Holocene Earthquakes on the Wassuk Range Fault Zone: Paleoseismic Observations from the Rose Creek Fan and Regional Geodetic Observations, Hawthorne, Nevada, USA

Jayne Bormann[1], Steve Wesnousky[2], Bill Hammond[1], and Alex Sarmiento[2]

[1]Nevada Bureau of Mines and Geology, University of Nevada, Reno
[2]Center for Neotectonic Studies, University of Nevada, Reno

Keywords

Wassuk Range, Walker Lane, Nevada, active faulting, paleoseismology, transtension, GPS, geodesy

ABSTRACT

The Wassuk Range fault zone is an east-dipping, high-angle normal fault that flanks the eastern margin of the Wassuk Range near the town of Hawthorne in central Nevada. We present new paleoseismic observations bearing on the displacement and recurrence characteristics of surface rupturing earthquakes along the Wassuk Range fault zone that result from investigating fault scarps at the head of the Rose Creek alluvial fan, located approximately 8 mi (13 km) northwest of Hawthorne. We examine the fault's recent slip history in two fault trenches and through detailed surficial mapping of the fan. Preliminary results from the Rose Creek trenches indicate;(a) at least two surface rupturing earthquakes between ~9400±95 calendar years B.P. and ~600-2000 ^{14}C years B.P. on the intermediate age surface at the apex of the fan, and (b) at least 2 surface rupturing events prior to ~600-2000 ^{14}C years B.P. on the younger fan surface. Offset of stratigraphic units provides evidence for a large penultimate event followed by a smaller most recent event, and we estimate a Holocene recurrence interval of ~3650-4450 years for surface rupturing earthquakes on the Wassuk Range fault zone. Additionally, GPS observation indicates that the Wassuk Range lies in a zone of transtensional strain accumulation. A marked increase in westward velocity between GPS sites WALK and EWLK suggests a geodetically estimated extension rate for the WRFZ on the order of 0.5-1mm/yr. These results highlight the WRFZ as a likely target for geothermal productivity.

Introduction

The Wassuk Range fault zone (WRFZ) is an east-dipping, normal fault that strikes north-northwesterly for a distance of over 50 miles (80 km) along the eastern margin of the Wassuk Range, accommodating E-W extension near the town of Hawthorne in central Nevada (Figure 1). The Wassuk Range is a steep, actively uplifting, west-tilted fault block that forms the western boundary of the Walker Lake basin. Thermochronologic analysis suggests that rapid extensional deformation and uplift of the Wassuk Range occurred between ~15-12 Ma, with renewed uplift along the present-day, high-angle, rangefront fault beginning ~4 Ma (*Surpless et al.*, 2002; *Stockli et al.*, 2002). Reaching elevations of over 3,400 m, the Wassuk Range is a major tectonic feature in Central Walker Lane: a complex zone of transtensional faulting that accommodates up to 25% of the 50 mm/yr Pacific-North American relative right-lateral plate motion and separates the extending Basin and Range from the rigid Sierra Nevada block (e.g. *Thatcher et al.*, 1999; *Bennett et al.*, 2003; *Oldow et al.*, 2001; *Hammond and Thatcher*, 2007).

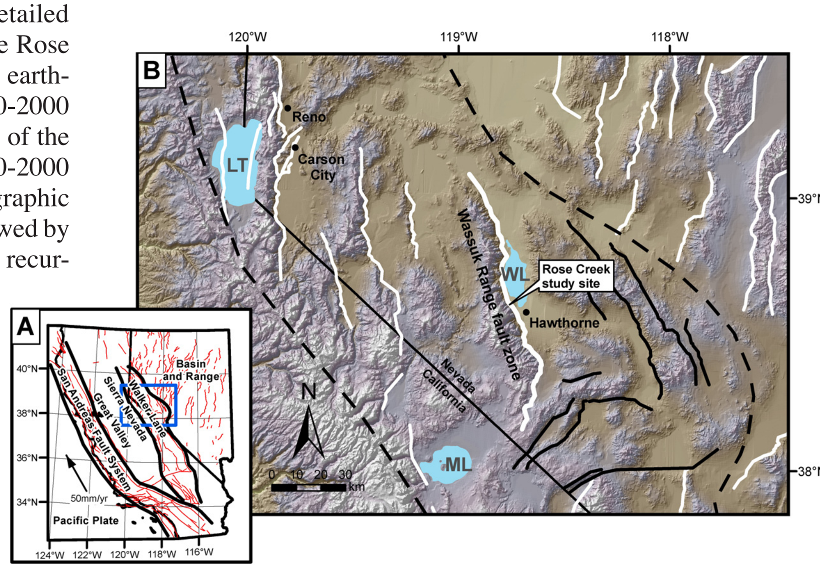

Figure 1. Location of (a) the Central Walker Lane (blue box) with respect to the Pacific Plate, the San Andreas fault system, the Sierra Nevada, and the Basin and Range province. Plate velocity is the Pacific plate relative to stable North America. (b) The Wassuk Range fault zone. Strike slip faults of the Central Walker Lane are black, normal faults are white. Lake Tahoe (LT), Walker Lake (WL), and Mono Lake (ML) are shown for geographic reference. Faults are modified from the USGS (2006).

The focus of this study is the Holocene active trace of the WRFZ. The fault trace is sinuous in nature, exhibits over-steepened, triangular facets at the bedrock alluvium contact, and is expressed in 2-8 m scarps present at the apexes of young and active alluvial fans (Figure 2). Fault scarps that truncate older alluvial fan surfaces and record long term Quaternary offset often show evidence of fluvial modification (*Dempsey*, 1987; *Wesnousky*, 2005) as water levels at the 13 ka late Pleistocene highstand of Lake Lahontan reached elevations of over ~1330 m in the Walker Lake Basin (e.g. *Adams and Wesnousky*, 1999).

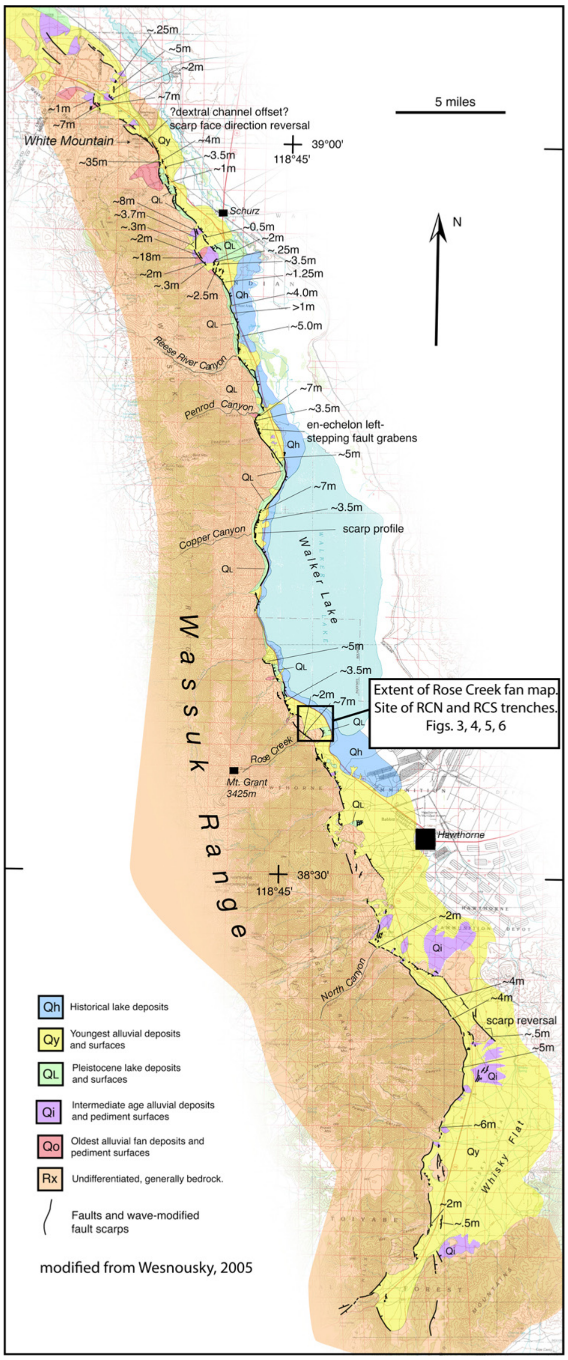

Figure 2. Map of the Wassuk Range fault zone. Fault trace is shown in relation to Quaternary surficial deposits. Numerical annotations indicate scarp height.

Previous work on the WRFZ by *Wesnousky* (2005) documents evidence for a single large surface rupturing earthquake at North Canyon between 3960±35 ^{14}C years BP and ~600-2000 ^{14}C years BP (southwest of Hawthorne, see Figure 2). Synthetic modeling of young scarp profiles along the length of the rangefront suggests that the entirety of the fault has ruptured during the late Holocene (*Wesnousky*, 2005). *Dempsey* (1987) found evidence for 2 major Holocene earthquakes along the WRFZ: one event rupturing 50 km of the fault in the northern portion of the range ~2.5 ka, and a smaller southern event rupturing 30 km of the southern WRFZ ~4.5 ka. In this paper, we report observations and results from a paleoseismic study on the WRFZ at Rose Creek in an effort to further characterize the timing and size of large earthquakes on the fault (Figures 2 and 3). The Rose Creek fan provides an ideal location for a fault study as the site sits high above the late Pleistocene Lake Lahontan highstand, and the fault offsets increasingly older Holocene surfaces by progressively greater amounts, thus certainly recording multiple Holocene earthquakes on the WRFZ. In a geothermal context, the occurrence of Holocene earthquakes on the WRFZ is important as *Bell and Ramelli* (2007, 2009) show a strong correlation between seismically active faults and high temperature geothermal wells. GPS measurement and modeling show that the Wassuk Range is located in a zone of transtensional strain accumulation. Previous work shows a positive correlation between geodetically observed transtensional strain accumulation and geothermal productivity (*Blewitt et al*., 2002, 2005; *Kreemer et al*., 2006; *Hammond et al*., 2007), suggesting that the WRFZ is a potential candidate for geothermal production.

Rose Creek Site

The relationship between Quaternary surficial deposits and the active trace of the WRFZ at the Rose Creek alluvial fan is illustrated in Figure 3 (location shown in Figure 2). At the mouth of Rose Canyon, normal offset along the fault is expressed by ~7 m and ~2 m scarps in intermediate and young alluvial fan deposits, respectively. In the fall of 2009, two trenches were excavated

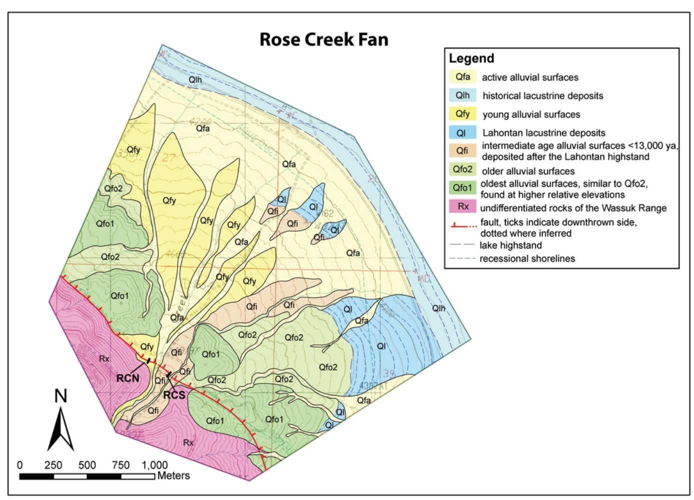

Figure 3. Map showing the relation of the Wassuk Range fault zone to Quaternary surficial deposits on the Rose Creek Fan. Mapping is based on field observations and low sun angle air photos with prior mapping by *Dempsey* (1987) and *Blair and McPherson* (2008). See Figure 2 for location.

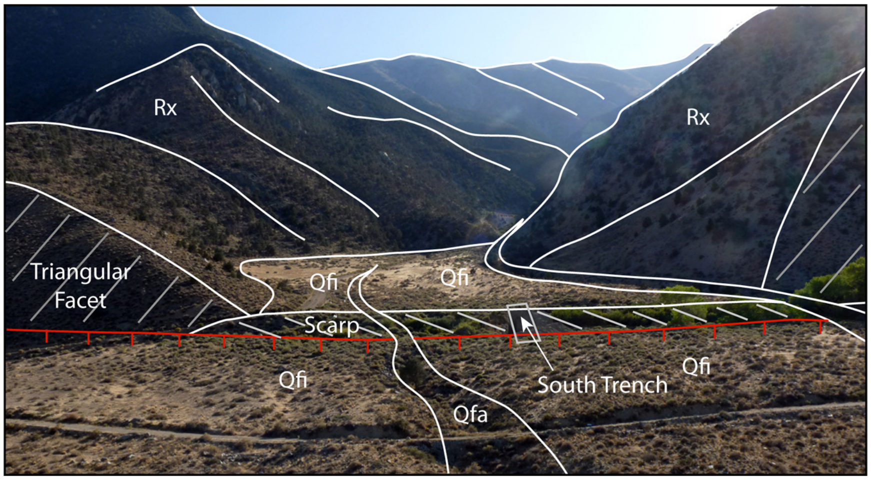

Figure 4. View looking up Rose Canyon across the Wassuk Range fault zone. Photo shows the geomorphic expression of the fault, the relationship between Quaternary deposits, and the location of the RCS trench.

across the WRFZ to determine the recency and recurrence of slip on the fault. The southernmost trench (RCS) was excavated across the larger, intermediate age scarp, whereas the northernmost trench (RCN) was dug across the smaller, young scarp. Figure 4 depicts the fault morphology across the mouth of the canyon and the location of the RCS trench in relation to the surficial deposits. On the basis of soil development and scarp morphology, *Dempsey* (1987) determined both the intermediate and young fan surfaces to be of Holocene age. *Blair and McPherson* (2008) describe the depositional setting of the different fan facies and the stratigraphic development of the Rose Creek fan, however they do not discuss the relationship between the fan units and faulting.

Paleoseismological Observations

Rose Creek South Trench

The Rose Creek South (RCS) trench was excavated across a ~7 m scarp cutting an intermediate age alluvial surface to the south east of Rose Creek (Figure 3). The exposure records approximately 30 m of thick, massively bedded, eastward dipping debris flow deposits cut by the down to the east WRFZ (Figure 5). The oldest unit exposed in the trench (unit 1) is a debris flow deposit capped by a 20-30 cm thick, organic-rich, peat-like layer. This unit is overlain by a thick package of light tan, massive, unsorted, matrix-supported debris flows (unit 2). Hiatuses in fan deposition are marked by slight reddening of the flow surfaces and are indicated in the trench log as thin dashed lines within the unit. Units 1 and 2 are cut by an eastward-dipping normal fault. Although the deposits are similar, an unambiguous match of internal layers present in unit 2 in the hanging and foot wall was not observed. Unit 3 is a tan, massive, wedge shaped deposit that lacks internal stratigraphy and thins to the east, separating the exposures of unit 2. Units 2 and 3 are overlain by a gray, poorly consolidated, unsorted debris flow (unit 4) which in turn is cut by fissures filled with reddish brown, loose, unsorted material with vertically aligned clasts (unit 5) in both the hanging and foot walls. Unit 4 is potentially offset by an upward continuation of the main fault strand, although this relationship is obscured by disturbed stratigraphy due to the presence of a large boulder in the trench wall. Unit 6 is an unfaulted, modern, slope-wash deposit that overlies units 4 and 5 and is capped on the distal end of the hanging wall by a tephra bearing fluvial deposit (unit 7) and slope-wash and aeolian sediments (unit 8).

The relationships in the RCS trench are interpreted to record at least two Holocene earthquake displacements. Fissures (unit 5) extending through units 2, 3, and 4 to the base of the modern surface are interpreted to be evidence of the most recent event (MRE). Unit 3 is interpreted to be fault-derived colluvium from the penultimate event. The mismatch between layers of unit 2 in the hanging and foot walls allows for the possibility of one or more previous events. Radiocarbon analysis of charcoal taken from the peat-like layer at the top of unit 1 at meter 20 yields an age of ~9400±95 calendar years B.P. We interpret this date as a maximum bound on the age of the penultimate event. Additionally, the tephra found in undisturbed unit 7 is regionally correlated with the latest episode of Mono Craters volcanism and dates between ~600-2000 ^{14}C years B.P. (Wesnousky, 2005; J. Bell, Nevada Bureau of Mines and Geology, Reno, Nevada, personal communication, 2010), bracketing the age of faulting observed within the trench.

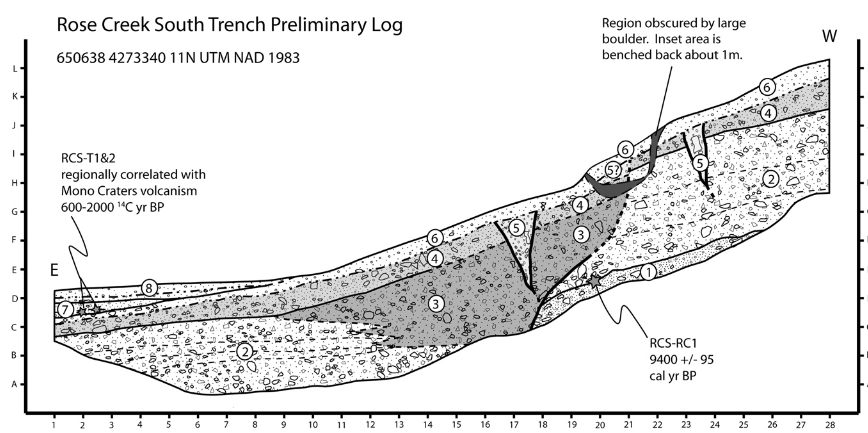

Figure 5. Sketch of the southern trench exposure across the Wassuk Range fault zone at the Rose Creek fan. Location is shown in Figures 3 and 4. Unit label numbers and shading correspond to description in text. Grid marks distance in meters.

Rose Creek North Trench

The Rose Creek North (RCN) trench was excavated across a ~2m scarp in a young alluvial fan surface to the northwest of Rose Creek (Figure 3). Figure 6 shows a sketch of the approximately 20 m long exposure. The trench exposed offset debris flow and alluvial gravel deposits in combination with a set of colluvial packages. The oldest unit exposed in the trench (unit 1) is composed of red brown alluvial gravel layers alternating with gray tan debris flow deposits. Although a similar fabric is present in unit 1 on both sides of trench, the correlation of layers within the unit is not possible. Unit 2 is composed of loosely compacted sand

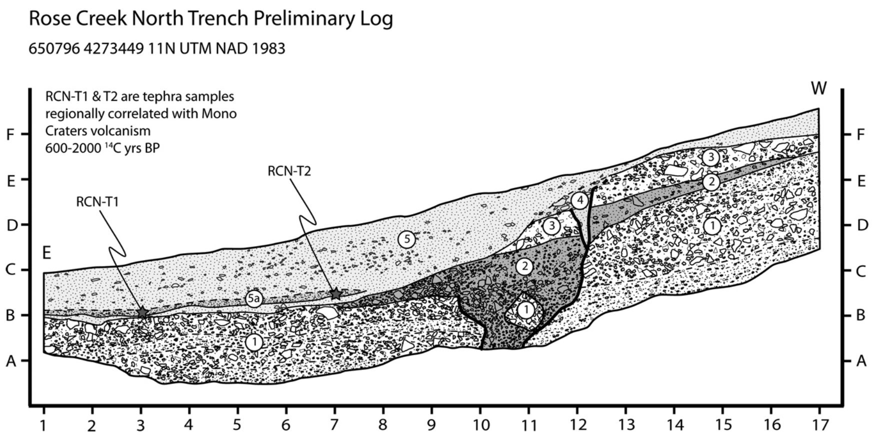

Figure 6. Sketch of the northern trench exposure across the Wassuk Range fault zone at the Rose Creek fan. Location is shown in Figure 3. Unit label numbers correspond to description in text. Grid marks distance in meters.

and gravel, with concentrations of clast supported cobbles and boulders. Unit 2 fills the fault-bounded fissure and forms a triangular shape that thins to the east over the hanging wall, separating the exposures of unit 1 in the trench. Unit 2 is overlain by a poorly consolidated, unsorted, gray tan debris flow (unit 3), which is offset and separated by unit 4. Unit 4 is composed of loose sand and gravels that fill a small fissure form a thin, coarse-grained, clast-supported, wedge-shaped deposit. The entire exposure is capped by a brown tan, matrix-supported, slope-wash deposit (unit 5) that contains a tephra bearing, waterlain subunit (unit 5a).

The stratigraphy in the RCN trench is interpreted to record at least two surface rupturing earthquakes. Unit 2 is a fissure fill and fault-scarp derived colluvial unit that accumulated after unit 1 was offset during the penultimate event. The colluvium was overlain by unit 3, which was subsequently faulted during the most recent event (MRE). The presence of the Mono Craters tephra (unit 5a) in unfaulted hanging wall deposits indicates that both earthquakes recorded in the trench occurred prior to ~600-2000 ^{14}C years B.P. The mismatch of unit 1 across the fault permits the possibility of at least one additional prior slip event. Vertical displacements for the MRE and the penultimate event determined from offset of unit 3 and the thickness of the penultimate colluvial wedge (unit 2) are at minimum ~0.7 m and ~1.5 m respectively.

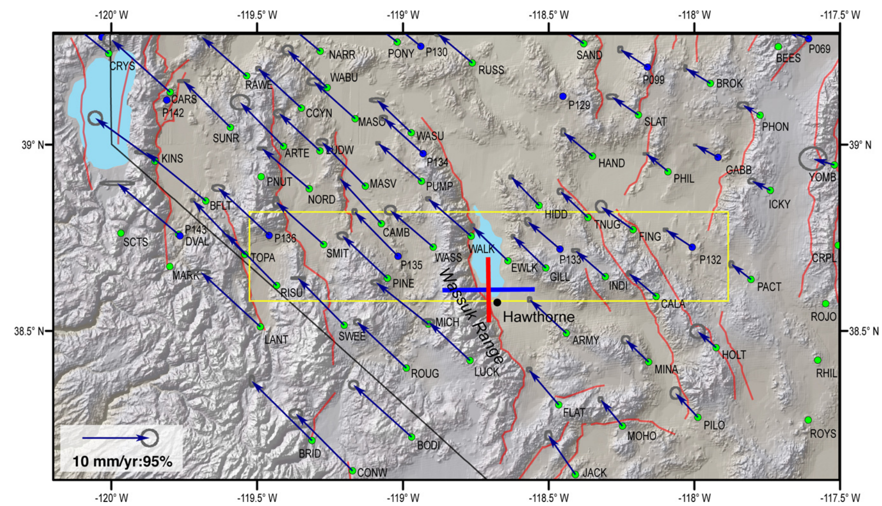

Figure 7. GPS velocity solution for the Central Walker Lane. GPS velocities are shown in blue arrows with respect to stable North America. GPS sites are labeled with the MAGNET network denoted by green dots and the PBO network distinguished by blue dots. The locations of major Quaternary active faults are marked with thin red lines, (USGS, 2006). The orientation of the horizontal strain rate tensor is shown by the blue (extensional) and red (compressional) bars. The yellow box shows the geographic extent of GPS sites included in the velocity profiles (Figure 8).

Regional Geodetic Observations

To place our paleoseismic observations from the WRFZ into a regional context, we present geodetic data from the University of Nevada, Reno's semi-continuous MAGNET GPS network supplemented with observations from EarthScope's Plate Boundary Observatory (PBO). The velocity solution (Figure 7) shows a smooth and continuous increase in shear across the Walker Lane in addition to extension increasing in rate from east to west (*Hammond et al*., 2010). An east-west velocity profile (Figure 8) shows a marked increase in westward velocity across the WRFZ (on the order of 0.5-1 mm/yr), which is consistent with the presence of a major normal fault. From this velocity solution we solve for the orientation and magnitude of the principal horizontal strain rate axes ($\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$) following the methods of *Savage et al*. (2001). For the Hawthorne area (region bounded by coordinates

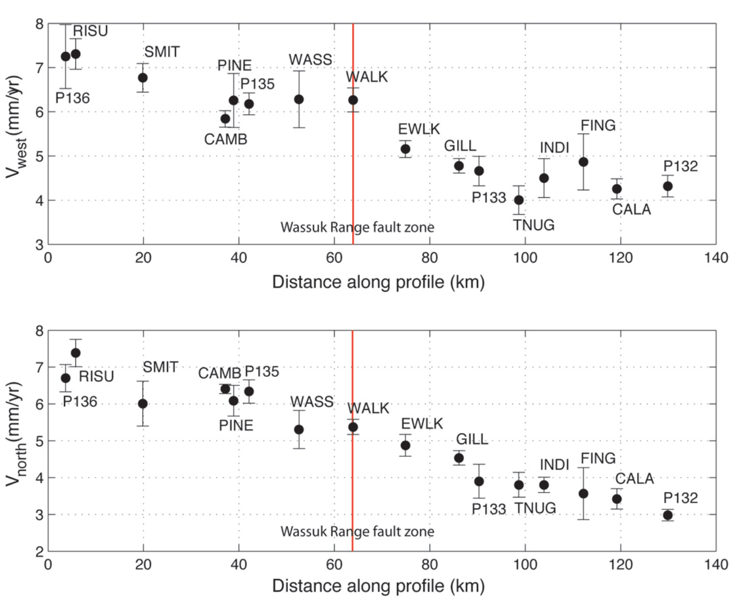

Figure 8. GPS velocity as a function of distance east along profile. Profile location is shown by the yellow box in Figure 7. The upper profile shows the rate in the westward direction whereas the lower profile shows the rate in the northward direction. The projection of the Wassuk Range fault zone is marked with a red line.

-119.3°W to -118.3°W longitude and 38.2°N to 39.2°N latitude), $\dot{\varepsilon}_1$ is extensional, oriented east-west with an azimuth of 272.3±1.8° at a rate of 32±2 nanostrain/yr, and $\dot{\varepsilon}_2$ is compressional, oriented north-south at a rate of -23±2 nanostrain/yr. In this transtensional strain regime, the north-northwest striking WRFZ is accomodating east-west extension. As suggested by previous work (*Blewitt et al*., 2002, 2005; *Kreemer et al*., 2006; *Hammond et al*., 2007), the location of productive geothermal systems is positively correlated with active faults in transtensional settings, highlighting the importance of the WRFZ as a geothermal conduit.

Discussion and Conclusions

The stratigraphic, structural, and age relations described at the Rose Creek fault trenches and fan provide the framework for our interpretations bearing on the frequency, size, and timing of large earthquakes on the WRFZ. The RCS trench records at least two faulting events in a ~7 m scarp on an intermediate age fan surface between ~9400 cal years B.P. and the deposition of the Mono Craters tephra (Figures 3 and 5). The RCN trench also records at least two surface rupturing earthquakes, however the trench crosses a smaller ~2 m scarp in a younger fan surface (Figures 3 and 6). We interpret colluvial unit 2 in the RCN trench and unit 3 in the RCS trench to result from the same earthquake. Both units are of similar shape and form, with the exception that unit 2 in the RCN trench is not associated with a large scarp. The lack of a large scarp may be attributed to erosion subsequent to the earthquake that produced the broad channel and younger surface in which the RCN trench sits (Figure 3) and was likely responsible for the deposition of unit 3 (Figure 6). We interpret the 0.7m offset of units 2 and 3 in the RCN trench to be correlative with the small fissures (unit 5) in the RCS trench (Figure 5), with both offsets resulting from the MRE. In light of the close proximity between the two trenches, we find it reasonable that sites share the same earthquake history: a large penultimate event followed by a smaller MRE. This conclusion opens the possibility that the simple scarps profiled by *Wesnousky* (2005) and *Dempsey* (1987) to the north and south of Rose Creek may also record multiple Holocene events. The combined paleoearthquake record from both trenches indicates at least two earthquakes occurred between ~9400 cal years B.P. and the deposition of the Mono Craters tephra, giving an average Holocene recurrence interval between ~3650-4450 years.

While we do not use GPS data to estimate a slip rate on the WRFZ in a formal inversion, the sharp increase in westward velocity between sites WALK and EWLK across the WRFZ (Figure 8) suggests an extension rate across the fault zone on the order of 0.5-1 mm/yr. It is interesting to note that the north-northwest strike of the WFRZ is not directly perpendicular to the east-west direction of maximum extension. This observation leaves the possibility that there is a dextral component of motion that is not observed geologically on the WRFZ or that strain is partitioned between extension on the WRFZ and dextral shear on the northwest striking Benton Springs and Petrified Springs fault zones to the east.

In summary, our observations confirm multiple Holocene surface rupturing earthquakes along the WRFZ. We report at minimum two events after 9400±95 calendar years B.P., with a large penultimate event followed by a smaller MRE. Geodetic observation supports geologic findings that the WRFZ is a major structure accommodating extension in the Central Walker Lane. The transtensional tectonic setting of the Hawthorne region and Holocene earthquakes on the fault highlight the WRFZ as potential target for geothermal exploration.

Acknowledgements

This work was supported by the National Science Foundation grant EAR-0635757 as part of the EarthScope project and by a Geological Society of America Graduate Student Research grant. We are grateful to the Hawthorne Army Depot and John Peterson for permitting us access to the Rose Creek site. Thank you to Bret Pecoraro for providing field support for the MAGNET GPS network. UNAVCO, Inc. provides essential services for GPS data archiving and support.

References

Adams, K.D., and S.G. Wesnousky, 1999. The Lake Lahontan highstand: Age, surficial characteristics, soil development, and regional shoreline correlations. Geomorphology, v. 30, p. 357-392.

Bennett, R.A., B.P Wernicke, N.A. Niemi, A.M. Friedrich, and J.L. Davis, 2003. Contemporary strain rates in the northern Basin and Range province from GPS data. Tectonics, v. 22, 1008, doi: 10.1029/2001TC001355.

Bell, J.W., and A.R. Ramelli, 2007. Active faults and neotectonics at geothermal sites in the western Basin and Range: Preliminary results. Geothermal Resources Council Transactions, v. 31, p. 375-378.

Bell, J.W., and A.R. Ramelli, 2009. Active Fault Controls at High-Temperature Geothermal Sites: Prospecting for New Faults. Geothermal Resources Council Transactions, v. 33, p. 425-430.

Blair, T.C., and J.G. McPherson, 2008. Quaternary sedimentology of the Rose Creek fan delta, Walker Lake, Nevada, USA, and implications to fan-delta facies models. Sedimentology, v. 55, p. 579-615.

Blewitt, G., M. Coolbaugh, W. E. Holt, C. Kreemer, J. L. Davis, and R. A. Bennett, 2002. Targeting of Potential Geothermal Resources in the Great Basin from Regional Relationships between Geodetic Strain and Geological Structures. Geothermal Resources Council Transactions, v. 26, p. 523-526.

Blewitt, G., W. C. Hammond, and C. Kreemer, 2005. Relating geothermal resources to Great Basin Tectonics using GPS. Geothermal Resources Council Transactions, v. 29, p. 331-335.

Dempsey, K., 1987. Holocene faulting and tectonic geomorphology along the Wassuk Range, west-central Nevada. MS Thesis, Tucson, University of Arizona, 64 p.

Hammond, W.C., and W. Thatcher, 2007. Crustal deformation across the Sierra Nevada, Northern Walker Lane, Basin and Range transition, western United States measured with GPS, 2000-2004. Journal of Geophysical Research, v. 112, B05411, doi: 10.1029/2006JB004625.

Hammond, W.C., C. Kreemer, G. Blewitt, 2007. Exploring the relationship between geothermal resources and geodetically inferred fault slip rates in the Great Basin. Geothermal Resources Council Transactions, v. 31, p. 391-395.

Hammond, W. C., C. Kreemer, and G. Blewitt, 2010. Crustal deformation of the Northern Walker Lane and Basin and Range form GPS data. Journal of Geophysical Research, in prep.

Kreemer, C., G. Blewitt, and W.C. Hammond, 2006. Using geodesy to explore correlations between crustal deformation characteristics and geothermal resources. Geothermal Resources Council Transactions, v. 30, p. 441-446.

Oldow, J.S., C.L.V. Aiken, J.F. Ferguson, J.L. Hare, and R.F. Hardyman, 2001. Active displacement transfer and differential motion between tectonic blocks within the central Walker Lane, western Great Basin. Geology, v. 29, p. 19–22.

Savage, J. C., W. Gan, and J. L. Svarc, 2001. Strain accumulation and rotation in the eastern California shear zone. Journal of Geophysical Research, v. 106, p. 21,995-922,007.

Stockli, D.F., B.E. Surpless, and T.A. Dumitru, 2002. Thermochronological constraints on the timing and magnitude of Miocene and Pliocene extension in the central Wassuk Range, western Nevada. Tectonics, v. 21, 1028, doi: 10.1029/2001TC001295.

Surpless, B.E., D.F. Stockli, T.A. Dumitru, and E.L. Miller, 2002. Two-phase westward encroachment of Basin and Range extension into the northern Sierra Nevada. Tectonics, v. 21, doi: 10.1029/2000TC001257.

Thatcher, W., G.R. Foulger, B.R. Julian, J. Svarc, E. Quilty, and G.W. Bawden, 1999. Present-day deformation across the Basin and Range province, western United States. Science, v. 283, p. 1714-1718, doi: 10.1126/science.283.5408.1714.

U.S. Geological Survey, Nevada Bureau of Mines and Geology, and the California Geological Survey, 2006. Quaternary fault and fold database for the United States: accessed 1/11/2008, http://earthquake.usgs.gov/regional/qfaults/.

Wesnousky, S.G., 2005. Active faulting in the Walker Lane. Tectonics, v. 24, TC3009, doi: 10.1029/2004TC001645.