Nevada Seismicity Studies—Input to Hazard Assessment, Clusters & Sequences, Source Physics, and Ground Motions: Collaborative Research between U.C. San Diego and U. Nevada Reno

USGS Earthquake Research Program Award # G19AP00028 & G19AP00029

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Abstract

This collaborative project between the University of California, San Diego (UCSD) and the University of Nevada, Reno (UNR), involved analysis of seismicity to inform seismic hazard in the Reno-Carson City urban area of Nevada. A range of processing methods were applied to seismic data recorded by the Nevada Regional Network and available temporary networks. This work is part of our longer term goal to use detailed analysis of ongoing seismicity in the region to identify active faults at depth, and characterize the spatial and temporal nature of Nevada seismicity and consequent seismic hazard. We performed waveform cross-correlation for similar event cluster identification and high-precision earthquake relocation (using the "GrowClust" algorithm, a product of the prior NEHRP award). We also investigated the stress regimes in which the earthquakes occurred, and the source processes of individual events. We focused on the Reno-Tahoe region, identifying active structures and resolving a clear relationship between the depth of seismicity and the crustal thickness. We performed more detailed analyses of individual events and sequences, including the one near Nine Mile Ranch in December 2016 that included three M5+ earthquakes, and a smaller swarm in 2014 that was widely felt in Virginia City. Both sequences involved faulting on multiple active structures, and we note many similarities between the geometry and timing of the Nine Mile Ranch sequence, and the 2019 Ridgecrest earthquakes to the south. In addition, we quantified the local relationship between seismic moment and local magnitude, and compiled a database of peak ground motions recorded within the network, particularly in populated areas, important input for research on seismic hazard analysis. The work directly addressed the priorities set by the Nevada Seismic Hazard Working Group and others (http://www.nbmg.unr.edu/_docs/Earthquakes/NBMG_priorities_NEHRP.pdf).

1. Introduction

Nevada is second only to California in the lower-48 states in long-term seismic activity. Nevada experiences an M 6 earthquake, on average, about every 6-7 years. Also, there have been three events of M ~7 since 1900. NSL processes an average of 1.7 M $\geq$ 3 events per week and locates nearly 15,000 events per year, far exceeding all WUS networks outside of California and Alaska. The NSL currently operates ~120 stations, and there are ~100,000 M $\geq$1 earthquakes in the NSL waveform database since 1984. Detailed analysis of the waveforms in this database using modern techniques will enable us to characterize the seismicity in Nevada and probe its causes, controls, and effects. Our research currently focuses on the urban area around Reno and Carson City because of its high station density, the recent occurrence of some active sequences, and the importance of earthquake activity near population centers.

Reno, Tahoe, and Carson City lie within the Walker Lane tectonic region. The majority of earthquakes in the western US east of the Sierra occur in the Walker Lane of western Nevada and eastern California (Figure 1). This activity reflects the ~20-25% relative Pacific-North America strain budget determined from geodetic studies (*Faulds and Henry, 2008*). Consequently, these regions have better monitoring than eastern Nevada. Additionally, NSL has operated a dense network in the southern Nevada area for DOE projects since 1992. Deformation within the Walker Lane is accommodated through a complex distribution of NW-striking dextral and secondary NE-striking sinistral strike-slip systems and primarily down-to-the-east normal faulting along the eastern Sierra. The NW-striking dextral faults of the southern, central and northern Walker Lane directly accommodate plate-boundary shear (e.g., *Faulds et al*., 2005), whereas range-front normal faulting and structural transition zones along left-stepping normal faults in the northeastern Sierra tend to dominate the seismic hazard in the populated areas of Reno-Carson City and Lake Tahoe. Instrumental seismicity is generally not observed on major range-bounding fault systems but is instead concentrated at the ends of these faults, or step overs, along the northeast Sierra (*van Wormer and Ryall, 1980; Ichinose et al., 1998*), However, clusters of seismicity, with a variety of characteristics, are distributed throughout the Walker Lane and the western Nevada/eastern California region. The largest historical events in Nevada have occurred on range-bounding normal faults of the Basin and Range and within the central Nevada seismic belt.

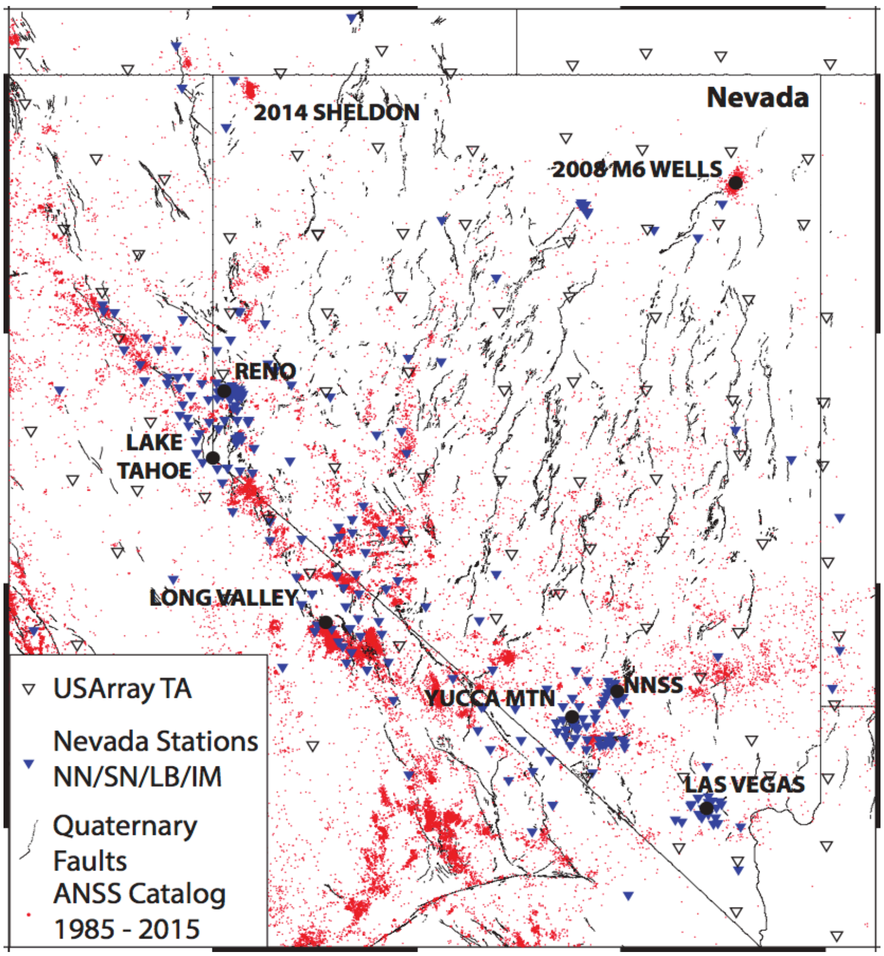

Figure 1. Seismicity features of Nevada and surrounding areas monitored by the NSL, as illuminated with the ANSS catalog 1984-2014 (red dots). NNSS: Nevada National Security Site. The gray lines are the USGS qfaults database (U.S. Geological Survey, Nevada Bureau of Mines and Geology, and California Geological Survey 2008, Quaternary fault and fold database for the United States). The Walker Lane bounds the eastern Sierra and extents about 100 km into the western Basin and Range. Regions of good network coverage include the Reno-Carson City-Lake Tahoe area, the eastern Sierraregion southward from near Sierraville, CA, to Long Valley, and in the Mina Deflection structural zone of west-central Nevada and eastern California.

Of particular importance and interest to the populated areas of the Reno-Carson City-Lake Tahoe region is the common occurrence of earthquake swarms. Seismic swarms are poorly understood, making it hard to forecast how long they will last, or how large the largest earthquakes will be. For example, the extended 2008 Mogul sequence caused significant damage and was widely felt throughout Reno. The largest, M5, earthquake occurred on a previously unknown fault with no surface expression, despite the shallow depth of less than 5 km (*Ruhl et al., 2016, 2017*). Van der Elst and Page (2018) have shown that comparing ongoing sequences to past ones is a useful forecasting tool.

During the Award, we relocated seismicity in the larger region around Reno and Lake Tahoe, identifying active structures, and their links to mapped faults, and also facilitating analysis of the controls on the seismogenic depth extent. All of these factors affect estimates of the size of future earthquakes in the region. In addition, we analyzed in detail two sequences of events discovering evidence for fluid migration and aseismic slip as driving forces.

The majority of the work in the award was performed by PhD student, Rachel Hatch, and forms a major part of her thesis (Defense planned for June 2020). Dr. Abercrombie advised and mentored Ms. Hatch, with Dr. Smith. Dr. Smith also compiled waveform and moment tensor databases for investigating ground motions. Dr. Shearer assisted with the GrowClust relocations, including procedures to assemble a waveform database and compute cross-correlation differential times. All the personnel met at the Nevada Seismological Laboratory in January for a week to collaborate on the work presented here. In addition, Dr. Shearer showed Dr. Abercrombie the sequence of processing steps involved in the application of his spectral decomposition codes, and together they applied them to the 2008 Mogul, Nevada sequence and compared the resulting stress-drop estimates with those obtained previously using a spectral ratio approach . This work continues a productive collaboration of researchers who together are gradually building the detailed picture of Nevada seismicity from the network-recorded data, that is needed to address the important outstanding seismic hazard questions.

2. Analysis of Seismicity around Reno-Tahoe

Characterized by abundant microseismicity and a history of moderate magnitude (M5-7) earthquakes, the Walker Lane is a natural laboratory for exploring the relationship between microseismicity and active faulting. Ruhl *et al.* (2020) develop high-precision absolute and relative earthquake relocations to highlight seismicity patterns related to active faulting in, and to explore variation in seismogenic depths across, the Northern Walker Lane. They first compute datum-adjusted and station-residual-corrected absolute relocations using Hypoinverse before relocating events based on waveform cross-correlation using GrowClust (Trugman and Shearer, 2017). Of the 40,581 routinely located earthquakes between 2002 and 2018, they were able to relocate 27,132 (66.9%) with resulting median horizontal and vertical location uncertainties less than ~500 m (Figure 2). Microseismicity occurs in large highly clustered source areas, often consisting of many short, distinct fault structures. Activity concentrates near the ends of mapped Quaternary faults rather than along them. The microseismicity defines structures in transition zones between the major surface faults, and these may represent active fault networks that link the faults at the depth. To map the depth extent of seismicity, they calculated the 95^{th} percentile depths and compare this to published Moho depths and topography.

Seismogenic depth shallows away from the Sierra Nevada to the east-northeast, from approximately 16 km to 12 km depth. This follows, to scale, the decrease in Moho depth across the same region from about 35 km to 30 km. Finally, we compare seismogenic and Moho depths to topographic relief and limited heat flow measurements to discuss controls on the depth of seismicity in the region.

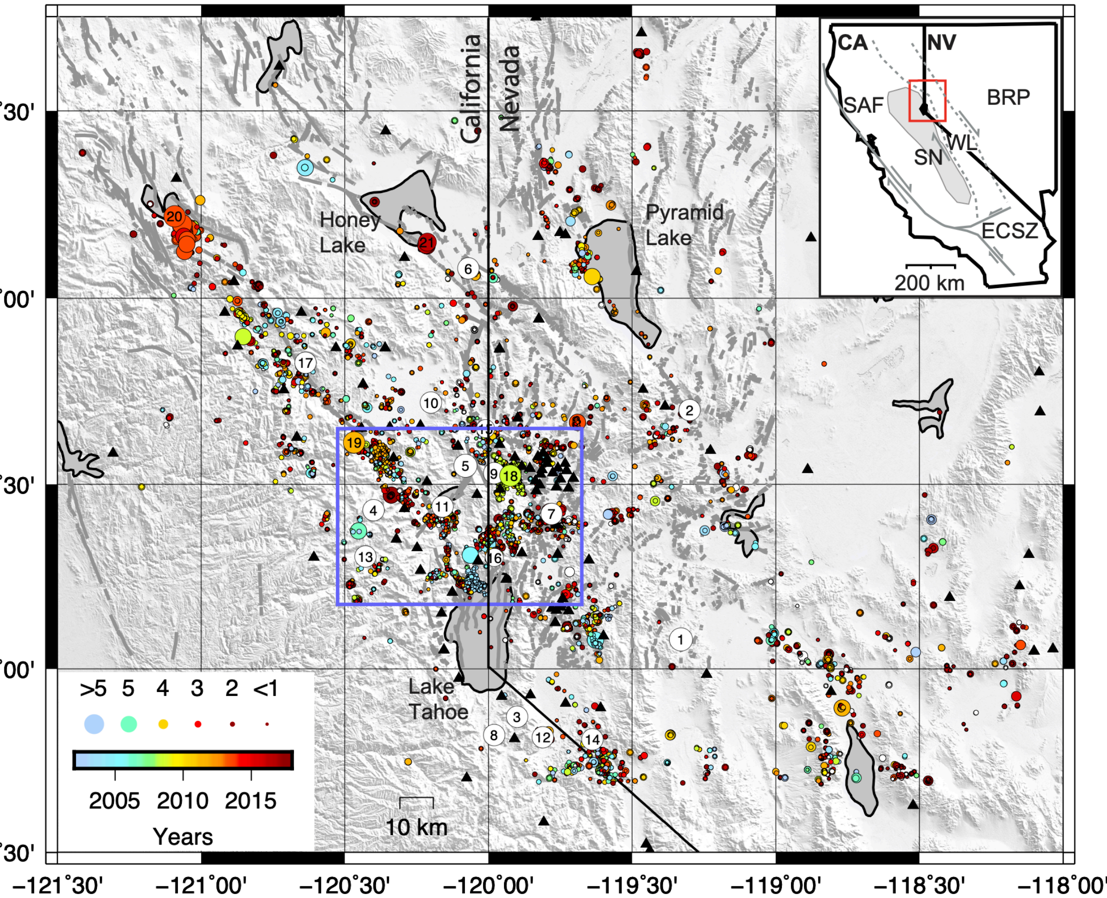

Figure 2. Earthquake location map of Reno-Tahoe area (Ruhl *et al.* 2020) showing both historical seismicity (numbered events) and relocated microseismicity from 2002-2019 developed in this study. Seismicity is sized by magnitude and colored by time. Additionally, USGS Quaternary faults are shown as gray lines and regional seismic stations are shown by black triangles. Nevada (NV) and California (CA) are shown for geographical reference in the inset at top right. Significant tectonic features are labeled: the San Andreas fault system (SAF), Eastern California Shear Zone (ECSZ), Sierra Nevada block (SN), Walker Lane (WL), and Basin and Range province (BRP).

3. Analysis of Individual Sequences

3.1 2014 Virginia City Nevada

In January 2014, over a period of about 10 days, a swarm of earthquakes were felt in Virginia City. After the initiation of this Virginia City sequence, both the public and emergency responders were alerted and responded to the swarm (Wolterbeek *et al*., 2014). Public concern was high, partly due to the recent Mogul sequence that had shaken and damaged Reno (e.g. Ruhl *et al*., 2016) and also because of several particulars of Virginia

City: 1) the historic city is mostly comprised of unreinforced masonry structures, 2) the city is built above the underground workings of the Comstock mining works with significant potential for ground failure, and 3) there is limited access to Virginia City along single lane roads with significant relief and potential to isolate the city from landslides and ground failure. Daily conference calls were conducted with local emergency managers to evaluate preparedness, event response planning scenarios, and availability of resources. As the sequence dissipated, the coordinated planning of the emergency management community acted as a practice run for future swarm activity in the area.

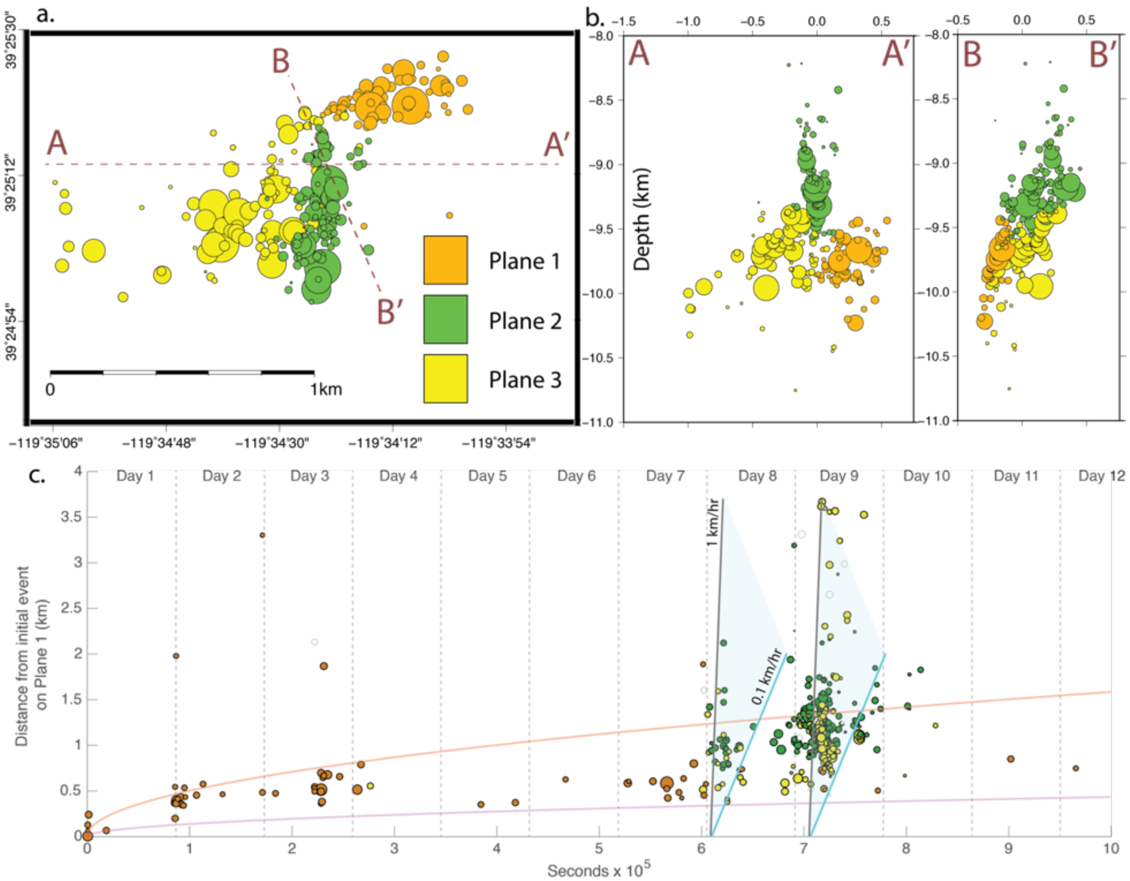

Figure 3. Virginia City Sequence (a) Relocations of 305 events in map view, which reveal three well-defined planar structures spanning ~1 km, on an unmapped fault. Events sized by magnitude and colored by plane number (1-3). **(b)** Cross section views across A-A' and B-B', with events ranging from 8.5-10.5 km in depth. (**c)** Graph showing time (in seconds) versus distance (in meters from initial event in the sequence). Events colored by plane (1-3) and sized by magnitude. Diffusion curve in orange is D = 0.2 m/s^2; diffusion curve in magenta is D = 0.015 m/s^2. Grey line shows rate of 1 km/hr and light blue line shows rate of 0.1 km/hr. Range in between these rates shown in light blue triangle. Plane 1 (orange) events appear to migrate at a rate consistent with fluid diffusivity, while events on Planes 2 (green) and 3 (yellow) appear to migrate at a much faster rate, between 1-0.1 km/hr, consistent with aseismic creep. (Hatch *et al*., 2020).

Analysis of the small earthquake swarm near Virginia City, NV published in the AGU Geophysical Research Letters by Hatch *et al*. (2020), identifies the active structures and driving forces for the earthquakes (see Figure 3). The swarm of events reveals complex structural features, including an interplay of both fluid-driven and aseismic-driven earthquake migration within a naturally occurring tectonic sequence. The Virginia City earthquake sequence occurred over ~10 days in January 2014. Hatch *et al*. (2020) relocate 305 events to reveal three separate, well-defined planar structures (Figure 3). The earthquakes initially migrate at a rate consistent with pore fluid diffusion, outlining a moderately dipping plane. The earthquakes then jump to a vertical plane, and migrate at a higher rate; the sequence continues to migrate rapidly onto a third, shallowly dipping plane, consistent with rates observed elsewhere associated with aseismic creep. Focal mechanisms indicate right-lateral strike-slip on the vertical plane and both normal and left-lateral strike-slip movement on the other planes, and the newly imaged structures illuminate the orientation of active faults at depth in the Walker Lane tectonic region.

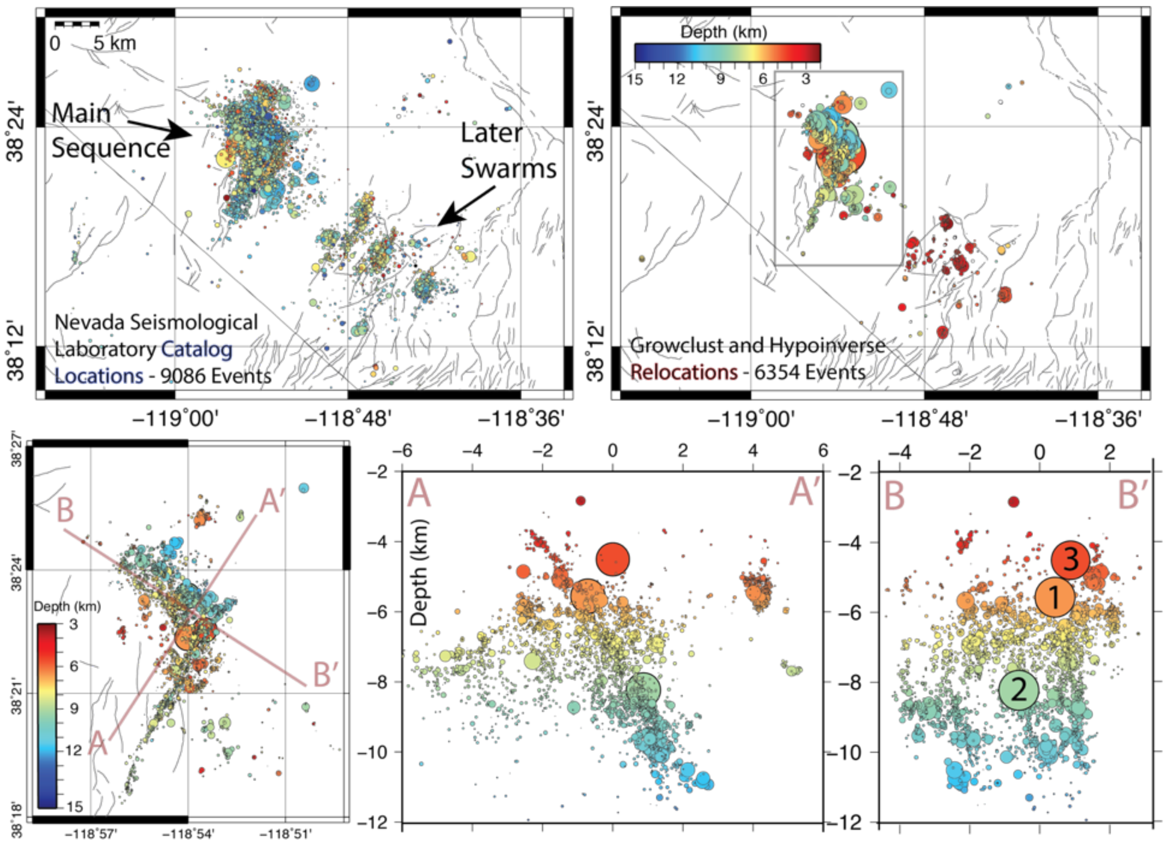

Figure 4. Nine Mile Ranch Sequence (Hatch *et al*., 2020). Catalog and Relocated Seismicity. The M5+ earthquakes are numbered, and locate near the junction of the two conjugate planes.

3.2 2016-2017 Nine Mile Ranch Sequence, 3 Mw ~5.5 Events West Central Nevada

On December 28th, 2016, three moderate sized earthquakes (Mw 5.6, 5.4, and 5.5) occurred within one hour in the central Walker Lane, near historic Nine Mile Ranch, ~30 southwest of Hawthorne, Nevada (Figure 4). The initial event, Mw 5.6, was followed 4 minutes later by an Mw 5.4. The third, Mw 5.5, occurred 55 minutes after the initial moderate event. NSL moment tensor solutions for the three events are similar and show high-angle strike-slip faulting with an ENE-WSW extension direction. Summing the moment of the three main events equates to an M_w 5.9. These events resulted in surface cracks and damage to the recently refurbished house and out buildings of Nine Mile Ranch, historical late 1800s brick and stone structures. These are the largest earthquakes in the central Walker Lane Mina Deflection region since the 2003-2004 Adobe Hill earthquake sequence about 20 km to the SE, which also included 3 M ~5.5 events and an extended aftershock sequence. Analysis of these earthquakes is of particular interest due to the strong similarity in geometry to the 2019 Ridgecrest sequence in eastern California. Both sequences began with a large event on a ENE-WSW trending fault that increased failure stress on a conjugate, NW-SE trending fault, which subsequently failed in another large earthquake.

Hatch *et al*. (2020) describe our detailed analysis of this sequence of events, and the information it provides about active structures and stress state of the Walker Lane. The Nevada Seismological Laboratory has located over 9000 events from the sequence, with depths ranging from 3-13 km. Moment tensor solutions show high-angle strike-slip faulting for the three main events, with focal mechanisms and moment tensors of smaller events showing predominantly strike-slip and normal ruptures. The relocations performed in this study indicate several substantial unmapped structures. The largest structure in the sequence implies right-lateral strike slip faulting on a ~N57W striking fault plane. This fault plane is also dipping at a high angle to the NE. An orthogonal conjugate ~S33W striking, vertical-dipping fault plane lies at the southern terminus of the larger fault plane; this fault plane is interpreted as a left-lateral fault plane. The three main events are located very near one another at the intersection of the two major conjugate structures.

We use Coulomb stress analysis to investigate which of thw two structures was most likely to have ruptured first as the seismic recordings are inadequate to distinguish which of the M5+ earthquakes occurred on which structure. If the left-lateral fault ruptured first, then it would have stressed the right-lateral faults, but the opposite is not true. Hence, we infer the first fault to move was the left-lateral, which is the same sequence and geometry as that of the Ridgecrest sequence, to the south in eastern California (REF??).

Additionally, we use nearby GPS stations to invert for the long-term average strain rate and attain coseismic offset for the sequence for comparison with the orientation of the earthquake slip.

3.3 Continuing Studies Highlighted During the Course of Study:

In addition to the detailed studies above, we also began analysis of other notable sequences For example, on December 22nd, 2015, an M_w 4.3 occurred in south Reno, NV, and was widely felt throughout the Reno basin and Tahoe area, and followed by over 200 aftershocks. Several large faults are active in this densely populated region, but their orientation at depth is unknown limiting basin modeling. This sequence provided an opportunity to determine which fault ruptured, and its orientation at depth, important for understanding the seismic hazard in the area. We relocate 157 events using both absolute and relative relocation techniques. The relocations indicate the sequence occurred on a NNE-striking, west-dipping structure, and project to the west side of the Virginia Range along the eastern boundary of the Reno-area basin. This interpretation suggests active normal faulting bounds the eastern Reno basin, at this latitude defining a structural graben with the main Mt. Rose fault system along the Carson Range, to the west. Moment tensor solutions and focal mechanisms show predominantly normal faulting as well as oblique sinistral faulting within the sequence. We continue to improve the locations, and investigate source properties for sufficiently well-recorded earthquakes, including stress drop and directivity, to more completely understand this sequence and active structures involved.

4. Database Compilation for Seismic Hazard Analysis

We have compiled all waveform data in SAC files and subsets of Peak Ground Motions (SAC: DEPMIN/DEPMAX) in associated lists/datafiles of all earthquakes M>= M3.5 in the western Nevada region 2000-present (this set does not include the ongoing 2020 M5.2 Mono Lakes, 2020 M 4.5 Carson City or 2020 M6.5 Monte Cristo Range sequences). Several scripts were developed to create a more easily accessible dataset for strong ground motion purposes. This subset from the UNR archive is being built into a separate data files in both Antelope Datascope and flat file listings in order to be directly useful. The large UNR archive is cumbersome for this specific purpose. The dataset is currently being applied by Dr. John Anderson (NSL), Dr. John Louie (NSL) and Elnaz Esmaeilzadeh Seylabi (UNR-Engineering) for the western Nevada region and, in particular, Reno-Carson area GMPEs and site response. Dr. Louie is also using the data set in forward modeling (using the code SW4) to compare basin model synthetics with empirical earthquake ground motions. Currently SW4 models have been restricted to 2Hz with limited computer resources. Graduate Student Eric Eckert used the empirical ground motion data, and structures identified from precise earthquake relocation by Ms. Hatch, to model Reno basin ground motions with SW4 for his Masters thesis (defended May 2020).

The database includes data from the entire network, not just western Nevada stations. It was simpler to subset the entire waveform database than retrieve specific strong motion or velocity station data and then reduce that dataset. As a result, much of the clipped analog data is being removed but the waveform database is complete. The network has evolved significantly since the late 1990s early 2000s when the initial ANSS strong motion stations were deployed in Reno. The dataset includes ~780,000 time-series records in SAC format corrected for CALIB into nm/sec velocity records and nm/sec/sec acceleration records. The dataset is currently being reviewed for correct station response information in preliminary GMPE assessments. Thorough review of station response histories is being conducted and once reconciled, NSL response holding will be corrected and the dataset will be made available through the UNR web page. The compilation of waveforms is complete, review of instrument response is demanding.

The data set includes waveform data from 183 M>=3 western Nevada region earthquakes. Also, the data set includes the near source deployment ground motion data for the 2008 M5 Mogul, 2011 M4.6 Hawthorne and 2015-2016 (3) M5+ Nine Mile Ranch sequence.

5. Conclusions

We made considerable progress in our collaborative work to analyze Nevada seismicity to identify active faults and characterize the spatial and temporal behavior of a number of earthquake clusters and explore the implications for seismic hazard near populated regions of the state. Our work applied modern techniques for earthquake relocation and spectral analysis to the rich waveform database collected by the Nevada Seismic Network. We performed waveform cross-correlation and high-precision earthquake relocation for seismicity in the greater Reno-Tahoe area, which illuminated fault structures and networks in this complicated region. We conducted detailed analyses of several prominent sequences, including the 2014 Virginia City swarm, the 2016–17 Nine Mile Ranch sequence, and aftershocks of a 2015 M 4.3 earthquake in south Reno. We found that the Nine Mile Ranch sequence has many similarities to the 2019 Ridgecrest earthquakes in

California further south in the Walker Lane seismicity belt. We compiled a new database of peak ground motions recorded by the Nevada network, which can be used for future planned seismic hazard analyses. Our work addresses research priorities defined by the Nevada Seismic Hazard Working Group.

<u>Publications Related to this Study:</u>

Anderson, J. G., Koehler, R. D., R. E. Abercrombie, S. K. Ahdi, S. Angster, J. Bormann, J. N. Brune, *et al.,* (2019). A seismic hazards overview of the urban regions of Nevada: Recent advancements and research directions, 2018, *Seismological Research Letters,* doi: https://doi.org/10.1785/0220180357.

Hatch, R. L., Abercrombie, R. E., Ruhl, C. J., & Smith, K. D. (2020). Evidence of aseismic and fluid-driven processes in a small complex seismic swarm near Virginia City, Nevada. *Geophysical Research Letters*, 47, e2019GL085477. https://doi.org/10.1029/2019GL085477

Hatch, R. L., Smith, K. D., Hammond, W., Pierce, I. K. D., Abercrombie, R. E., and Ruhl, C. J., (2020 in prep.). Orthogonal Conjugate Faulting in the Walker Lane: Comprehensive Case Study of 3 M_w 5.4-5.6 and the Nine Mile Ranch Sequence from 2016-2019 near Hawthorne, Nevada, *to be submitted to JGR or BSSA*.

Ruhl, C.J., Abercrombie, R.E., Hatch, R.L., and Smith, K.D., (2020.), Seismogenic Depth Variation across the Transtensional Northern Walker Lane, *Geophysical Research Letters,* in prep.

Hatch, R. L., Smith, K. D., Abercrombie, R. E., Ruhl, C. J., Hammond, W., and Pierce, I. K. D. (2019) Relocations and Tectonic Implications of the Nine Mile Ranch Sequence from 2016-2018: 3 M_w 5.4-5.6 near Hawthorne, Nevada, *Seismological Research Letters*, 90, 964.

Hatch, R. L., Smith, K. D., Abercrombie, R. E., Ruhl, C. J., Hammond, W., and Pierce, I. K. D. (2019) Recent Damaging Earthquakes on Conjugate Structures in the Walker Lane: Characteristics of the The Nine Mile Ranch Sequence (2016-2019) and Comparison to the Ridgecrest Sequence of 2019, SCEC Annual Meeting, Palm Springs, Poster #263, *SCEC Contribution #9824*

<u>Presentations and Outreach:</u>

Rachel Hatch presented the results of this work to a range of audiences.

Friends of the Pleistocene - Pacific - Central Walker Lane - The Nine Mile Ranch Sequence (3 Mw 5.4-5.6) from 2016-2019:Relocations, Tectonic Implications, and Comparisons to Recent Sequences *(poster and presentation)*

UNR Graduate Student Association 2019 - Recent Damaging Earthquakes on Conjugate Structures in the Walker Lane: Characteristics and Comparisons of the Nine Mile Ranch Sequence (2016-2019) *(poster, 1st place poster/presentation contest)*

Cal Poly Pomona Dept Seminar Invited Speaker Dec. 2019 - Recent Damaging Earthquakes on Conjugate Structures in the Walker Lane: Characteristics and Comparisons of the Nine Mile Ranch Sequence (2016-2019) *(talk and presentation)*

Panorama Elementary School (Maryland) - Science Tools and Science Safety *(hands-on interactive talk and demonstration)*

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Faulds, J.E., Henry, C.D., and Hinz, N.H. (2005). Kinematics of the northern Walker Lane: An incipient transform fault along the Pacific – North American plate boundary: Geology, v. 33, no. 6, p. 505-508.

Hatch, R. L., Abercrombie, R. E., Ruhl, C. J., & Smith, K. D. (2020). Evidence of aseismic and fluid-driven processes in a small complex seismic swarm near Virginia City, Nevada. *Geophysical Research Letters*, 47, e2019GL085477. https://doi.org/10.1029/2019GL085477

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Ruhl, C.J., Abercrombie, R.E., Hatch, R.L., and Smith, K.D., (2020.), Seismogenic Depth Variation across the Transtensional Northern Walker Lane, *Geophysical Research Letters,* in prep.

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van der Elst, N. and M. T. Page (2018). Regional and spatial variations in aftershock productivity, AGU Fall Meeting Abstract, #S52B-05.

van Wormer, J.D., and A.S. Ryall, Sierra Nevada-Great Basin boundary zone: Earthquake hazard related to structure, active tectonic processes, and anomalous patterns of earthquake occurrence, *Bull. Seismol. Soc. Am.*, **70**, 1557-1572, 1980.

Wolterbeek, M., Smith, K., Curtis, J. (2014). Nevada Seismological Lab reports swarm of earthquakes near Virginia City University of Nevada, Reno reports several magnitude-3.2 quakes, no damage reported. Newsroom.unr.edu. http://dps.nv.gov/media/PR/2014/Nevada_Seismological_Lab_reports_swarm_of_earthquakes_near_Virginia_City/