007). They also appear to be orange-tan on aerial photographs. Le et al (2007) describes this deposit as being partly varnished, highly dissected, and strongly weathered with scarce but strongly weathered boulder deposits with elephant skin-like texture. The deposit also contains a grus and sand matrix along with granitic fragments of rounded to sub-rounded clasts which are cobble to pebble size (Le et al 2007). This surface is present just south of Bairs Creek.

Qf2

Qf2 is divided into two units: Qf2a and Qf2b. Qf2a is the older of the two surfaces, and they appear yellow to yellow-tan on aerial photographs. They have a ridge and ravine topographic pattern ranging from a few meters to tens of meters above the modern channel (Le et al 2007). This surface is slightly varnished and highly dissected with moderate vegetation and a lack of boulders. These surfaces are typically underlain primarily by unconsolidated weathered coarse angular to sub-angular grus (Le et al 2007).

Qf2b is the younger of the two surfaces and look similar to Qf2a, however there isn't a ridge and ravine topographic pattern associated with this surface. The mean age of this surface is 60.9 +/- 6.6 ka. Qd2b are less weathered than Qf2a and consist of moderately weathered granitic boulders that make up 2 percent of the surface (Le et al 2007). This surface is moderately dissected and less weathered compared to Qf2a. It contains more boulders close to drainages and less boulders away from drainages. This surface is underlain by loose sub-angular granitic clasts of cobble to pebble-size, along with grus (Le et al 2007).
Qf3

Qf3 is the most dominant alluvial surface along the range front and covers the most area. This surface contains three units: Qf3a, Qf3b, and Qf3c. Qf3a is the oldest of the three Qf3 surfaces and typically has a yellow-tan to tan-white color on aerial photographs. It is covered in vegetation and exhibits weakly developed desert varnish. Very few boulders are present and the surface mostly contains a grus matrix with finer-grained granitic clasts. The mean Be-10 age of this deposit is 25.8+/ - 7.5 ka.

Qf3b is the second youngest of the three Qf3 surfaces. These are best distinguished by dendritic channel networks ranging from 1-2.5 meters deep (Le et
al 2007). It contains granitic boulders that average 1-3 m in height. This is underlain by a coarse-grained sand matrix that contains subangular to subrounded granite clasts boulder, cobble, and pebble-size.

Qf3c is the youngest of the three Qf3 surfaces. It extends ~2-4km away from the range front and displays a well-preserved bar-and-swale morphology (Le et al 2007). The mean age of this deposit is 4.4 +/- 1.1 ka. These alluvial surfaces are unvarnished, undissected, and hummocky, and contain channels lined with boulders. These boulders are fresh and are roughly 1-9 meters in height. Due to the 20% coverage of this surface by fresh boulders it is likely this is a glacial outburst or flood deposition (Blair, 2001; Le et al., 2007).

Qf4

Qf4 is the youngest of all the alluvial surfaces. It contains recent debris flows such as tree trunk clasts and boulder levee bars. The surfaces tend to be unvarnished and Be-10 dating suggests a mean age of 4.1 +/- 1.0 ka (Le et al 2007).

Faults

Three distinct faults define the boundary between the Basin and Range Province and the Sierra Nevada: The Owens Valley fault, Lone Pine fault, and the SNFFS. The Owens Valley fault is a right-lateral strike slip fault that is sub-parallel to the SNFFS and is located a few kilometers to the east (Le et al., 2007). The Lone Pine Fault is an oblique slip fault located south of the Owens Valley Fault and approximately 3-5 kilometers east of the SNFFS (Le et al., 2007). The SNFFS west of Lone Pine and Independence is characterized by NNW-striking normal fault scarps that mostly dip east, though some dip west (Le et al., 2007). These faults cut through
Qf1, Qf2, and Qf3 alluvial surfaces, and also cut through Qls (landslide deposit north of Independence Creek) and Qm (glacial moraine deposit). These faults typically place Quaternary deposits in the hanging wall upon granite bedrock or more Quaternary sediment in the footwall (Le et al 2007). Along the range front, the SNFFZ faulting is dominantly normal dip-slip. The assumed dip of these faults is 60° east (Le et al., 2007).

Le et al. (2007) measured scarp profiles and combined with CRN Be-10 dating to approximate vertical slip rates. The moderately eroded and vegetated fault scarps yielded vertical-surface offset measurements ranging from 41.0 +/- 2.0 m to 2.0 +/- 0.1 m. This combined with CRN Be-10 dating yielded approximate vertical slip rates of 0.2-0.3 +/- 0.1 mm/yr since ca. 124 ka, 0.2-0.4 +/- 0.1 mm/yr since ca. 61 ka, 0.3-0.4 +/- 0.2 mm/yr since ca. 26 ka, and 1.6 +/- 0.4 mm/yr since ca. 4 ka. Using the assumed 60° dip, Le et al. (2007) calculated horizontal extension rates as well. Calculated horizontal extension rates for the late Pleistocene to Holocene range from 0.1 to 0.2 +/- 0.1 mm/yr to 0.9 +/- 0.4 mm/yr. Holocene slip rates of Owens Valley range from 1.8-3.6 mm/yr (Le et al., 2007). A long-term slip rate of 0.3-0.4 mm/yr was found on a 2.2-3.6 Ma volcanic unit vertically separated by ~980 m across the fault zone at the headwaters of the San Joaquin River (Wakabayashi and Sawyer, 2001).

Le et al. (2007) velocity vector diagrams show that the Sierra Nevada microplate moves at a rate of ~3.0 mm/yr toward an azimuth of ~331 degrees with respect to a fixed block east of the Owens Valley Fault. With the 1872 earthquake along the Owens Valley Fault and the last earthquake along the SNFFS (~4.1 +/- 1.1
ka), there is a 2000-year interval between earthquakes in the region, pointing to a possible rapid change in stress regime (Phillips & Majkowski, 2011).

IV: METHODS

Basic Field Mapping

Before a section of the SNFFS could be used for orientation analysis, it needed to be accurately located in the field. A strand of the SNFFS was mapped using Google Earth images and on maps from Le et al. (2007). The fault scarp, since it was so heavily eroded, was best viewed from down-dip during mid-afternoon to early-evening when the angle of the sun would create a shadow where the fault is located (Figure 7). The mapping goal was to refine general mapping conducted by Le et al. (2007). As a result of this mapping, four fault strands were located in the same locations as located by Le et al. (2007), with three strands cutting the Qf1 alluvial surface (figure 5). The main scarp used for analysis is located along the range front (figure 8), cutting all seven Quaternary surfaces and located closest to the granitic bedrock. The fault scarp has a sufficient elevation change along strike to be used for a dip analysis.
Figure 7: Field photo of fault exposure. The shadows caused by indirect sunlight helped locate the fault in outcrop. Basic field mapping was conducted to help locate the fault in Quaternary surfaces. TopCon GPS was used to take measurements along the bottom cusp of normal fault exposures.

Figure 8: Field photo example of fault scarp crossing the road at George Creek, looking southwest towards the range front. Black line represents the approximate trace of the fault.
Differential GPS

After accurately locating the fault in the field, the fault was walked out using both a TopCon differential GPS and a handheld GPS. The TopCon receiver measured the Easting, Northing, and Elevation \((x, y, z)\) points for each exposed section of the fault. The handheld GPS was used as a comparison to the TopCon differential GPS receiver. The exposed fault was walked out and 60 data points each were collected from both the TopCon GPS and the handheld GPS.

**Figure 9:** Picture showing use of the TopCon differential GPS system in the field near Independence Creek (Shagam 2011). The green tripod to the left is the base station and was immobile throughout the duration of the survey. The yellow tripod to the right is the rover station and was carried along \(\sim 2\) km along the fault surface, where 60 waypoints were collected during the survey.
The TopCon differential GPS system required a precise setup and careful planning. The TopCon GPS had two different receivers; one was set as a base station and the other was set up as a rover (figure 9). The base station had a receiver on top of a fixed tripod. To initialize the GPS, a base station needed to be set up and left alone for 30-45 minutes minimum to maximize accuracy. The base station recorded stationary coordinates in a single location and was used to correct the rover during the survey.
**Figure 10:** Schematic diagram showing where GPS fault locations were collected. Waypoints were collected by placing the rover pole at the intersection of hanging wall deposits and the base of the degraded fault scarp.
Figure 11: Field photo illustrating use of the TopCon GPS Receiver Rover Unit in the field.
Data Post-Processing and Data Analysis

The data were post-processed for better accuracy using the TopCon Tools software. Post-processing of the raw GPS data required the determination of a reliable base station, which served to correct data collected by the rover. The post-processed data were then analyzed using a spreadsheet provided by professor Fred Phillips of New Mexico Tech (table 1). This program is used for analyzing a set of waypoints (northings, eastings, and elevation) to create a 3-dimensional analysis of the fault surface surveyed. In the spreadsheet (table 1), northings are labeled Y, eastings are labeled X, and elevation is labeled Z. The other variables of the spreadsheet are delta X for line, delta Y for line, line X, line Y, zeroed X, zeroed Y, d, slope, and the dip (table 1). The value “d” is the distance along dip direction. Table 1 also shows the calculations for each variable used to determine fault dip. Once the elevations (point Z) and distance along dip direction (d) are computed, the dip is computed by finding the best fit to these z versus d points (figure 12). The dip ($\theta$) is calculated using the following equation:

$$\theta = \tan^{-1} \left( \frac{\text{(elevation)}}{\text{(distance along dip direction)}} \right)$$
Table 1: Spreadsheet used for analysis. Spreadsheet was modified from one provided by Fred Phillips (2012). Points x, y, and z collected at Bairs Creek were plotted onto this spreadsheet and calculated to give proper orientation of the fault surface using the equations above. The slope is calculated by determining the best fit to elevations (point Z) and distance along dip direction (d) using the slope regression formula. \( \theta \) represents the dip, which is calculated by taking the inverse tangent of the slope of the regression line.

\[
\begin{align*}
\text{Delta X for line} & = (\text{point } X) - xo^9 \\
\text{Delta Y for line} & = (\text{delta X for line})/\tan(20) \\
\text{Line X} & = (\text{point } X) - (\text{deltaux}9) \\
\text{Line Y} & = (\text{delta Y for line}) + yo^9 \\
\text{Zeroed X} & = (\text{point } X) - xo^9 \\
\text{Zeroed Y} & = (\text{point } Y) - yo^9 \\
\text{d} & = [((\text{Zeroed X})\cos(20^\circ)) + (\text{Zeroed Y})\sin(20^\circ))] -350 \\
\text{Slope} & = -1 \times \frac{\sum(d - \bar{d})(Z - \bar{Z})}{\sum(d - \bar{d})^2} \\
\text{\( \theta \)} & = \tan^{-1}(\text{Slope})
\end{align*}
\]
V: RESULTS

The survey was carried out over roughly 2,000 m of fault exposure on Quaternary alluvial surfaces. The elevations ranged from 1,888.9 m at the highest point on the survey to 1,781.6 m at the lowest point of the survey. This elevation change allowed for an analysis of dip on this fault. The points are not on a straight line, but vary depending on topography and elevation (figure 12). There was more significant elevation change along the northern section of the surveyed fault, whereas in the southernmost section the elevation range was less significant. The plot of elevation versus distance along dip direction (figure 12 C) shows that the data mostly are well fit by a straight line with $R^2$ of 0.95325. Ideally, for a perfectly plotted fault that is well mapped on the topography, the data should all fit along a straight line. However, considerable scatter is present, especially at northern and southern ends of the profile. At the southern end, elevations at a common distance along dip range and vary up to ~25 m. Data are less variable at northern end. The apparent variation in elevation at a common distance along dip direction actually reflects the low variability in elevation change along strike for the southern section; the elevation of sites along ~1 km of strike length vary by ~25 m making the points cluster with the 25 m elevation change at about the same distance along dip direction. Analysis of these waypoints indicate a best-fit strike of N20°W. The best-fit dip from all waypoints collected at Bairs creek is 23° east.

Due to a more significant elevation range over shorter distance along the northern section of the fault, the northernmost 35 waypoints were used for analysis. This was done to see if more elevation range over the shorter distance would result
**Figure 12**: Compilation of 60 GPS waypoints collected at Bairs Creek. Figure 11A is a Google Earth image showing location of northings and eastings of GPS waypoints collected along the fault surface. This image shows that the waypoints are not on a straight line but vary on location depending on elevation. Figure 11B shows the 60 waypoints. The black line east of the data points represents a best-fit strike of N20°W. Figure 11C is a plot of these waypoints as a function of distance from the strike line. The best-fit line corresponds to both a best-fit strike and dip. Dip is computed from inverse tangent of the slope in equation. The best-fit dip is 23° east. Excel program was provided by professor Fred Phillips of New Mexico Tech.
in a better dip estimate. The southern section (the data points south of the northern thirty-five points) was not used because the waypoints lack sufficient elevation change for analysis of dip. The northernmost thirty-five data points resulted in a best-fit strike of N20°W and a 21.3° east dip (figure 13). This low-angle normal fault in the SNFFS is slightly lower than the low-angle normal fault findings by Phillips and Majkowski (2011), Shagam (2011) and Gadbois (2014).

The 23° east dip result from all 60 points from the survey was more highly correlated than the 21.3° east dip result from the northernmost 35 data points. The analysis of the points with a more significant elevation change over a shorter distance resulted in a slightly lower dip than the analysis of all 60 waypoints. Both analyzed data sets resulted in low-angle normal faults that are significantly less than 30° east.
Alpha 9 = -20, or N20°W, which is the strike of the fault plane based off waypoints.

Figure 13: Compilation of 35 GPS waypoints collected at Bairs Creek along the northern part of the survey along the fault surface. These northern thirty-five waypoints were used for analysis to see if more elevation range over shorter distance results in a better dip estimate. Figure 12A is a Google Earth image showing location of northings and eastings GPS waypoints collected along the fault surface. Figure 12B shows the 35 northern waypoints. The black line east of the data points represents a best-fit strike of N20°W. Figure 12C is a plot of these waypoints as a function of distance from the strike line. The best-fit line corresponds to both a best-fit strike and dip. Dip is computed from inverse tangent of the slope in equation. The best-fit dip is 21.3° east. Excel program was provided by professor Fred Phillips of New Mexico Tech.
VI: DISCUSSION AND INTERPRETATIONS

The low-angle normal faulting documented in this study has consequences for computed horizontal extension rates in the region. Le et al. (2007) calculated vertical slip rates on the SNFFS to be 1.6 mm/yr. Horizontal slip rates were consequently calculated to be 0.9 mm/yr based of a 60° dip. At Bairs Creek, the data indicate that at least one main strand of the SNFFS dips 21°-23° east. This low-angle fault plane geometry agrees with the findings of previous and current studies. Evidence of the low-angle normal fault geometry bounding the western side of Owens Valley include geometrical projections from fault trace mapping, spatial distribution of alluvial fan/drainage basin area ratios, distribution of earthquake hypocenters, deformation of the Bishop tuff, and land-surface profiles adjacent to faults (Phillips & Majkowski, 2011). Fan/drainage ratios are correlated with variations in the style of normal/oblique faulting along the mountain front, with the fault dip appearing to decrease northward the fan/drainage ratio increases (Phillips & Majkowski, 2011). Fracture orientations along the SNFFS surface cross-cutting the bedrock are also evident of the low-angle normal fault geometry found here (Gadbois, 2014)

Figure 14 shows why the horizontal extension rates are in need of re-evaluation because of low-angle normal fault geometry. The Le et al. (2007) measurement of a vertical slip rate of 1.6 mm/yr means that with a 60° dip the horizontal slip rate is 0.9 mm/yr. Using the 23° east dip measured at Bairs Creek as representative of typical fault dip of SNFFS, the calculated horizontal slip rate is 3.8
mm/yr., or roughly four-fold higher than previously assumed. This implies that extension rates along the SNFFS would need to be recalculated.

To calculate extension rates across Owens Valley, one would need normal fault orientations of the White Mountains fault on the eastern side of Owens Valley, as well as fault orientations from the other faults all along the eastern Sierra. If low-angle normal faults are common in Owens Valley, or the entire Basin and Range Province, the regional long-term extension rates would need to be re-examined. Seismic hazard estimates regarding these faults require a better understanding of fault geometry, and these insights could give us a better understanding of seismic risks to other portions of the Basin and Range Province (Phillips & Majkowski, 2011).
Assumed 60° Normal Fault Dip  

\[ Z = 1.6 \text{ mm/yr} = \text{vertical slip rate} \]
\[ \theta = 60° \]
\[ X = 1.6/\tan(\theta) \]
\[ X = 1.6/\tan(60°) \]
\[ X = 0.9 \text{ mm/yr} \]

---

23° Normal Fault Dip found at Bairs Creek

\[ Z = 1.6 \text{ mm/yr} = \text{vertical slip rate} \]
\[ \theta = 23° \]
\[ X = 1.6/\tan(\theta) \]
\[ X = 1.6/\tan(23°) \]
\[ X = 3.8 \text{ mm/yr} \]

**Figure 14:** This schematic diagram shows how low-angle normal faulting affects horizontal extension rates. In this example, Z is the Holocene vertical slip rate of 1.6 mm/yr (Le et al., 2007). X is the horizontal slip rate. \( \theta \) represents the dip of the fault. Based on a 60° dip, horizontal extension rates would be estimated to be 0.9 mm/yr. Based on the 23° dip found at Bairs Creek, horizontal extension rates would be 3.8 mm/yr. Based on this example, Holocene horizontal extension rates are as much as a factor of 4 greater than assumed with a 60° dipping fault.
VII: CONCLUSIONS

Due to recent studies suggesting low-angle normal faults found along the Sierra Nevada Frontal Fault System (SNFFS) in eastern California, a SNFFS fault exposure was examined near Bairs Creek west of Manzanar National Historic site to determine its dip. Northing, easting, and elevation data were collected using TopCon GB-1000 Receiver Differential GPS along the fault scarp. These data were evaluated using an Excel spreadsheet provided by professor Fred Phillips of New Mexico Tech to determine fault dip. A 3-D fault model based on these data yields a best-fit strike of N20°W and 21°-23° east dip. The shallow dip of normal faults of the SNFFS found near Manzanar National Historic site is slightly lower than the low-angle normal fault dips found by Greg Shagam (2011) and Phillips and Majkowski (2011). These data suggest that extension rates based of 60° dipping normal faults could be underestimated by as much as a factor of four, which means that long-term horizontal extension rates in Owens Valley may need to be re-evaluated.
REFERENCES


Shagam, Greg, 2011, Analysis of the Sierra Nevada Frontal Fault orientation in the vicinity of Lone Pine and Independence, California. B.S. Thesis, California State University, Fullerton
