University of Nevada, Reno

Nevada Seismological Laboratory

Nevada Bureau of Mines and Geology

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2018 Working Group on Nevada Seismic Hazards

Summary and Recommendations of the Workshop, February 5–6, 2018

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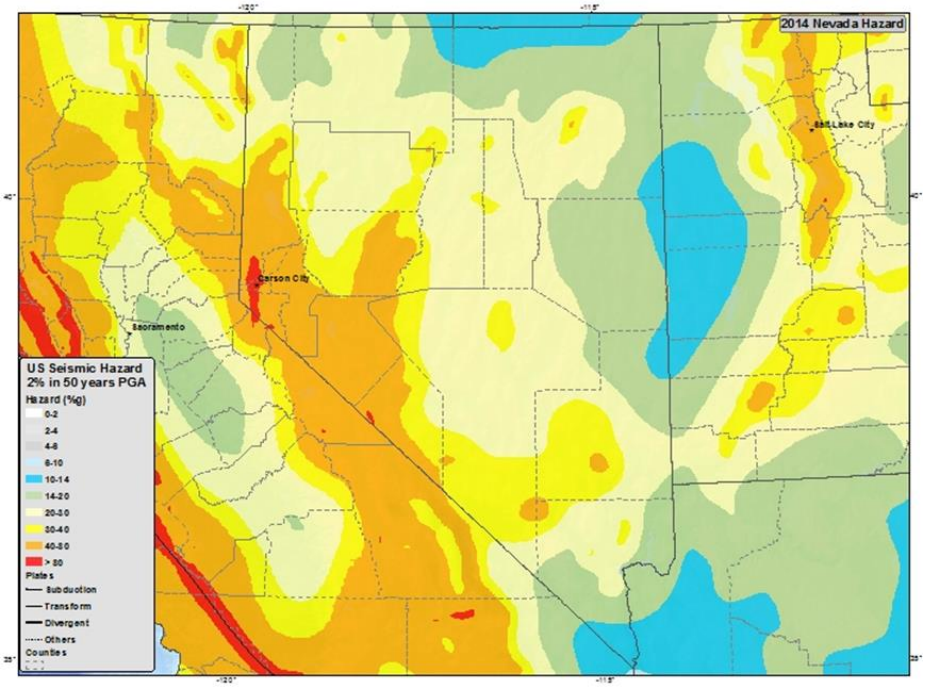

The Nevada Bureau of Mines and Geology (NBMG) is a research and public service unit of the University of Nevada, Reno and is the state geological survey. Established by the Nevada Legislature as a public service division of the Nevada System of Higher Education, NBMG is a department within the Mackay School of Earth Sciences and Engineering within the College of Science and one of the Statewide Programs at the University of Nevada, Reno. NBMG's mission, to provide the state's needs for geological and mineral- and energy-resource information and research, is defined in its enabling legislation. NBMG scientists conduct research and publish reports that focus on the economic development, public safety, and quality of life in urban and rural areas of Nevada.

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INTRODUCTION

Ranked by the numbers of tectonic earthquakes, Nevada is the third most seismically active state in the United States, behind Alaska and California (Anderson and Miyata, 2006). Major earthquakes in Nevada (dePolo et al., 1997) have included the 1915 Pleasant Valley earthquake (Mw7.2), the 1932 Cedar Mountain earthquake (Mw7.1), and the 1954 cluster of earthquakes in central Nevada including Stillwater (Mw6.8), Fairview Peak (Mw7.1), and Dixie Valley (Mw7.0) earthquakes. While these earthquakes have all fortunately been relatively removed from major population centers, these earthquakes, as well as widely distributed smaller earthquakes throughout the state demonstrate that the seismic hazard of the region is high. The U.S. Geological Survey (USGS) has consequently and appropriately been highly concerned that the National Seismic Hazard Map (NSHM) for this region should be as reliable as possible.

Seismic hazard in western Nevada is characterized by two main tectonic elements, the Walker Lane Belt (WLB) and Basin and Range extension. The WLB is characterized by transtensional strike-slip motion along the eastern side of the Sierra Nevada block at 6–9 mm/year to the NW relative to central Nevada. This motion is accommodated along northwest striking right-lateral faults, northeast striking left-lateral faults, and north-northeast striking normal faults (Stewart, 1988; Wesnousky, 2005a, 2005b; Wesnousky et al., 2012). Geologic deformation rates along many of the faults in the Reno-Carson City-Lake Tahoe region, which is in the WLB, remain poorly constrained, and urban development has made assessing paleoseismic parameters difficult along many structures. East of WLB, the main tectonic element is Basin and Range extension. Crustal motion in the eastern third of central Nevada is relatively block-like, and characterized by the 1–2 mm/yr westward motion relative to stable North America (Hammond et al., 2011, 2014; Koehler and Wesnousky, 2011). In the Las Vegas region of southern Nevada, deformation is accommodated across a widely distributed series of faults. Many of these faults are poorly characterized, and paleoseismic parameters are currently insufficient to include several mapped faults in the National Seismic Hazard Map. Strain-rate models for the southwestern United States show zones of elevated strain across these structures (Kreemer et al., 2010; 2012). Thus, seismic hazards have the potential to impact any region of the state.

Improvements to future updates to the National Seismic Hazard Map are dependent on developing a better understanding of spatio-temporal patterns of crustal strain accumulation and release (geodesy and geology), better defining fault geometry, predictive models of source characteristics and ground motions (seismology), and better characterizing site response, basin amplification, and basin depths (geophysics), among other issues. To address future research priorities related to these issues, a two day workshop was convened at the University of Nevada, Reno to discuss technical issues related to earthquake hazards in Nevada and develop a path forward to reduce uncertainties and improve the National Seismic Hazard Map. The workshop builds on the results of previous working group efforts (Briggs and Hammond, 2011).

This report presents a summary of the key issues discussed at the workshop. A formal publication of the workshop results has been submitted for publication in a peer-reviewed journal. The summary presented here is intended to be a resource for guiding future earthquake research in Nevada and will be archived on-line at the Nevada Bureau of Mines and Geology (NBMG). The workshop provides a model for future working group meetings of earthquake professionals in Nevada in efforts to better characterize seismic hazards in the state.

WORKSHOP ORGANIZATION AND SUMMARY

The main goal of the workshop was to review ongoing earthquake hazard research in Nevada, discuss technical issues related to earthquake hazards in Nevada, and identify priorities for future research that will reduce uncertainties and improve the National Seismic Hazard Map. The workshop included technical presentations and discussions focused on five main topics relevant to earthquake hazards in the Reno-Carson-Lake Tahoe and Las Vegas regions including: 1) general aspects of seismic hazard models, 2) Quaternary fault parameters, 3) seismology, 4) ground motions, and 5) geodesy.

Participants included a wide variety of professionals from Federal and State government agencies, academia, and private industry (Appendix 1). Attendees presented their recent relevant research, with the goal of improving the USGS hazard model as it affects hazard estimates in Nevada. Attendees were asked to identify the most important research issues needed to improve the USGS hazard model. It is intended that the conclusions of the workshop will be reflected in future updates of the "Research priorities for Nevada", which is updated annually, archived on the NBMG website, and referred to in the NEHRP RFP.

For brevity, main points and discussion topics related to each presentation for each day are summarized in bullet form. The workshop agenda is contained in Appendix 2, and individual abstracts are listed in Appendix 3.

Day 1 Summary

Day 1 began with introductory remarks related to the purpose and format of the workshop followed by a presentation on the funding history and current status of the USGS external grants program. Next, a series of talks focused on data needs and uncertainties in building the Nevada hazard model, updates of the seismic hazard model for Nevada planned for 2018 and 2020, and lessons learned from the Working Group on Utah Earthquake Probabilities including implications for better

characterizing seismic hazards in Nevada. These presentations summarized many of the challenges and unresolved issues related to the Nevada hazard model and were followed by subsequent mini sessions on Quaternary faulting and paleoseismolgy in northern and southern Nevada. These presentations focused on summarizing prior paleoseismic results, highlighting new and ongoing paleoseismic research, and evaluating the implications of including various sources in the hazard model. The day finished up with a discussion of Quaternary fault parameters aimed at identifying priority faults for future study that would have the greatest impact on future updates of the hazard model.

Key Points and Discussion Items from Day 1

Update on the U.S. Geological Survey external grants program, led by Ryan Gold, USGS Intermountain West Regional Coordinator

- The Intermountain West region of the USGS external grants program funded 12 proposals in FY2017 for a total of ~$439k, approximately 12% of the total program budget.
- There is a possibility for a slight reduction of the total available funding amount in FY 2019; however, the program is moving forward. Out-of-cycle proposals are discouraged, and all research proposals should be submitted to the competitive cycle.
- The on-line interface for the USGS Quaternary Fault and Fold database was updated in 2017 and significant updates were completed for Utah, Arizona, California, New Mexico, Alaska, Washington, and Oregon. The states of Colorado and Nevada are in need of updates. In the future the USGS will only maintain limited metadata fields and will become increasingly reliant on individual states to update and maintain Quaternary fault maps.

Building the Nevada Hazard Map—information needed and some important uncertainties, led by John Anderson, Nevada Seismological Laboratory

- The hazard map represents a compilation of hazard curves (peak acceleration vs. annual exceedance rate) for a contoured grid of points and incorporates a seismicity model based on fault geometry, slip rate, magnitudes, and a smoothed, declustered seismicity catalog converted to Mw. Ground motion prediction equations (GMPEs) based on strong motion data, Vs30, and basin velocity models are also incorporated. Future improvements to GMPEs may incorporate site response and waveform models.
- Tornado plots can be used to evaluate the relative contribution and uncertainty of various parameters in the model such as slip rate, GMPE, fault dip, and Mmax.
- Aleatory uncertainty has a strong impact on low probability hazard estimates. Epistemic uncertainty is important at all ground motion levels because the preferred best estimate of hazard is the weighted average taken at a fixed spectral acceleration.
- It is important for users to understand the uncertainties in the mean hazard estimates, and it was recommended that the USGS provide these uncertainties with each update of the NSHM.
- Building the National Seismic Hazard Map is a community effort. For each new version, the USGS holds workshops, and invites contributions of improvements to existing models and/or new models. It was recommended that contributors utilize a web portal maintained by the USGS in order to submit new information or proposed modifications to the model.

The 2018 and 2020 U.S. National Seismic Hazard Model for Nevada, led by Mark Petersen, USGS

- The 2018 update of the NSHM will incorporate central and eastern United States ground motion models (i.e., NGA-East), western U.S. sedimentary basin effects, and an updated seismicity catalog.
- Potential updates that are being considered for the 2020 update include incorporation of magnitude area relationships, the national crustal model, 3D simulations, new geologic and geodetic models, NGA-subduction, directivity, point-source modeling, and the GK15 ground motion model for western U.S. ACRs.
- The outcomes of three methods to incorporate sedimentary basin effects into the 2018 NSHM were demonstrated for the Reno-Carson City area. The default basin terms are provided by the developers of the ground motion prediction equations. The second uses laterally varying Vs30 from the USGS Vs30 database. The third uses a composite basin depth model based on published regional and national velocity models. The second and third methods are proposed as an improvement over the 2014 NSHM, which used default basin depths. For a map based on Vs30=260 m/s, the second and third models give generally smaller ground motions for SA(5 sec) with a probability of 2% in 50 years.
- The Las Vegas Valley fault system was highlighted as being a large contributor to ground motions in downtown Las Vegas. A logic tree approach was proposed as an option to quantify the relative weights of individual slip-rate estimates.
- Continued progress in geodesy, seismicity, ground motion, and crustal modeling was also highlighted as important tasks for improving the NSHM.

Insights into Basin and Range seismic hazards from the Working Group on Utah Earthquake Probabilities, led by Ivan Wong, Lettis Consultants International (LCI)

- The Working Group on Utah Earthquake Probabilities (WGUEP, 2016) published its earthquake forecast for the Wasatch Front region of the Intermountain West after a six year collaborative effort. The forecast focused on characterizing Quaternary active faults and background seismicity. The methodologies of the evaluation are applicable to seismic hazard assessment in Nevada.
- An adequate characterization of the epistemic uncertainties in the models and parameters was an essential component of the Utah effort.
- The success of the project was achieved with inputs from scientists from State and Federal agencies, and private industry that were discussed and evaluated during many working group meetings.
- The forecast evaluated multiple time-dependent and time-independent earthquake probability models. The considered rupture models included segment-specific, multi-segment, and whole fault ruptures of the Wasatch fault, segment-specific and fault-specific ruptures for the Oquirrh-Great Salt Lake fault, time-independent fault-specific ruptures for 45 additional faults along the Wasatch Front, time-independent models for background earthquakes, and total probabilities for the Wasatch Front region.
- Data from over 23 paleoseismic trenches were essential for evaluating the various rupture models.
- Careful examination of magnitude estimates from various empirical relations indicated discrepancies in estimates of characteristic magnitudes. A methodology to estimate Mmax was developed to reconcile these differences.
- The expected mean frequency of earthquakes and the elapsed time since the most recent event was used to develop time-dependent recurrence intervals. Characterizing the periodicity of the large earthquakes proved to be challenging and required scrutiny in the choice of the coefficient of variation (COV).
- A robust earthquake catalogue was developed and used to construct an earthquake magnitude-frequency distribution (MFD). The paleoseismic estimate of the recurrence rate of earthquakes agreed well with the MFD based on background seismicity emphasizing the importance of paleoseismic data in calibrating models.
- Geodetic data was not directly used in estimating fault slip rates due to the wealth of available paleoseismic data along the Wasatch Front. This suggests that in Nevada, where paleoseismic data are limited, GPS data may have a more important role in seismic hazard assessment.
- It was acknowledged that more rigorous testing of segmentation models will require more complete paleoseismic records. Until these data become available, the working group will not be able to evaluate fault interactions and stress-shadow models.
- It was emphasized that the Utah working group benefitted from the formation of multiple sub-groups and the dissemination of sub-group results at comprehensive working group meetings.

Questions bearing on the estimation of seismic hazard in the Reno-Carson-Lake Tahoe region, led by Steve Wesnousky, Center for Neotectonic Studies and Nevada Seismological Laboratory

- The neotectonic framework of the southern part of the northern Walker Lane was described and presented in the context of the distribution of paleoseismic research sites. In general, paleoseismic research sites are concentrated along the major faults, but many less prominent faults remain unstudied. Furthermore, with the exception of the Pyramid Lake fault and the Carson Range fault system (Genoa fault), most faults have not been investigated at multiple sites.
- Previous paleoseismic research results were summarized for faults in the northern Walker Lane.
- The Washoe shear zone has been proposed as a potential 28–48-km-long structure extending northwest and southeast from the Truckee Meadows area of Reno; however, the only definitive Quaternary displacements occur along the Mount Rose fan.
- Detailed evaluation of previous paleoseismic results is compromised for many faults due to the limited publication of results in grey literature. USGS final technical reports often do not contain plates (and sometimes trench logs and figures) referenced in the reports.
- Large uncertainties in paleoseismic parameters remain for many faults in the region.
- The majority of the deformation in the Reno area thus far documented is predominantly accommodated by normal displacement. This is in contrast to dominantly right-lateral shear recorded by GPS data. Right-lateral displacement has been suggested in several paleoseismic studies; however, these studies are poorly documented and have not been independently verified.

Efforts to better characterize the seismic potential of faults in the North Valleys region, Reno, Nevada, led by Rich Koehler, Nevada Bureau of Mines and Geology.

- Efforts by the NBMG to better characterize faults in the North Valleys area north of Reno were presented. Additionally, a synopsis of the current state of knowledge on Quaternary faults in the Reno area as they relate to the National Seismic Hazard Map was discussed and potential methods to prioritize faults for future research was proposed.
- A comparison of maps showing faults included in the 2014 update of the NSHM and the National Quaternary Fault and Fold Database indicates that several faults that have well-documented Quaternary fault parameters are not included in the 2014 update. In particular, the Toquima and Monitor Range faults, the Carson lineament, and the East Carson fault zone. Several faults in the North Valleys (not all) are included but associated with uncertain parameters.
- North- and northeast-trending normal faults in the North Valleys are associated with moderate tectonic geomorphology and discontinuous scarps in Pleistocene alluvium and collectively accommodate 0.9–1.2 mm/yr of extension. Faults include Last Chance/Long Valley, Petersen Mountain, Fred's Mountain, Spanish Springs Valley, Spanish Springs Peak faults and unnamed faults in Hungry and Lemmon valleys. On-going projects include LiDAR evaluation, Quaternary mapping, and trenching. Additionally, fault data archived at the NBMG is being evaluated to determine whether modern methods can better characterize previously evaluated sites.
- Information for 50 Quaternary faults within approximately 100 km of Reno was compiled. The 2014 NSHM considers 24 of these 50 faults. A qualitative matrix was developed to prioritize faults for future research.
- The matrix consisted of various categories including length, slip rate data quality, slip rate, existence of recurrence/timing data, age of most recent deformation, linear distance to Reno, and whether or not the fault is currently considered in the hazard model. Workshop attendees discussed ways in which the matrix could be improved. Suggestions included weighting various parameters, including estimates of dip and dip uncertainties, and consideration of the availability of LiDAR data.
- Prioritization results indicate that the Mount Rose fault zone, East Carson Valley fault zone, Carson lineament, Last Chance/Upper Long Valley fault, Little Valley fault, Genoa fault, Bonham Ranch fault zone, and North Tahoe fault should be prioritized for future research.

The search for strike-slip in the Northern Walker Lane—new slip rates and characterization of active faults in Antelope, Mason, and Smith valleys, Nevada, led by Ian Pierce, Center for Neotectonic Studies and University of Nevada, Reno.

- New observations based on evaluation of LiDAR data and Quaternary geologic mapping yield information on sense of slip, and slip rate for faults in Antelope, Mason, and Smith valleys in the Walker Lane.
- Basins at the latitude of Lake Tahoe have similar geometries and despite strong geodetically observed shear through the region, right-lateral faults have not been previously documented. Block rotation between major faults can accommodate some, but not all, of the strain budget.
- Mason Valley is characterized by subdued range-front morphology and few fault scarps in Quaternary deposits. A late Pleistocene (155 ka) alluvial fan is vertically offset 6.5 m indicating a vertical slip rate of 0.04 mm/yr.
- Lateral faults have been identified in southern Mason Valley based on displaced terrace risers (18–30 m), pop-up ridges, right deflected streams, beheaded channels, shutter ridges, and uphill-facing scarps. Slip rate evaluation in Mason Valley is ongoing.
- Smith Valley is characterized by active tectonic geomorphology along the range-front and numerous fault scarps in Quaternary alluvium. Progressively greater offset across progressively older surfaces combined with cosmogenic ages indicate a vertical slip rate of ~0.5 mm/yr across the range bounding fault.
- Antelope Valley is characterized by active range-front morphology along its western margin and numerous fault scarps. Faulting also recognized along the eastern side of the valley. A vertical displacement rate of 0.6 mm/yr was determined based on an alluvial fan estimated to be 51 ka that is offset 29 m across the fault. A possible right-laterally offset terrace riser was identified in one location.
- Along the West Tahoe-Dollar Point fault a 59 m vertical offset was documented in a Tahoe-aged (120 ka) glacial moraine from which a vertical slip rate of 0.5 mm/yr was inferred.
- Extension rates (assuming a 60 dip for faults) for faults bounding the Lake Tahoe, Antelope, and Smith valleys are similar to geodetically observed extension rates; however, geologic rates of extension inferred in Mason valley are considerably less than geodetic rates.
- Subtle evidence has been observed for right-lateral displacement in Antelope, Smith, and Mason Valleys. Lateral faults were not observed along the West Tahoe-Dollar Point fault.
- Deformation is dominantly range-front extension. Component of lateral motion is inferred to be small compared to vertical deformation.

New estimates on the rate of slip for faults of the central Walker Lane, led by Steve Angster, Center for Neotectonic Studies and University of Nevada, Reno.

- New slip-rate estimates were determined for the Pyramid Lake fault in the northern Walker Lane. Quaternary surficial geologic mapping was conducted along approximately 14 km of the fault. Drone photography and structure from motion software was used to produce detailed Digital Elevation Models (DEMs). Evaluation of the DEMs resulted in the documentation of seven sites that preserved evidence of lateral displacement across the fault.
- Geochronologic information on the age of displaced Quaternary surfaces related to pluvial Lake Lahontan were combined with the offset measurements to estimate a geologic slip rate of 1.3 mm/yr for the Pyramid Lake fault, which is lower than previous estimates and consistent with geodetic observations.
- In the central Walker Lane, Quaternary surficial geologic mapping, geochronology, and offset measurements were employed to constrain geologic slip rates and characterize the geomorphic expression of the Benton Springs, Indian Head, Petrified Springs, and Gumdrop Hills faults.
- Mapping to date has only identified Holocene displacements along the Benton Springs and Indian Head faults.
- For the Benton Springs fault, a 35 m displacement of an alluvial fan estimated to be ~22 ka indicates a slip rate of 1.8 mm/yr. For the Petrified Springs fault, an offset of 92 m of an alluvial fan estimated to be 124 ka indicates a slip rate of 0.7 mm/yr. Additional slip rate estimates include 0.2–0.8 mm/yr and 0.1–1.1 mm/yr for the Indian Hills and Gumdrop Hills, respectively.
- Cumulative observations from the central Walker Lane indicate that geologic slip rates (2.0–5.2 mm/yr) appear to be at the high end of the rates determined from geodetic block modeling (1.0–3.1 mm/yr) but overlap within error.

Recent paleoseismicity of the Kings Canyon fault zone between Ash and Vicee canyons, Carson City, Nevada, led by Craig dePolo, Nevada Bureau of Mines and Geology.

- A paleoseismic trench study was conducted across the Kings Canyon fault at the Vicee-Ash Canyon site.
- The Kings Canyon fault is part of the Carson Range fault system and is characterized by compound fault scarps, springs, grabens, triangular facets, and over-steepened basal range-front slopes. The fault is within a few kilometers of Carson City and dips beneath it.
- Trench results indicate that four events have occurred along the fault in the last ~5,000 years. Surface offsets were estimated to be around 2 m per event with a total vertical displacement of 8.4 m.
- A slip rate of 1.5–2 mm/yr was estimated for the late Holocene based on the age of the displaced fan deposit (4,420–5,260 ybp) and the cumulative offset (8.4 m).
- Comparison of the earthquake record to the event chronologies on other nearby faults indicates that the Kings Canyon fault did not rupture during the most recent event on the Genoa fault; however, the penultimate and/or triultimate events may have been involved with penultimate events on the Genoa or Washoe Valley faults. Thus, the fault is capable of independent events, but discussion noted the possibility of interaction with other nearby faults in multi-fault ruptures.
- Earthquake timing data suggest short inter-event timing between some events, suggesting that the fault may be characterized by clustered behavior.

Fault interactions along a N-S belt around 114.75 degrees W longitude in southern Nevada, led by Wanda Taylor, University of Nevada, Las Vegas.

- Presentation focused on recent and ongoing studies of Quaternary faults east and north of the Las Vegas Valley including the Frenchman Mountain, California Wash, Arrow Canyon Range, Wildcat Wash, Kane Spring Wash, Coyote Spring, and Maynard Lake faults.
- Geologic and kinematic studies along the Frenchman Mountain fault indicate that the sense of slip is dip slip near the center and oblique slip on the northern and southern ends of the fault trace. The east-northeast striking northern end of the fault is characterized by oblique left normal slip and may link to a 15-km-long zone of right-stepping en echelon faults that extend to and overlap with the California Wash fault.
- The California Wash fault is associated with beveled scarps up to 10 m high in relatively older Quaternary deposits, and scarps of 1–2 m on younger surfaces have been documented. Several exposures of the California Wash fault have been documented and indicate the occurrence of three paleoearthquakes. A radiocarbon date from one colluvial wedge suggests a possible age for an event around 1,825 radiocarbon years; however, further details on the event chronology have been hindered by a general lack of quality radiocarbon results. The California Wash fault overlaps with and is separated from the Arrow Canyon Range fault across a 25 km step.
- For the Arrow Canyon Range fault, scarp heights of >0.5–3 m have been documented. A gentle relay ramp associated with an anticline occurs between the Arrow Canyon Range and Wildcat Wash fault suggesting a tectonic connection.
- Several colluvial wedges were documented in an exposure of the Wildcat Wash fault. Radiocarbon analyses from sediments within the wedges suggest the occurrence of earthquakes around 1,400 yr and 16,500 cal yr B.P. The

northern end of the Wildcat Wash fault bends to a northeasterly strike and overlap with the southern end of the northeast striking left-lateral Kane Spring Wash fault.

- The Maynard Lake fault is characterized by left offsets of older Quaternary drainages, offset of a young resurgent fan, and a transpressional right stepover.
- Discussion debated the potential of these faults to work together to accommodate regional strain due to their close proximity to each other, map view relations that indicate that fault tips curve towards each other, and the presence of relay ramps and left-lateral strike-slip faults that may accommodate slip transfer.

New paleoseismic data from the Frenchman Mountain fault, Las Vegas, led by Seth Dee, Nevada Bureau of Mines and Geology.

- Presentation focused on new mapping and paleoseismic trenching along the Frenchman Mountain fault, a west-dipping range-front fault bounding the eastern side of the Las Vegas basin. The deepest part of the basin (~4.7 km) is immediately west of the fault.
- The fault is well expressed by scarps in Quaternary alluvial fans and bedrock range-front morphology that extend for at least 16 km.
- Geodetic block modeling results indicate that 0.2–0.3 mm/yr of the 0.4–0.6 mm/yr of extension across the Las Vegas Valley may be accommodated across the Frenchman Mountain fault.
- Previous mapping efforts in the area have determined three main ages of alluvial-fan units including Qfy^2 (1–7 ka), Qfi (5–20 ka), and Qfo (500 ka–2 ma). The distribution of these alluvial-fan units were refined by new mapping on LiDAR and orthorectified photomosaics (historic black and white aerial photographs processed in AgiSoft photoscan).
- Tectonic scarps up to 10.4 m and 2 m were identified in Qfo and Qfi deposits, respectively.
- A previous trench excavated for a housing development was reoccupied and described. Three colluvial wedge deposits were documented from which three paleoearthquakes were inferred. Total displacement for the three events was estimated at 1.6 m.
- Optically stimulated luminescence (OSL) ages from alluvial-fan sediments in the footwall indicate that the three earthquakes occurred within the last 53.3–62.1 ka. OSL ages from scarp colluvium indicate that the triultimate earthquake occurred around 43.5–53.5 ka and the penultimate earthquake occurred around 24.6–28.8 ka. The OSL sample from the most recent earthquake colluvium was similar to the penultimate age suggesting that the sample may have been inadvertently collected from the underlying wedge or was not adequately reset.
- Based on the total offset and the age of the alluvial sediments in the footwall a slip rate of 0.03–0.037 was estimated.

The Las Vegas Valley fault system—a 2017 progress report, led by Craig dePolo, Nevada Bureau of Mines and Geology.

- Presentation focused on summarizing previous information on the Las Vegas Valley fault system.
- The Las Vegas Valley fault system consists of many faults within the Las Vegas Valley including the Decatur, Valley View, Cashman, Whitney Mesa faults and several other lesser studied faults. Faults are generally expressed as scarps, monoclines, and vegetation lineaments and are typically associated with east or southeast side down apparent normal separation.
- Mechanisms for formation of scarps is an ongoing debate. Potential mechanisms include tectonic displacement, differential compaction, groundwater discharge, salt dissolution, and/or a combination of processes.
- The Decatur fault is about 22 km long and bounds the western side of the basin. At least ten scarps have been identified including the prominent scarp across Alta Drive.
- The Valley View fault is associated with large scarps up to 10–14 m as well as scarps in young alluvium.
- The Cashman fault extends along the eastern side of the basin and is characterized by a 2-km-wide zone of scarps, a 22-m-high scarp in Pliocene–Pleistocene deposits at Bonanza Road, a 20-m-high scarp in late Pleistocene deposits, a possible small scarp in Holocene deposits near Main Blvd., possible liquefaction features along the southern part of the fault.
- The Whitney Mesa fault zone is a series of 3–4 discontinuous faults that bound the eastern side of the central basin. Combined scarps of up to 55 m have been documented.
- The Eglington fault is associated with a discreet northeast trending scarp in the northern part of the valley. Several previous investigations have documented scarp heights of up to 14 m. The inferred faulted deposits have been dated by several studies and used to estimate slip rates that range between 0.3 and 0.65 mm/yr. This slip rate has been controversial and is the subject of on-going studies. The main issue is that the slip rate appears high given the geodetic strain budget of about 0.4–0.5 mm/yr across the entire system.
- The major faults/scarps in the Las Vegas Valley all appear to deform Quaternary sediments. However, to improve seismic hazards assessment, better paleoseismic characterization is needed to resolve non-tectonic vs. tectonic mechanisms of deformation.

Seeking input on the inclusion of the Eglington fault, Nevada, in the National Seismic Hazard Map, led by Ryan Gold, U.S. Geological Survey.

- Presentation focused on the implications of the current state of knowledge on the Eglington fault and implications of previously determined slip rates to the National Seismic Hazard Map and ground motions estimated for the city of Las Vegas.
- Incorporating a slip rate of 0.44–0.55 mm/yr for the Eglington fault in the 2014 update of the National Seismic Hazard Map increased the hazard for Las Vegas. About 90% of the hazard in Las Vegas is driven by the Eglington fault.
- In the 2014 update, the occurrence rate of earthquakes was increased from 0.000071 (based on a 14.1 ky return period) used in the 2008 map to 0.000465 (based on a 2.15 kyr return period).
- Arguments were presented for both seismogenic and non-seismogenic origins for the scarp.
- A seismogenic origin for the scarp is supported by an 11-km-long escarpment associated with a 14 m vertical separation of 27.6–31.6 ka spring deposits interpreted to have been deposited horizontally, possible correspondence with a subsurface fault, and seismicity in the Las Vegas basin.
- Non-seismogenic origins include differential compaction related to dewatering (hydrocompaction) and/or salt dissolution consistent with numerous published studies on hydrocompaction and salt tectonics in the basin.
- Examples of salt tectonics from Canyon Lands National Park were presented as a possible analog.
- Resolving the seismogenic vs. non-seismogenic origin for the scarp is problematic. Several observations were discussed including; (1) the general lack of a stratigraphic record of paleoearthquakes, (2) regional strain is extremely low, geodetic block models indicate only 0.2 mm/yr across a single structure, (3) connectivity to other Quaternary faults to the north and south is not clear, and (4) uncertainties related to hydrocompaction/salt tectonics and their influence on surface morphology.
- It was suggested that a logic tree approach in which the uncertainties in scarp origin and relative activity could be weighted could be useful for future NSHM updates.

Nevada Working Group 2018, Day 1 discussion summary, led by Rich Koehler and John Anderson

- Quantitative criteria for evaluating priority faults for future research is generally useful, but could benefit by incorporating information known from other disciplines in addition to geology. Additional parameters that could be considered include distance to adjacent faults. Organizing parameter data will help identify research priorities as well as highlight potential inclusion of under characterized faults in future updates of the NSHM.
- New fault information should be added to existing databases to develop a coherent, organized, and vetted consensus database. Peer-review publication of new research is critical to ensure that future updates of the NSHM incorporates the latest published data.
- Future research should focus on faults capable of causing MMI VII or greater in urban areas.
- For northern Nevada: better characterization of the geometry of faults beneath Reno (dip, subsurface relationships, etc.) is needed. This would be best addressed by a coordinated team approach using geology, seismology, geophysics, and geodesy. The Mount Rose, Genoa, East Carson, Little Valley faults, and faults of the North Valleys are in close proximity to Reno and warrant further study to better characterize fault parameters.
- For southern Nevada: a better understanding of the Las Vegas Valley fault system is needed. In particular, additional study is warranted for the Eglington, Frenchman Mountain, Black Hills, and California Wash faults. Seismic reflection and trenching may help resolve the debate on seismogenic vs. non-seismogenic origin for scarps within the system. Geodesy is important for evaluating faults that have little geologic information. More complete mapping is necessary to identify and characterize additional active faults.

Day 2 Summary

The second day began with a recap of the discussions from the first day and a reiteration of the purpose and objectives of the workshop. This was followed by a series of presentations on recent areas of seismology research including talks on seismic monitoring associated with the Nevada Seismic Network, applications of microseismicity to characterizing source parameters and evaluating directivity effects, and recent advances in fault scaling relationships. The next group of presentations addressed ground motions including engineering design applications, development of community velocity models and databases, and basin amplification effects. After lunch, presentations on geodesy included a summary of previous GPS constraints on slip rates in the Walker Lane and a review of recent advances in evaluating the strain rate field in northern and southern Nevada. The final presentation of the day highlighted uncertainties in the assessment of precariously balanced rocks in estimating ground motions along normal faults. Discussions at the end of the day focused on priorities for future research in seismology, ground motions, and geodesy. They also emphasized the need for leadership and the formation of

task groups focused on maintaining momentum, maintaining state-of-the-art summaries of the results needed for hazard estimation, and collaboratively pushing the state-of-the-art forward.

Key Points and Discussion Items from Day 2

Review of Nevada and eastern California seismicity and the Nevada Seismic Network, led by Ken Smith, Nevada Seismological Laboratory, University of Nevada, Reno.

- A comprehensive summary of seismicity in Nevada evaluated by the Nevada Seismological Laboratory was presented. The Nevada catalog from 1852–2018 includes over 300,000 events. A yearly recurrence rate plot over this time interval indicates ~2 event/yr and ~1 event/5 yr for M5 and M6 events, respectively.
- Moment tensor solutions (140 solutions) for events that occurred between ~1990 and 2000 have been developed by Ichinose et al. (2003). Network operations have routinely developed moment tensor solutions since 2011 (330 solutions).
- Status of the NSL seismic/fire-camera network was summarized. This network now has over 50 HD/4K pan-tilt-zoom cameras in California and Nevada and is currently expanding into Oregon and Idaho. The system provided response assistance to 207 fires in 2017.
- The distribution of seismicity by magnitude was summarized on maps for the northern Nevada/Reno area, central Nevada, and southern Nevada.
- Seismic data was discussed for several recent earthquake sequences including the 2012–2013 Spanish Springs, 2016–current Nine Mile Ranch, and 2011 Hawthorne sequences.
- HypoDD phase data relocations have been developed for ~7000 events between 2000 and 2018. Notable events that have been evaluated with this method include the Mogul (2008), Spanish Springs (2013), Thomas Creek (2016), Virginia City (2014), and south Reno (2018) sequences.

Characterizing earthquake sources in the urban Reno-Carson-Lake Tahoe regions, led by Christine Ruhl, University of California, Berkeley Seismological Laboratory.

- Presentation focused on results from studies utilizing seismicity and source physics analyses to characterize abundant microseismicity in the western Basin and Range and Walker Lane. Case studies included analyses of Reno-Tahoe microseismicity, and the Sheldon and Mogul earthquake swarms.
- Assessment of the Sheldon earthquake sequence included seismicity depth, kinematics, and fault plane solution analyses. Results indicate a steep eastward dip for most events and suggest that the sequence occurred on unmapped antithetical faults and/or fracture zones between well-defined surface faults.
- Assessment of the Mogul earthquake swarm included analyses of focal mechanisms, stress drop, and spatiotemporal patterns in microearthquake events and clusters. Results indicate the sequence was associated with strike-slip faulting near the surface and normal faulting at depth. Robust identification of fault planes with conjugate and en echelon fault geometry reveal that the source is characterized by a complex mesh of interacting active faults. Individual sequences behave like mainshock-aftershocks within a broader seismicity migration. Directivity analyses confirm slip on fault structures identified by cluster analyses.
- Directivities for events in Truckee, CA match the source plane and indicate that the mainshock ruptures toward a seismicity void surrounded by aftershocks.
- Microseismicity studies can aid probabilistic seismic hazards analyses (PSHA) by providing information on subsurface fault geometry and kinematics using earthquake relocation and focal mechanisms. Earthquake source properties can be refined by stress drop and rupture directivity measurements. Areal source regions can be better characterized by evaluating recurrence rates, seismogenic depths, and ML-Mw relations.
- Future seismicity-based research that could benefit the NSHM includes updating focal mechanism and moment tensor catalogs for the entire state of Nevada, areal source zone identification, robust finite source identification, and regional stress drop variation analyses.

Precise relocations, source parameters, and directivity effect for five recent earthquake sequences near Nevada urban areas, led by Rachel Hatch, Nevada Seismological Laboratory, University of Nevada, Reno.

- Presentation described methods and results of microearthquake relocation, stress drop, and directivity analyses for five recent earthquakes including the Thomas Creek (2015–2016), Herlong (2016), Carson City (2013), Virginia City (2014), and Truckee (2017) earthquake sequences. Implications of refining earthquake properties for hazard assessment were also discussed.
- Analyses for the Thomas Creek sequence indicate that it occurred along a west-dipping structure striking NNE-SSW and was characterized by normal and left-lateral, oblique-normal faulting consistent with the orientation of the Virginia Range.

- Relocated hypocenters associated with the Herlong sequence indicate it occurred along a steeply dipping planar structure striking NW-SE. Moment tensor solution for the mainshock indicates a strike-slip mechanism consistent with the orientation of the Honey Lake fault.
- The Carson City sequence occurred within a highly distributed, 13-km-wide fault zone. Relocated hypocenter and moment tensor analyses indicate normal faulting on a northeast dipping plane and strike-slip faulting along NNE trending planes.
- Analyses for the Virginia City sequence define three distinct structures: two northwest-dipping structures and a vertical structure trending north-south. Focal mechanisms show both normal and strike-slip movement.
- Relocated hypocenters for the Truckee sequence indicate a linear distribution of events confined to a small area at ~5–6 km depth, trending ~N45E and dipping ~70–80° NW.
- Refining the absolute location of events greatly improves the hypocentral locations and indicates that 3 out of the five sequences occurred on unmapped faults.
- Individual stress drops range from 0.4–110 MPa.
- The methods highlight the potential to identify structures with seismicity, refine complex faulting geometry, and potentially incorporate stress drop values and directivity into future seismic hazard models.

Fault-scaling relationships depend on the average fault-slip rate, led by John Anderson, Nevada Seismological Laboratory, University of Nevada, Reno.

- Presentation summarized the results of Anderson et al., 2017, which addresses whether knowing the slip rate on a fault improves estimates of magnitude of surface-rupturing earthquakes. The research was motivated by the question of whether or not the introduction of slip rate on a fault helps to reduce the uncertainties in estimates of magnitude from observations or rupture length.
- The analyses included re-evaluation of previous relations of magnitude and rupture length dependence on slip rate and incorporated an expanded data set of 80 earthquakes.
- A reasonably well-established slip-rate dependence is demonstrated for strike-slip faults: as the slip rate increases for any given fault length, the predicted magnitude tends to decrease.
- Whether or not the slip-rate term is present, linear models of magnitude and rupture length over all rupture lengths imply that stress drop depends on rupture length. An alternative form for the relationship of magnitude and rupture length, with constant stress drop, fits the data in this study equally well. This is more consistent with teleseismic observations of earthquakes.
- Observed dependence on slip rate for strike-slip faults, supports the conclusion that for faults of a given length, the static stress drop, tends to decrease as the fault slip rate increases.
- Slip-rate dependence is not conclusive for normal and reverse faulting. For reverse faults, the limited data weakly suggest that higher slip-rate faults tend to have larger magnitudes, but without more data, this tendency cannot be trusted.
- Consideration of average-slip and down-dip extent of rupture may improve the models.

Characterization of earthquake ground motions for engineering design in the Reno basin—geotechnical and seismological perspectives, led by Steve Dickenson, New Albion.

- Presentation described the state of the practice on basin effects in engineering design, the limitations of using ground motion prediction equations (GMPEs), and applied research in the Reno basin. Research needs were also discussed.
- Geotechnical studies are focused on performance-based design of tall buildings (H>160 ft.) but often have to rely on 1-D site response approximations. Analyses require GMPEs, and pertinent data including Vs30, Z1.0, and Z2.5.
- A PSHA is the first step including an evaluation of the site-specific response spectra (adjusted for dynamic soil response). Spectral amplification factors due to 1D basin effects are also evaluated. The building Code now includes minimal basin amplification factors and risk coefficients, incorporated to develop risk-targeted probabilistic maximum-considered earthquake ground motion models.
- The use of GMPEs is limited by the applicability of mostly 1D basin-effect models, availability of basin amplification measurements for particular basins, and the quality and availability of basin-dependent structural and amplification data (Vs profile, 3D basin geometry, and wave propagation).
- The Reno basin has been characterized by multiple deep refraction microtremor (ReMi) arrays with National Earthquake Hazards Reduction Program (NEHRP) funding. These studies have developed shear-wave velocity profiles for the basin, refined the basin geometry and structure, and contributed towards site-specific soil response analyses. Response spectra incorporating basin effects coefficients have been developed.
- Future research needs include refining the geophysical characterization of basins, reducing the uncertainties and variability in estimation of 3D basin effects, developing and proving computational 3D basin models, and developing specific basin amplification factors for use in engineering practice in a given basin. Enhanced strong motion instrumentation would contribute to these research needs.

Comprehensive community velocity models for Nevada's urban basins—the key to predicting earthquake ground motions, led by John Louie, Nevada Seismological Laboratory, University of Nevada, Reno.

- Presentation focused on advances in community velocity models for the Las Vegas and Reno basins. Comparisons between 1D ground motion estimates and 3D sensitivity tests were discussed with respect to hazard assessment.
- For the Las Vegas basin, Clark County obtained Vs30 measurements for >10,000 sites, at a maximum spacing of 300 m. Predicted peak ground velocity maps computed for likely nearby earthquake scenarios indicate areas of horizontal resonance, trapping, and channeling with violent ground velocity (60 cm/sec) in some areas. 3D synthetic sensitivity tests indicate a factor of 2 ground motion amplification from the Vs30 measurements alone. Comparison of HAZUS loss estimates derived from a 1D USGS ShakeMap (4.8 billion dollars) to 3D physics-based model (8.6 billion dollars) highlights the importance of physics-based models.
- For the Reno basin, gravity measurements using multiple models, seismic reflection surveys, and deep ReMi have been used to develop basin shear velocity models—including Z1.0 and Z2.5—to a depth of >1 km. These studies have also resulted in improved characterization of basin structure and geometry.
- Annual rate of exceedance can now be added up for multiple computed earthquake scenarios to generate annual-rate-of-exceedance maps for severe, 30 cm/sec ground shaking. Software is open-source and easily taught to graduate students.
- An approach was proposed for Nevada to push analyses beyond 1-D utilizing constraints of community velocity models. This approach would use refined basin characterization based on parcel mapping by cities in addition to whole-basin surveys by the USGS, up-to-date geophysical information, and "gigaShake" results to generate annual-rate-of-exceedance maps. Training geoscientists and engineers in shake-modeling methodologies would help push this approach to fruition.
- Hazard characterization through community velocity models can be improved by better characterization of ground motions, including more recordings and modeling of small earthquakes, inclusion of Vs measurements in site characterization (parcel mapping and additional surveys), consideration of probabilistic uncertainties, and better communication between seismologists and engineers.

Development of a community shear-wave velocity profile database in the United States, led by Sean Ahdi, University of California, Los Angeles.

- Presentation described work conducted to date on a community shear-wave velocity profile database, the data types and sources, database structure, and its potential expansion to the entire United States as an open-access database.
- The database is important for geotechnical and seismological practitioners as shear-wave velocity is a critical parameter for ground motion and ground failure studies, including ground response analyses, liquefaction assessment, and nonlinear seismic crustal models. However, at present Vs profile data is difficult to access and visualize.
- A wide variety of data sources include multiple State and Federal agencies, research and consulting reports, utilities, and other academic and industry groups.
- Data types include Vs profile measurements at known locations as well as any additional data from the site including boring logs, SPT/CPT measurements, geology, site plans, etc. Data are digitized, and associated information are archived in the database including source, reference, number of profiles, methods, and types of information stored.
- All data (digital, images, PDFs, scanned hard copies, etc.) are translated to a common digital format (e.g., ASCII). JavaScript Object Notation (JSON) is used to hierarchically format and organize data and metadata for all sites with a nested structure. Data querying and transfer is made possible using SQL relational database schema similar to UNIFY (program developed by UT).
- Goal is to have the database accessible online and allow users to download data, visualize and plot data, and eventually enable select user groups to upload data.
- To date, 1156 data locations have been digitized and archived in the United States primarily in California and western Nevada, as well as the greater Seattle and Salt Lake City areas. A total of 2997 sites have been identified in the United States and the database is continuing to grow.
- Potential overlap with existing USGS Vs30 database should be avoided. The database will benefit from discussions regarding how the database may be utilized in Nevada.

Investigating basin amplification factors for shaking in the Reno-Tahoe and Las Vegas regions for local and regional events, led by Michelle Dunn, Nevada Seismological Laboratory, University of Nevada, Reno.

- Basin amplification factors were evaluated for several earthquakes in the Reno and Las Vegas areas including the 2015 M4.4 Thomas Creek, 2016 M5.5 Nine Mile Ranch, 2014 M3.6 Enterprise, and 2015 M5.3 Caliente earthquake

sequences. Presentation described on-going efforts to investigate whether GMPEs can adequately predict basin amplification.

- Data was presented for each event including mapped location, ShakeMap results, focal mechanism, observed ground motions, and peak ground velocity ratios. Peak ground velocity ratios of basin over bedrock stations were developed for each sequence and compared to ShakeMap results.
- Efforts to date have focused on generating 3D physics-based SW4 synthetic seismograms that partially account for basin effects at low frequencies of shaking (<1.0 Hz).
- The variation of amplification factor with spatially distributed source locations and lithologic variability was also discussed.
- For the Thomas Creek sequence, 3D modeling results of 0.5 Hz indicate a close match between synthetic and measured PGV estimates, except at deeper basin sites. This suggests that velocities used at deeper depths may be too low.
- For the Nine Mile Ranch sequence, PGV estimates were compared to Vs30 and basin depth.
- Future efforts will include other measures of shaking intensity (spectra and/or duration), sensitivity testing with 3D models, and validation/verification studies on other recorded events.
- The implications of this ongoing research is potential incorporation of site and/or basin amplification factors in seismic hazard models.

GPS constraints on present-day slip rates in the northernmost Walker Lane—Reno, Carson City, and Tahoe region, NV and CA, led by Jayne Bormann, California State University, Long Beach.

- Previous elastic block modeling results from the northern Walker Lane based on geodetic measurements were presented in terms of the regional slip budget. Improvements to the GPS velocity field since 2013 were discussed including updated slip-rate estimates for faults in the North Valleys area, Carson Valley, and Reno basin.
- Advances in GPS velocity modeling methodology and a longer time series has led to an improved interpretation of the GPS velocity field and a reduction in uncertainties of slip-rate estimates.
- The cumulative right-lateral deformation budget across the northern Walker Lane decreases northward from ~7mm/yr in the Reno/Lake Tahoe region to ~5 mm/yr across the Honey Lake and Mohawk Valley faults.
- Block-model results:
    - Right-lateral slip rates for major faults in the northern Walker Lane, not including potential strain accumulation across the Grizzly Valley fault, are determined to be ~2.2 mm/yr (Mohawk Valley fault), ~1.1 mm/yr (Honey Lake fault), ~0.3 mm/yr (Warm Springs Valley fault), and ~0.9 mm/yr (Pyramid Lake fault). When potential strain accumulation across the Grizzly Valley fault is considered, the slip rates across the major faults are slightly slower. A slip rate across the Grizzly Valley fault between 0 and 1.4 mm/yr is allowed by the GPS data.
    - Cumulative horizontal extension rates across faults in the North Valleys area north of Reno range from 1.0–1.7 mm/yr. These faults include the Last Chance, Peterson Mountain, Fred's Mountain, Spanish Springs Valley, and Spanish Springs Peak faults.
    - In the Reno basin area, horizontal extension rates across the Mt. Rose and northern Genoa faults are estimated to be ~0.5 and 0.8 mm/yr, respectively.
    - In the Carson Valley area, horizontal extension rates across the Genoa and East Carson Valley faults are estimated to be ~0.5 and 0.8 mm/yr, respectively. The block model allows up to 1.5 mm/yr of right-lateral deformation along the East Carson Valley fault system.

Robust estimation of fault slip rates using GPS imaging in the Walker Lane and western Great Basin, led by William Hammond, Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, University of Nevada, Reno.

- Presentation focused on the integration of GPS observations into seismic hazard products including improvements in measurement of the GPS velocity field and innovations in block modeling methodology. In particular, geodetic velocities were discussed in terms of slip-rate estimates across active faults and uncertainties related to the assessment of slip rates including "off-fault" deformation, transient deformation from the earthquake cycle, nearby magmatic systems, and climate-induced hydrological loading changes.
- Measurement of the geodetic velocity field in the Walker Lane has been refined through extending the precision and geographic coverage of GPS measurements, and innovations in applying robust estimation techniques to the data. GPS imaging techniques are being applied to integrate and interpolate data from all networks, resulting in a gridded velocity field with reduced uncertainties in station velocities and more stable solutions for block motions.
- Posterior distributions of fault-slip rates are being developed using advanced computational power that iterates thousands of models incorporating uncertainties in velocity data, block geometry, fault database, and "off-fault" deformation. The result is a self-consistent suite of models that fit the data. Final runs are in progress.

- Seasonal variability in uplift rates of the Sierra Nevada as well as increased uplift rates during the drought period of 2012–2016 are observed in the GPS data. This suggests that hydrologic loading signals need to be considered in assessing tectonic uplift rates.
- Changes in velocity and strain rate have been observed in the Long Valley caldera area. The changes are correlated with accelerated inflation of the magmatic system, resulting in measurable changes in strain rates, magmatic uplift, and seismicity. During times of robust magmatic inflation, shear strain rates are enhanced north of Long Valley. Magmatic inflation may also be influenced by drought conditions, which act to redistribute active crustal strain and seismicity.

Robust estimation of the secular and time-variable strain-rate field in the American southwest, led by Corné Kreemer, Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, University of Nevada, Reno.

- Presentation focused on describing the importance of geodetic strain-rate analyses (which require less assumptions than block models) in seismic hazard assessment. Strain-rate analyses highlight deformation across wide regions in which a region's seismic productivity is a function of its deformation rate.
- A new algorithm ("MELD"—median estimation of local deformation), which provides robust estimates of the strain-rate tensor at a given location and uncertainties in strain-rate estimation, were also discussed.
- The algorithm "MELD" is particularly effective in retrieving long-wavelength strain-rate signals from noisy data in areas of low deformation and provides robust error estimation that helps evaluate which strain-rate features are significant. The method allows the assessment of median and standard deviation values for strain and rotation rates. Signal to noise ratios have been produced to evaluate the uncertainty in the strain-rate signal at particular points.
- Application of the "MELD" method to intraplate North America was presented. Additionally, "MELD" results highlighting the secular deformation field for the western U.S. including uncertainty maps were also presented.
- Strain rate vs. standard deviation plots were presented for the Reno and Las Vegas areas. The results indicate ~0.3 mm/yr of extension in the Las Vegas area distributed across a 102 km wide zone.
- Seasonal vertical and horizontal variations in strain rate are observed in the data. Maps showing the combined seasonal vertical and horizontal strain signal were presented.
- Seasonal displacement models identify large-scale coherent signals, which can be divided into three domains for which the time of year of maximum deformation is different: northern and southern California, and the Great Basin.
- The signal is largest and most coherent in northern California, where compression and extensional deformation in an orientation normal to the coast and Sierra Nevada in the Spring and Fall, respectively is observed.

Update on PBR constraints on ground motion from normal faults, led by James Brune, Nevada Seismological Laboratory, University of Nevada, Reno.

- Presentation described studies on precariously balanced rocks (PBRs) in Carson and Antelope valleys. Ages and rupture parameters for paleoseismic events along the Genoa and Antelope Valley faults were discussed in terms of ground motions for normal faults.
- Numerous examples of PBRs (field photographs) were shown. Models of the PBRs were created using photogrammetry methods.
- Estimated toppling accelerations were plotted against distance from the fault.
- The existence of many PBRs in the vicinity of the Genoa and Antelope Valley faults suggests that modeling of normal faults warrants re-evaluation. Foam rubber and lattice numerical models are currently being developed.

Nevada Working Group 2018, Day 2 discussion summary, led by Rich Koehler and John Anderson

- Relocation of microearthquakes is a promising research focus area that will contribute towards better defining the location and geometry of active faults. Questions remain regarding how to best incorporate active fault features identified by earthquake sequences into PSHA models.
- Reliable funding and densification of the Nevada seismic network was recognized as an essential component to continued earthquake monitoring and research in Nevada.
- Continued evaluation of moment tensor solutions may help define the locations of dominantly normal vs. dominantly strike-slip deformation.
- Studies of stress drop in normal faults and how it may or may not differ from other faulting mechanisms warrants further attention. It is unclear how stress drop results could be incorporated into PSHA models.
- Constraints on the dips of normal faults at seismogenic depths are needed.
- Discussions on priorities for ground motion studies focused on the importance of better understanding the variability of ground motions across different geologic environments. Further investigation of precariously balanced rocks was recommended as a means to better constrain ground motions on the hanging wall of normal faults.

- Better proxies are needed for Vs30 and basin amplification specific to the Basin and Range. Physics-based ground motion models are needed and will require further development, testing, and demonstration on how they may be applied to the NSHM.
- Densification of GPS networks in southern Nevada is needed to reduce the uncertainties in strain-rate estimates and will contribute to more robust strain-rate maps.
- Increased attention to "off-fault" deformation will contribute towards better characterization of slip rates based on joint inversions of geologic and geodetic data. Efforts should continue to resolve slip-rate discrepancies between geologic and geodetic estimates.
- Continued communications between geologic, geodetic, and seismologic earthquake researchers is essential for improving the characterization of active faults and ensuring that the most up-to-date information is incorporated into future seismic hazard models.

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APPENDIX 1. WORKSHOP ATTENDEES

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Hans AbramsonWard—Lettis Consultants International
Sean Ahdi—University of California, Los Angeles
John G. Anderson—Nevada Seismological Laboratory, University of Nevada, Reno
Steve Angster—Center for Neotectonic Studies, University of Nevada, Reno
Rich Briggs—U.S. Geological Survey
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APPENDIX 2. WORKSHOP AGENDA

AGENDA

2018 Working Group on Nevada Seismic Hazards Workshop
February 5 and 6, 2018, Reno, Nevada
Harry Reid Engineering Laboratory, University of Nevada, Reno

- **Day 1: Monday, 5 February, 2018—Quaternary fault parameters and seismic hazards**
  - 8:30–8:45 Introductory remarks – Koehler and Anderson
  - 8:45–9:00 Update on the USGS External Grants program – Gold
  - 9:00–9:20 Anderson, J.G., **Building the Nevada Hazard Map: information needed and some important uncertainties**
  - 9:20–9:40 Petersen, M., Zeng, Y., Gold, R., and Shumway, A., **The 2018 and 2020 U.S. National Seismic Hazard Model for Nevada**
  - 9:40–10:00 Wong, I., Lund, W., DuRoss, C., Thomas, P., Arabasz, W., Crone, A., Hylland, M., Luco, N., Olig, S., Pechmann, J., Personius, S., Petersen, M., Schwartz, D., and Smith, R., **Insights into Basin and Range seismic hazards from the Working Group on Utah Earthquake Probabilities**
  - 10:00–10:20 Coffee Break
  - Northern Nevada
    - 10:20–10:40 Wesnousky, S., **Questions bearing on the estimation of seismic hazard in the Reno-Carson-Lake Tahoe region**
    - 10:40–11:00 Koehler, R.D., **Efforts to better characterize the seismic potential of faults in the North Valleys region, Reno, Nevada**
    - 11:00–11:20 Pierce, I.K.D., Wesnousky, S.G., and Owen, L.A., **The search for strike-slip in the northern Walker Lane: new slip rates and characterization of active faults in Antelope, Mason, and Smith valleys, Nevada**
    - 11:20–11:40 Angster, S., **New estimates on the rate of slip for faults of the central Walker Lane**
    - 11:40–12:00 dePolo, C., Gold, R., Briggs, R., Crone, A., Mahan, S., and Borchardt, G., Recent **Paleoseismicity of the Kings Canyon fault zone between Ash and Vicee canyons, Carson City, Nevada**
  - 12:00–1:20 Lunch
  - Southern Nevada
    - 1:20–1:40 Taylor, W.J., Abdelhaleem, S., Peck, A., Dee, S., and dePolo, C., **Fault interactions along a N-S belt around 114.75 degrees W longitude in southern Nevada**
    - 1:40–2:00 Dee, S., dePolo, C., Taylor, W., Mahan, S., **New paleoseismic data from the Frenchman Mountain fault, Las Vegas**
    - 2:00–2:20 dePolo, C., Taylor, W., and Dee, S., **The Las Vegas Valley fault system—a 2017 progress report**
    - 2:20–2:40 Gold., R., Briggs, R., dePolo, C., Dee, S., and Petersen, M., **Seeking input on the inclusion of the Eglington fault, Nevada, in the National Seismic Hazard Map**
    - 2:40–3:00 Break
  - 3:00–3:20 Summary of Quaternary fault parameters and future directions – Koehler
  - 3:20–4:20 Discussion: Implications to the National Seismic Hazard Map and priorities for future research – All
  - 4:20–4:30 Summary and concluding remarks – Koehler and Anderson
  - 4:30 Adjourn
- **Day 2: Tuesday, 6 February, 2018—Seismicity, ground motions, and geodesy**
  - 8:30–8:45 Introductory remarks – Koehler and Anderson
  - 8:45–9:05 Smith, K.D., Hatch, R.L., Ruhl, C.J., Kent, G.M., Kell, A., Slater, D., Plank, G., Williams, M., Cassar, M., Rennie, T., Torrisi, J., and Presser, R., **Review of Nevada and eastern California seismicity and the Nevada Seismic Network**
  - 9:05–9:25 Ruhl, C.J., Smith, K.D., Abercrombie, R.E., Kent, G.M., Zaliapin, I., and Hatch, R.L., **Characterizing earthquake sources in the urban Reno-Carson-Lake Tahoe regions**
  - 9:25–9:45 Hatch, R., Ruhl, C., Smith, K, and Abercrombie, R., **Precise relocations, source parameters, and directivity effect for five recent earthquake sequences near Nevada urban areas**

- 9:45–10:05 Anderson, J.G., Biasi, G.P., and Wesnousky, S.G., **Fault-scaling relationships depend on the average fault-slip rate**
- 10:05–10:30 Coffee Break
- 10:30–10:50 Dickenson, S., and Louie, J.N., **Characterization of earthquake ground motions for engineering design in the Reno basin: geotechnical and seismological perspectives**
- 10:50–11:10 Louie, J.N., Dunn, M., and Pancha, A., **Comprehensive community velocity models for Nevada's urban basins: the key to predicting earthquake ground motions**
- 11:10–11:30 Ahdi, S.K. , Stewart, J.P. , Kwak, D.Y., Yong, A., Sadiq, S., Ilhan, O., Park, D., Hashash, Y.M.A., and Bozorgnia, Y., **Development of a Community Shear-Wave Velocity Profile Database in the United States**
- 11:30–11:50 Dunn, M., Louie, J., Smith, K.D., Dickenson, S., and Hatch, R.L., **Investigating basin amplification factors for shaking in the Reno-Tahoe and Las Vegas regions for local and regional events**
- 11:50–1:30 Lunch
- 1:30–1:50 Bormann, J., Hammond, W.C., Kreemer, C., and Blewitt, G., **GPS constraints on present-day slip rates in the northernmost Walker Lane: Reno, Carson City, and Tahoe region, NV and CA**
- 1:50–2:10 Hammond, W., Kreemer C., and Blewitt, G., **Robust estimation of fault slip rates using GPS imaging in the Walker Lane and western Great Basin**
- 2:10–2:30 Kreemer, C., Young, Z. Hammond, W., Blewitt, G., **Robust estimation of the Secular and Time-Variable Strain Rate Field in the American southwest**
- 2:30–2:50 Brune, J., **Update on PBR constraints on ground motion from normal faults**
- 2:50–3:10 Break
- 3:10–4:10 Discussion: Implications to the National Seismic Hazard Map and priorities for future research – All
- 4:10–4:30 Summary of seismicity, ground motions, and geodesy and concluding remarks – Koehler and Anderson
- 4:30 Adjourn

APPENDIX 3. WORKSHOP PRESENTATIONS (ABSTRACTS)

Day 1, February 5, 2018

Abstract 1

Building the Nevada Hazard Map: information needed and some important uncertainties

John G. Anderson
Nevada Seismological Laboratory, University of Nevada, Reno

Seismic hazard maps are built from seismic hazard curves. The hazard curve that uses an amplitude of ground motion on the x-axis, and the y-axis gives the average annual rate of exceedance of that ground motion. Many different amplitudes of ground motion are used, and unique hazard curves exists for each at every point on the Earth. Hazard curves should be thought of as the outcome of a conceptual experiment, based on statistics of ground motions observed at that point over a long time. Unfortunately, because the user community is interested in annual exceedance rates smaller than 10–3 per year, the measurement cannot be performed, but I take the description of an experiment to measure it as evidence for existence.

Considering this, hazard curves need to be calculated. Two types of input are needed. The first is a seismicity model, i.e., a description of the location, magnitude, and occurrence rates of all earthquakes in the region. The second is a ground motion prediction equation (GMPE), i.e., a model that gives an estimate of the amplitude of the ground motion of interest for each possible earthquake in the seismicity model.

The seismicity model is generally a composite model that considers all known faults, and "area sources" that allow for the possibility of unknown large faults and characterize the distribution of small earthquakes. The rates of earthquakes on the known faults are established by a moment balance. In other words, the slip rate based on geological or geophysical information is set to balance the rate of earthquakes. A critical input to this moment balance is the description of the subsurface fault geometry and estimates of the sizes of earthquakes that can occur on the fault. Seismic network data is used to characterize the distribution of locations of small earthquakes. A method is used to "smooth" the distribution of locations of events in the catalog. Catalog magnitudes need to be converted to moment magnitude using a regional conversion scheme that considers uncertainties. California has systematically compared the final USGS model to the historical rates of earthquakes as an overall check.

The 2014 National Seismic Hazard Map considers alternative published GMPEs. Acceptable models need to meet a long list of standards established by the USGS. While this is the most practical approach, state-of-the-art hazard estimates attempt to adjust the GMPE to specific regions, or at least select the GMPEs on the basis of which ones best fit available data from the region. The next generation of hazard maps will use estimated depths of sedimentary basins in estimates of some of the considered ground motion parameters. An essential part of every GMPE is a description of the uncertainty in the estimate of the ground motion parameter, and this uncertainty can have a strong effect on the final results.

The probabilistic seismic hazards in the larger cities of western Nevada are dominated by the Mount Rose and Carson Range faults. These are normal faults; Reno and Carson City are on the hanging wall. I have examined the sensitivity of the hazard posed by these faults to uncertainty of dip, slip rate, magnitude, and choice of GMPE for an earthquake that ruptures the length of each fault. SA(0.01s) with exceedance probability of 2% in 50 years was determined for each branch of a logic tree for those properties. The distribution of SA(0.01s) values, weighted by the branch weights, is fit with a lognormal probability distributions. The standard deviation is used as an alternative to the 15- and 85-percentile values to track the width of this distribution. This measure of the epistemic uncertainty of the hazard estimate generally increases with distance, but is also high on the hanging wall. Tornado plots show that on the hanging wall, the uncertainties in fault dip and the choice of the GMPE dominate. On the footwall and at intermediate distances in all directions, uncertainties in fault slip rate dominate, while at larger distances uncertainties in the magnitude of the full-fault rupture dominate. This study does not examine all the contributions to the hazard. Smaller earthquakes on the subject faults, other faults, and background sources all contribute to the total hazard, and dominant at larger distances. Thus, the results are limited, and furthermore cannot be generalized to other exceedance rates or response spectral periods. It is nevertheless notable that each of the considered parameters is the dominant source of epistemic uncertainty in at least one of the sampled locations.

Abstract 2

The 2018 and 2020 U.S. National Seismic Hazard Model for Nevada

Petersen, M., Zeng, Y., Gold, R., and Shumway, A.
U.S. Geological Survey, Golden, CO

The USGS plans to update the hazard model for the NSHM in 2018 and 2020 to account for recent scientific developments. These models have been the basis for building codes, insurance rate structures, and public policy decisions

and it is critical that only the best available science is incorporated in these models. The plan for updating the maps in 2018 includes: (1) incorporating new ground motion models for the central and eastern U.S., (2) applying ground motion models that incorporate basin depth in the western U.S., and (3) updating the earthquake catalog and smoothed seismicity models. The update plan for the 2020 model needs to be published by June, 2018. Currently we are considering the following updates: (1) update of the geodetic and geologic joint inversion data for estimating crustal fault recurrence, (2) implement logic trees for faults in the Las Vegas basin, (3) incorporate magnitude-area equations with slip-rate parameters, and (4) refine models that incorporate basin information in the ground motion models. Some of these updates may be incorporated in future models if they are not sufficiently documented and accepted in the NSHM workshops. The USGS is open to suggestions on how the models can be improved in the future.

Abstract 3

Insights into Basin and Range seismic hazards from the Working Group on Utah Earthquake Probabilities

The Working Group on Utah Earthquake Probabilities: Ivan Wong, William Lund, Christopher DuRoss, Patricia Thomas, Walter Arabasz, Anthony Crone, Michael Hylland, Nicolas Luco, Susan Olig, James Pechmann, Steve Personius, Mark Petersen, David Schwartz, and Robert Smith

After a nearly six-year effort, the Working Group on Utah Earthquake Probabilities (WGUEP, 2016) published its earthquake forecast for the Wasatch Front region in Utah, Idaho, and Wyoming (fig. 1). The WGUEP estimated a 43% chance of one or more large ($M \geq 6.75$) earthquakes occurring in the Wasatch Front region in the 50-year period from 2014 to 2063 and a 57% probability of one or more M 6.0 and larger earthquakes. The probability of one or more surface-faulting earthquakes along the Wasatch fault was estimated to be 18% in the next 50 years.

Although not a hazard study, the forecast focused on characterizing Quaternary active faults (fig. 2) and background seismicity following the same process that is needed for seismic source inputs for a probabilistic seismic hazard analysis. Particular attention was paid to adequately characterizing the epistemic uncertainties in the models and parameters. Several issues regarding the characterization of Quaternary faulting and background seismicity in the Wasatch Front region were addressed in the WGUEP analysis. These issues have direct bearing on the evaluation of seismic hazard elsewhere in the Basin and Range Province, including Nevada. The following are some key elements of the methodology employed by the WGUEP.

1) The rupture models for faults emphasize segmentation models which allow for both single-segment and multi-segment rupture. For the best-studied faults such as the Wasatch and Oquirrh-Great Salt Lake fault zones, we relied heavily on the paleoseismic evidence from fault trenching (fig. 3). For 45 other faults and fault segments (fig. 2), segmentation was based on limited paleoseismic and structural arguments.
2) Characteristic magnitudes (Mchar) were calculated from rupture dimensions and displacements. A significant effort was made to review the existing empirical relations between magnitude and various fault parameters and select relations which best fit the event displacement data for the Wasatch fault. The magnitude relations based on average displacement or seismic moment yield magnitudes that exceed those based on surface rupture length and rupture area for the Wasatch fault. This difference had to be reconciled.
3) The probability calculations used both time-independent and time-dependent average recurrence intervals for large surface-faulting earthquakes on the central Wasatch fault segments (fig. 3) and the Great Salt Lake fault segments, based on their paleoseismic chronologies. The time-dependent recurrence intervals were estimated using the Brownian Passage Time (BPT) model. An important issue was characterizing the periodicity of the large earthquakes through the choice of the coefficient of variation (COV).
4) The magnitude-frequency relationships assumed for faults and fault segments were the maximum magnitude model and two different doubly-truncated exponential models ($6.75 \leq M \leq$ Mchar), with weights that depended on the rupture model and the characteristic magnitude. The weighting of these models was subjective given that the historical record, particularly in the Basin and Range Province including the Wasatch Front region, indicates that the observed seismicity is generally off-fault.
5) For antithetic fault pairs such as the Salt Lake City segment/West Valley fault pair, we put considerable effort into characterizing the maximum magnitudes, rupture behavior (simultaneous or independent) and activity rates.
6) To quantify the rates of background earthquakes, the WGUEP developed a robust and comprehensive earthquake catalog for the Wasatch Front region for the time period 1850 through September 2012. This task entailed estimating magnitudes of pre-instrumental events, converting all magnitudes uniformly to moment magnitude, and removing induced earthquakes. Our background seismicity rate calculations with this catalog accounted for magnitude uncertainties.
7) Moment rates estimated from the geodetic data were compared to geological and seismological moment rates across the Wasatch Front region and four sub-regions. The WGUEP did not use geodetic data directly for estimating fault

slip rates, as has been done by the USGS in the National Seismic Hazard Map, due in large part to the robust paleoseismic record available for the Wasatch fault and our reliance on recurrence intervals.

The maximum magnitude (Mmax) for background earthquakes is a controversial and significant issue. The USGS assigns most of the Mmax weight to Mmax 7.45 in the National Seismic Hazard Map for the western U.S. (including Utah) because they believe that the inventory of Quaternary faults in the western U.S. is incomplete. The WGUEP believes the inventory of Quaternary faults that are capable of generating surface-faulting earthquakes is complete or nearly complete in the Wasatch Front region. Hence, using the minimum magnitude for surface faulting as a basis for the Mmax, the WGUEP adopted a Mmax of 6.75 ± 0.25 for background seismicity.

We compared the earthquake magnitude-frequency distribution (MFD) determined from the earthquake catalog with the MFD for all seismic sources in the WGUEP source model. A mismatch (bulge) is observed at $M \geq 5.5$. However, our paleoseismic estimate of the recurrence rate of large surface-faulting earthquakes in the Wasatch Front region is in excellent agreement with the MFD.

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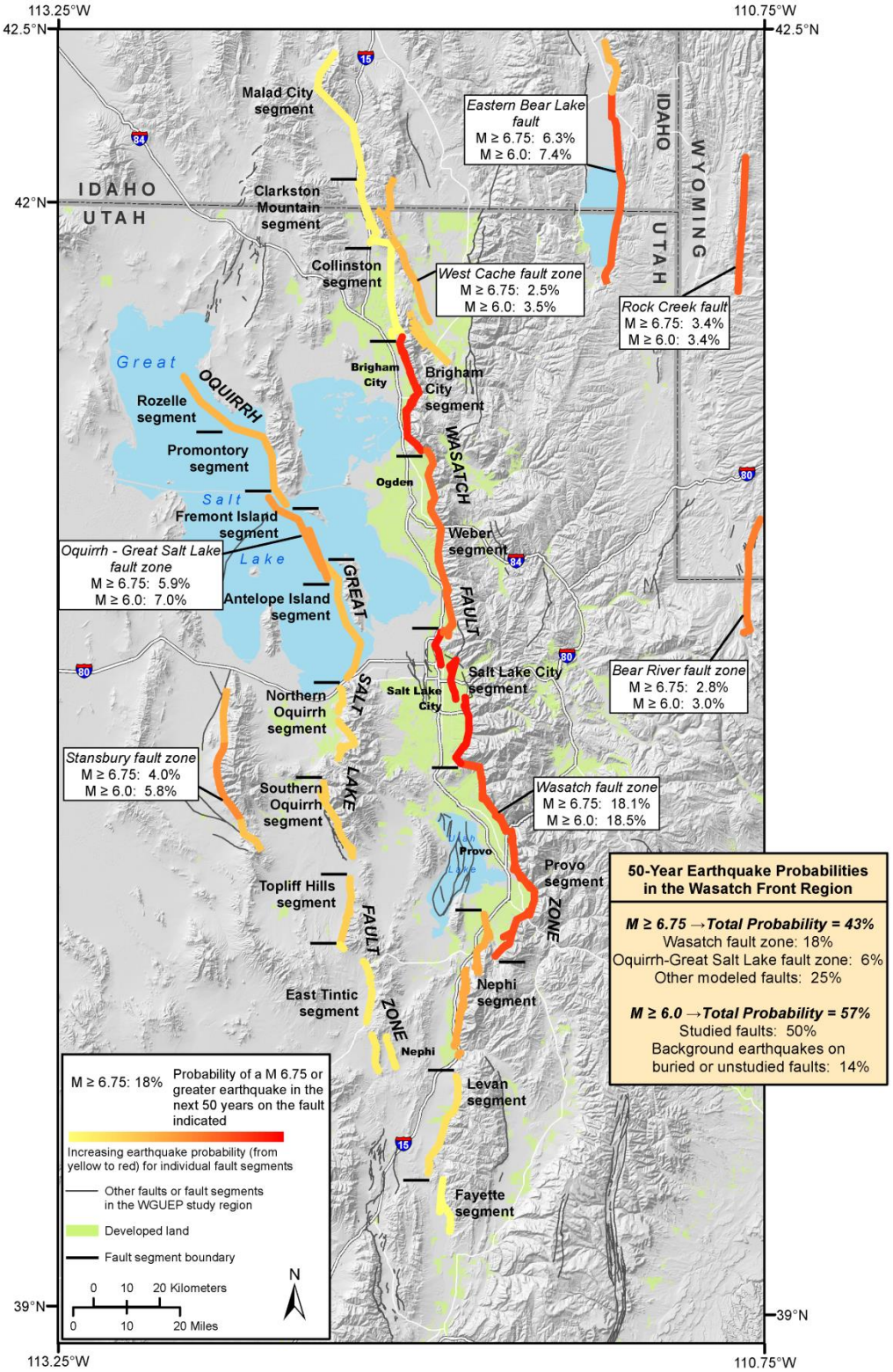

Figure 1. Probabilities of one or more earthquakes of M 6.0 and 6.75 or greater in the next 50 years (2014–2063) in the Wasatch Front region (WGUEP, 2016).

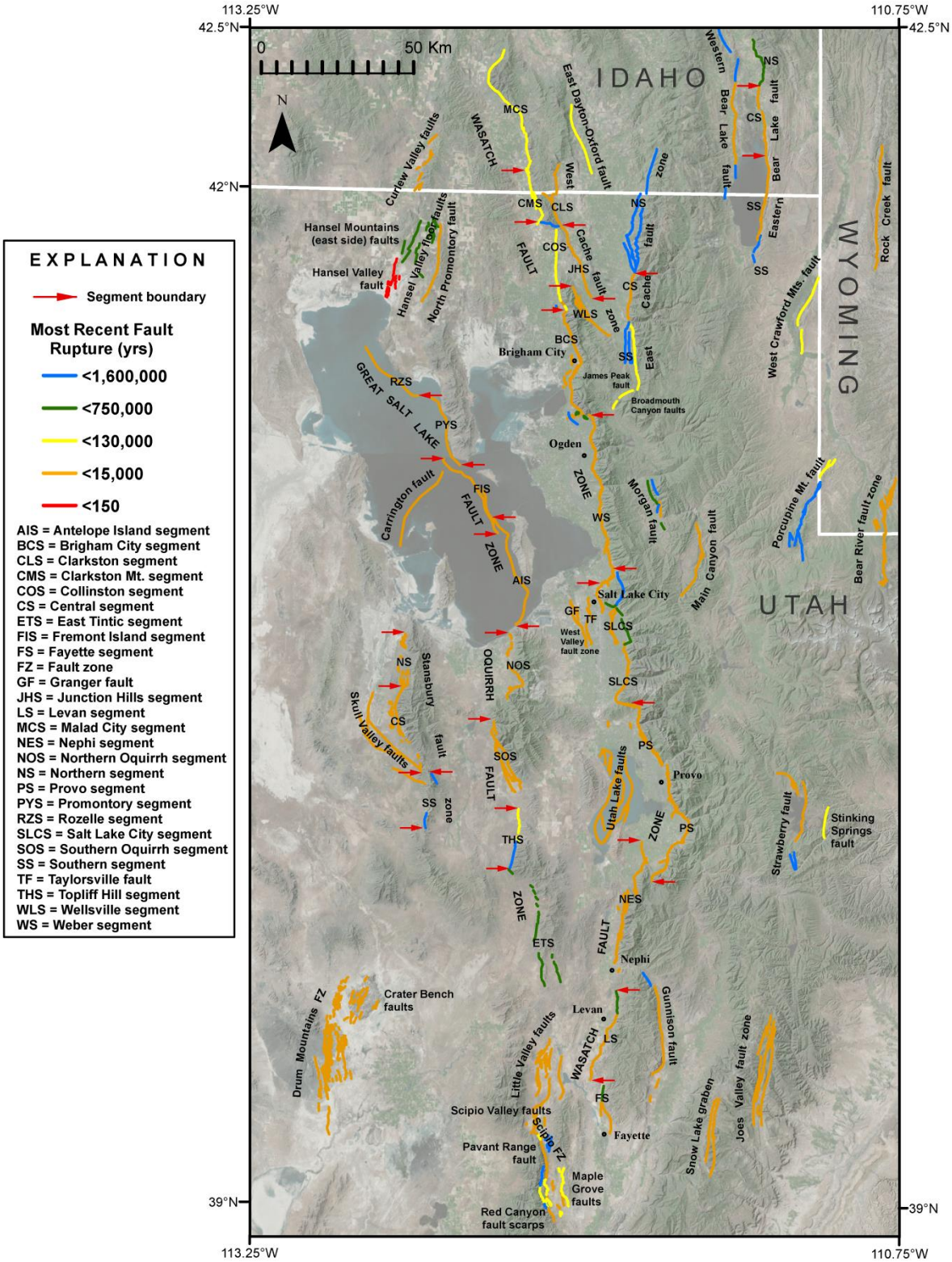

Figure 2. Faults and fault segments included in WGUEP forecast (WGUEP, 2016).

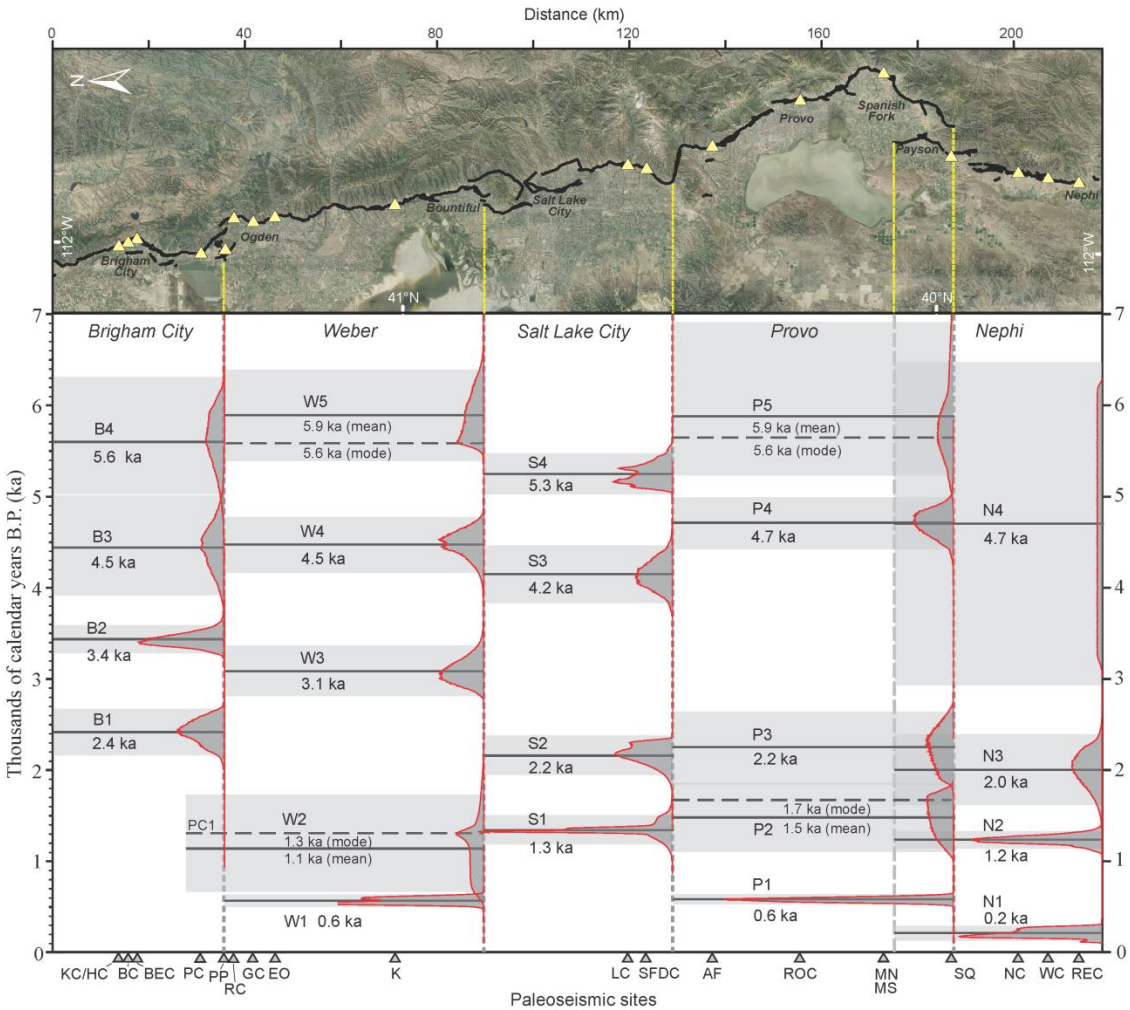

Figure 3. Single-segment rupture model for the central WFZ (WGUEP, 2016). The lower panel shows times of earthquakes on each segment. Solid horizontal lines indicate mean earthquake times and dashed horizontal lines indicate modal times for some earthquakes. The gray boxes show 2σ time ranges. Red lines with gray-shaded fill are earthquake probability density functions derived from the WGUEP integration of site paleoseismic data.

Abstract 4

Questions bearing on the estimation of seismic hazard in the Reno-Carson-Lake Tahoe region

Steven G. Wesnousky
Center for Neotectonic Studies and Nevada Seismological Laboratory, University of Nevada, Reno

A region of transtension in the northern Walker Lane, the Reno-Carson-Lake Tahoe region encompasses normal faults, and both right-lateral left-lateral faults. The sources of potentially large earthquakes in the Reno-Carson-Lake Tahoe appear well defined. Significant sources proximal to the region include the major normal faults of Carson and Washoe Valleys and Lake Tahoe Basin, the Little Valley fault zone and its extension toward Reno, the East Carson Valley fault zone, the right-lateral Warms Springs, Pyramid Lake and Polaris faults to the east and west of Reno, and the left-lateral faults of the Olinghouse and Carson lineaments. Less though can be said of the confidence in estimates bearing on the recurrence rates, the rupture lengths and size of future large earthquakes on these sources. The uncertainties arise due to factors ranging from

lack of paleoseismic information, questions of how faults may link to one another during large earthquakes, and an inability at this stage to match well the deformation rates being reported by geodesy as compared to those assessed from geology.

Abstract 5

Efforts to better characterize the seismic potential of faults in the North Valleys region, Reno, Nevada

Rich D. Koehler
Nevada Bureau of Mines and Geology, University of Nevada, Reno

The North Valleys are an approximately 60 km X 60 km region of active north and northeast trending faults that pose a direct seismic hazard to the rapidly expanding Reno urban area. Normal oblique (dextral) faults of the Sierra Nevada frontal fault system and dextral strike-slip faults of the northern Walker Lane bound the North Valleys on the west and east, respectively, and accommodate the majority of the Pacific/North American plate boundary strain at this latitude. Although the faults of the North Valleys are only moderately expressed in the geomorphology, discontinuous scarps in mid-Pleistocene deposits, triangular facets, and observations from reconnaissance trenching indicate that many of the faults are active. This activity is reflected in contemporary geodetic studies which indicate that the faults of the North Valleys may collectively accommodate 0.9–1.2 mm/yr of extension and <0.3 mm/yr of dextral slip (Bormann, 2013). Despite the general lack of geologic studies and limited paleoseismic data, the 2014 update of the National Seismic Hazard Map (NSHM) included faults of the North Valleys using modeled slip rates. Faults used in the model include the Petersen Mountain, Fred's Mountain, Spanish Springs Valley, Spanish Springs Peak faults. Notably absent are the Western Lemmon Valley and Hungry Valley faults, as well as the Last Chance fault zone in California.

In this presentation, I describe recent efforts of the NBMG to better characterize hazardous faults in the Reno area (including the North Valleys). Additionally, I present Quaternary fault parameters compiled for faults within an approximately 100 km radius of downtown Reno (focus area) in an effort to begin discussions on how to best prioritize faults for additional research that will have the greatest impact on future updates of the NSHM. Although not the focus of this talk, the NBMG is involved in similar efforts to better characterize Quaternary faults and prioritize future research in the Las Vegas valley.

During 2018, NBMG will be conducting two paleoseismic studies within and adjacent to the North Valleys including investigations along the Petersen Mountain and Warm Springs Valley fault zones. Both projects will focus on detailed Quaternary geologic strip mapping, identification of active fault strands, and geochronologic studies of displaced alluvial fans to place constraints on fault slip rate. Paleoseismic trenching will be performed in each study to assess earthquake timing and recurrence. Additionally, NBMG is performing reconnaissance studies of the Spanish Springs Peak and East Reno fault zones and evaluating unpublished legacy data to assess the potential of future study sites.

Inspection of the National Quaternary Fault and Fold Database (NQFFD) indicates that at least 50 active faults occur in Nevada within approximately 100 km of the Reno-Carson City-Lake Tahoe urban areas. For completeness, faults in California (9 faults) are also included in this compilation. Of the 50 faults in Nevada, the current National Seismic Hazard Map model only includes 24 sources. This is largely due to poorly constrained fault-source characterization for most of the faults including unknown paleoseismic histories and the lack of consensus slip-rate and recurrence-interval data. The 2014 update of the NSHM included adjustment of throw rate for 12 faults in Nevada, including 2 faults in the Reno focus area. These updates reflect recent research, much of which is not recorded in the NQFFD. During the Quaternary fault parameter compilation for this workshop, it was noted that a slip rate study along the Antelope Valley (Sarmiento et al., 2011) apparently was not considered in the 2014 update. New slip rate information is now available for the Pyramid Lake and West Tahoe-Dollar Point fault zones which could contribute towards refinement of parameters for these sources in the 2018 update (Angster et al., 2014; Pierce et al., 2017).

The list of faults shown in table 1 serves as a starting point to discuss the current state of knowledge on Quaternary fault parameters and evaluate priorities for faults requiring additional study. I propose the following criteria as an initial qualitative assessment for prioritization of future fault research. This criteria and scoring method includes the following characteristics:

Included in the model (yes = 0, no = 1);
Length (<8km = 0, 8–25 km = 1, >25 km = 2)
Slip rate data quality (well constrained = 0, moderately constrained = 1, no data = 2)
Slip rate (<0.2 = 0, 0.2–1 = 1, 1–5 = 2)
Recurrence/timing data (yes = 0, no = 1)
Age of most recent deformation (older than latest Pleistocene = 0, latest Pleistocene = 1, <15 ka = 2)
Distance to Reno (>30 km = 0, <30 km =1)

It is anticipated that this workshop will produce a consensus method for future research prioritization. The intent is to update the list annually, as studies are completed along individual faults. Class B faults should be a low priority until more definitive evidence of activity is developed.

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Bormann, J., (2013), New insights into strain accumulation and reléase in the central and northern Walker Lane, Pacific-North American plate boundary, California and Nevada, USA, Ph.D. dissertation, August 2013, University of Nevada, Reno.

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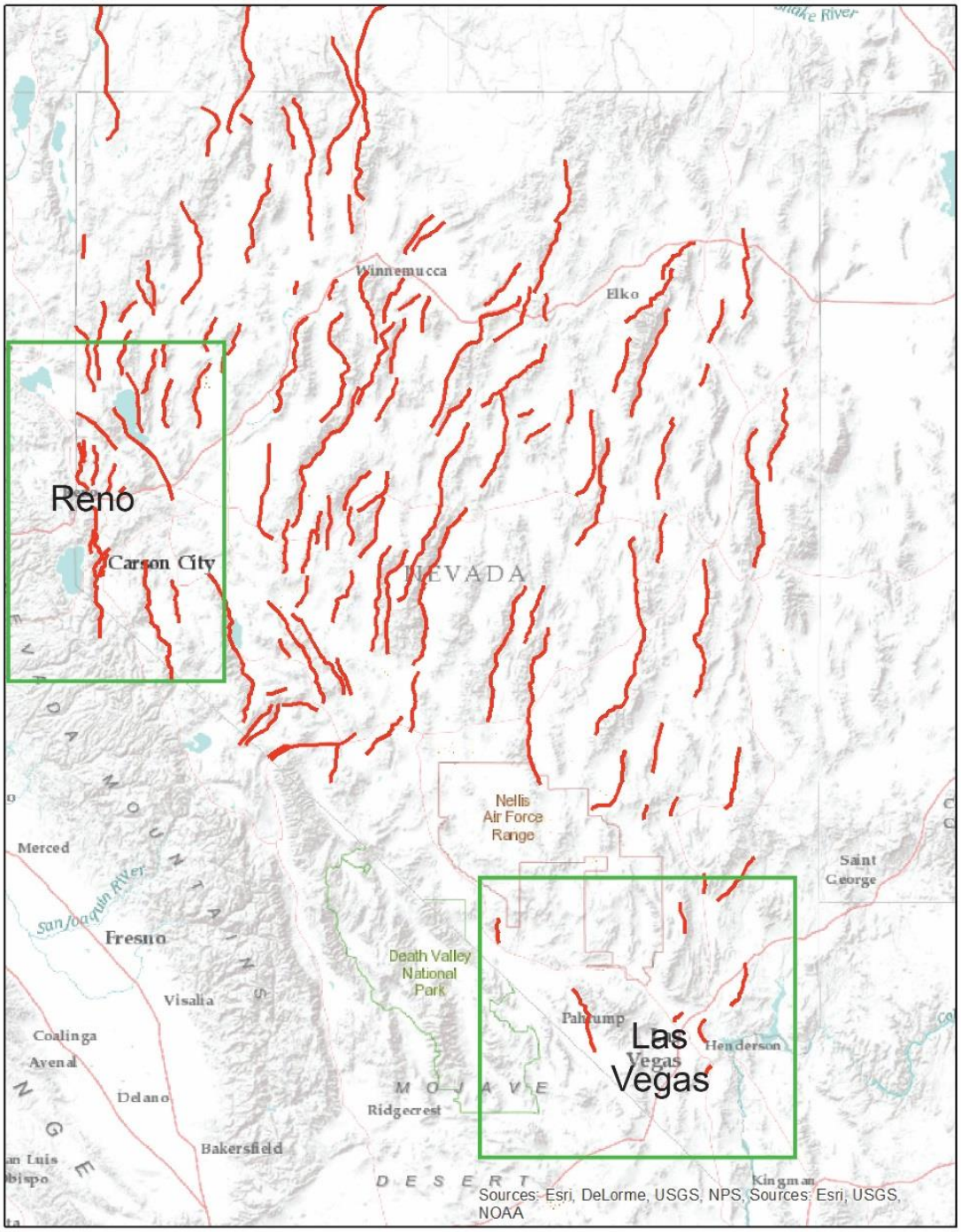

Figure 1. Map showing faults (red lines) included in the 2014 update of the National Seismic Hazard model. Quaternary fault parameters are compiled for the areas shown by green boxes including the Reno-Carson City-Lake Tahoe and Las Vegas urban areas.

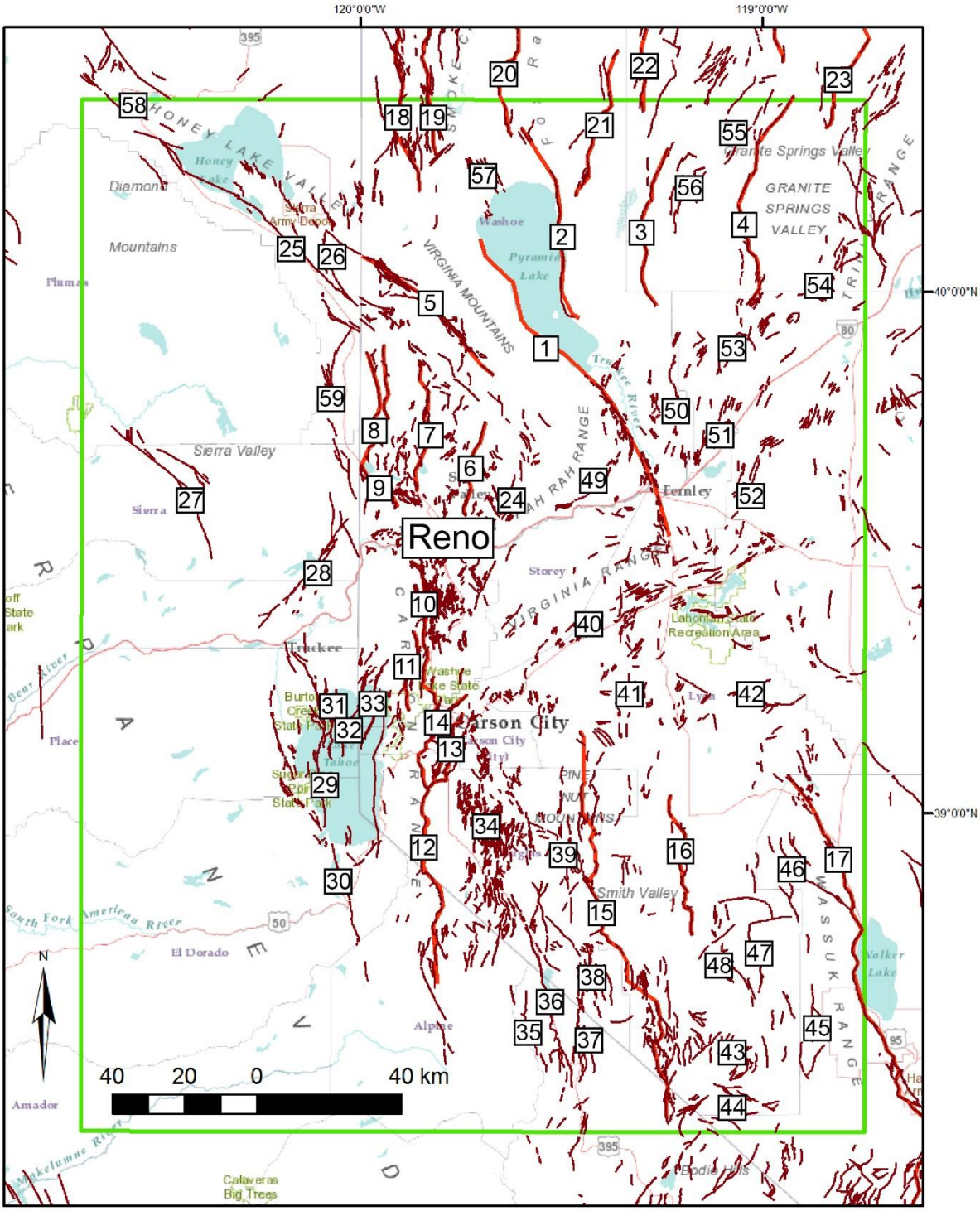

Figure 2. Map of the Reno-Carson City-Lake Tahoe focus area showing faults included in the National Seismic Hazard model (bold red lines) and active faults from the National Quaternary Fault and Fold Database (thin maroon lines). Fault numbers correspond to Table 1.

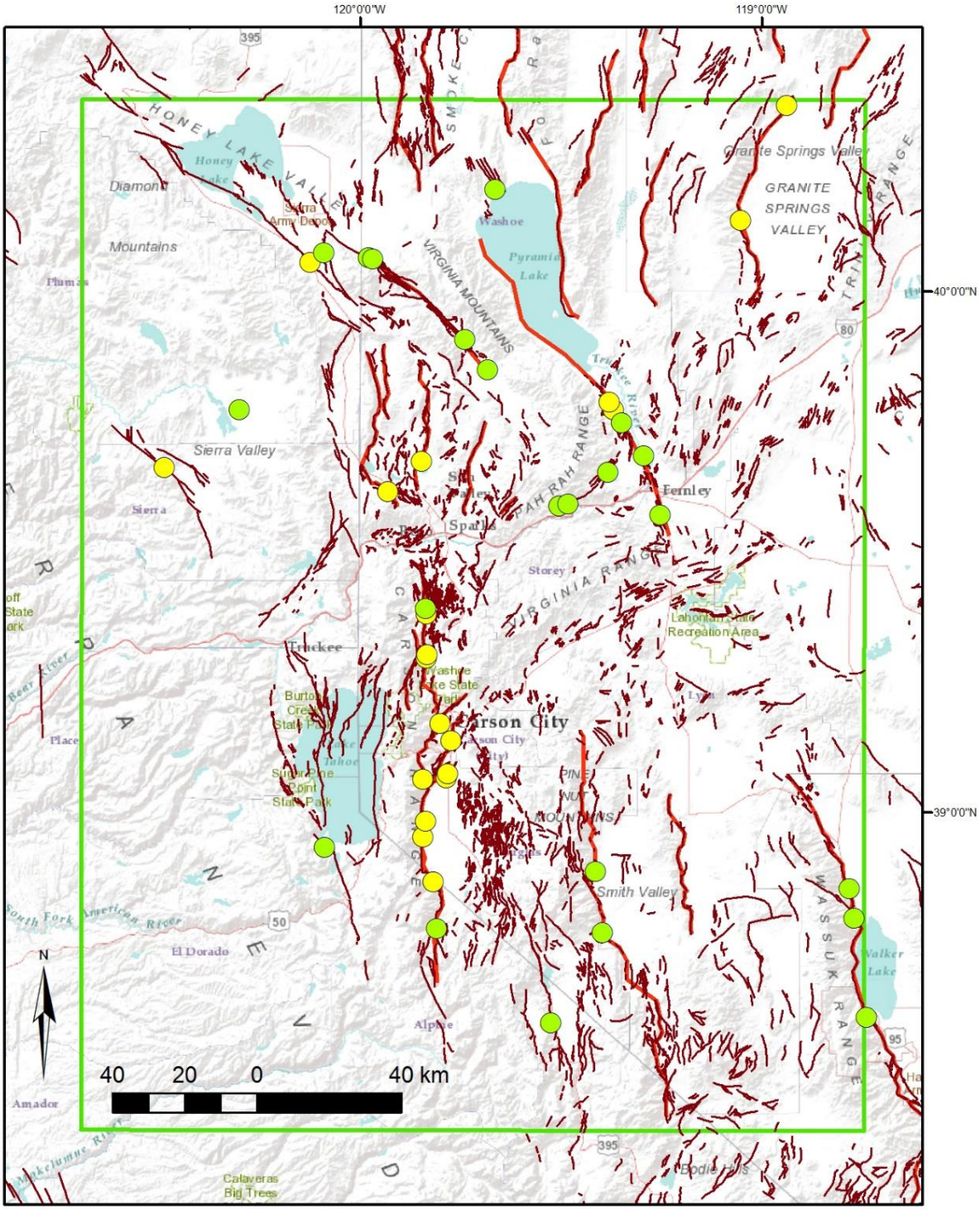

Figure 3. Map showing the distribution of paleoseismic studies that are recorded (yellow circles) and not recorded (light green circles) in the in the Quaternary Fault and Fold Database.

Table 1. Faults within the Reno focus area.

Fault number	Fault name	geologic slip rate (mm/yr) QFF	Geologic slip rate (mm/yr) NSHM	Timing data	length (km)	Most recent activity	Comment and score based on qualitative criteria defined in this presentation.
INCLUDED IN NSHM							
1	Pyramid Lake fault zone	1–5	2	Yes	77	<15	
2	Eastern Pyramid Lake/Lake Range fault zone	<0.2	0.131	no	44	<130	
3	Nightingale Mountains fault zone	<0.2	0.131	no	35	<1600	
4	Granite Springs Valley fault zone	0.2–1	0.261	yes	50	<15	
5	Warm Springs Valley fault zone	<0.2	0.5	yes	70	<15	
6	Spanish Spings Valley fault zone	<0.2	0.131	no	23	<15	
7	Freds Mountain fault	<0.2	0.131	yes	28	<130	
8	Petersen Mountain fault	<0.2	0.131; 0.065	no	25	<130	
9	Peavine Peak fault zone	<0.2	NA	yes	15	<15	
10	Mount Rose fault zone	1–5	1.958	yes	38	<15	
11	Little Valley fault	0.2–1	0.261	yes	17	<15	
12	Carson Range-Kings Canyon fault (Genoa fault)	1–5	2.61	yes	36	<15	
13	Indian Hill fault	<0.2	0.131	yes	8	<15	
14	Carson City fault	<0.2	0.131	yes	16	<15	
15	Smith Valley fault	<0.2–1	0.326	yes	96	<15	
16	Singatse Range fault zone	<0.2	0.131	no	40	<130	
17	Wassuk Range fault zone	0.2–1	0.914	yes	116	<15	
18	Dry Valley-Smoke Creek Ranch fault zone	<0.2	0.131	no	48	<15	
19	Bonham Ranch fault zone	0.2–1	0.261	no	54	<15	
20	Fox Range fault zone	<0.2	0.131	no	31	<15	
21	San Emidio fault zone	0.2–1	0.261	yes	32	<15*	*New age (Ramelli)
22	Selenite Range fault zone	<0.2	0.131	no	18	<1600	
23	Seven Troughs Range fault zone	<0.2	0.131	no	37	<1600	
24	Spanish Springs Peak fault zone	<0.2	0.1	no	13	<1600	
NOT INCLUDED IN 2014 NSHM							
25	Honey Lake fault zone	1–5		yes	98	<15	CA
26	Fort Sage fault	<0.2		yes	17	<15	CA
27	Mohawk Valley fault zone	0.2–1		yes	42	<15	CA
28	Dog Valley fault zone	NA		no	28	<1600	CA
29	West Tahoe-Dollar Point fault zone	0.2–1		yes	51	<15	CA
30	Tahoe-Sierra frontal fault zone	NA		no	50	<1600	CA
31	Agate Bay fault	NA		no	17	<1600	CA
32	North Tahoe fault	0.2–1		no	25	<15	CA and NV
33	Incline Village fault	0.2–1		yes	20	<15	
34	East Carson Valley fault zone	<0.2		no	48	<15	
35	Slinkard Valley fault zone	NA		no	25	<130	CA
36	Antelope Valley fault zone	0.2–1		yes	12	<15	CA and NV
37	East Antelope Valley fault zone	<0.2		no	18	<15	CA and NV
38	Unnamed faults west of Wellington Hills	<0.2		no	28	<1600	

Fault number	Fault name	geologic slip rate (mm/yr) QFF	Geologic slip rate (mm/yr) NSHM	Timing data	length (km)	Most recent activity	Comment and score based on qualitative criteria defined in this presentation.
NOT INCLUDED IN NSHM							
39	Unnamed faults in the Pine Mountains	<0.2		no	42	<1600	
40	Carson lineament	<0.2		no	72	<15	
41	Unnamed fault zone in Pine Mountains	<0.2		no	18	<1600	
42	Unnamed fault zone in Desert Mountains	<0.2		no	30	<1600	
43	Unnamed fault zone in Pine Grove Hills	<0.2		no	21	<1600	
44	Unnamed faults near East Walker River	<0.2		no	29	<1600	
45	Unnamed faults west of Pike Peak	<0.2		no	20	<1600	
46	Unnamed faults west of Wassuk Range	<0.2		no	24	<130	
47	Cambridge Hills fault	<0.2		no	15	<1600	
48	Unnamed fault zone near Pine Grove Flat	<0.2		no	33	<1600	
49	Olinghouse fault zone	<0.2		yes	18	<15	
50	Unnamed fault zone near Little Valley	<0.2		no	26	<1600	
51	Unnamed fault zone southeastern Truckee Range	<0.2		no	34	<15	
52	Hot Springs Mountain fault zone	<0.2		yes	43	<15	
53	Unnamed fault zone near North Valley	<0.2		no	17	<1600	
54	Unnamed fault zone on northwest side of Trinity Range	<0.2		no	34	<15	
55	Unnamed fault zone along Sahwave Mountains	<0.2		no	14	<1600	
56	Unnamed fault zone between Kumive and Sage Hen Valleys	<0.2		no	17	<130	
57	Terraced Hills fault zone	<0.2		yes	13	<15	Age from Vice, 2008
58	Unnamed faults in Susanville-Eagle Lake area	NA		no	20	<1600	CA
59	Last Chance/Upper Long Valley fault zone	NA		no	33	<15	CA and NV

Abstract 6

The search for strike-slip in the northern Walker Lane: new slip rates and characterization of active faults in Antelope, Mason, and Smith valleys, Nevada

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Antelope, Mason and Smith Valleys are half-grabens within the Northern Walker Lane, east and south of Carson City and Reno, Nevada. We apply recently acquired 0.5–1 m/pixel LiDAR data and terrestrial cosmogenic nuclide (TCN) surface exposure ages to characterize the geometry, Quaternary expression, and slip rates of active faults in these three valleys. Antelope Valley hosts a very active range-front fault with numerous uplifted and faulted alluvial fans and stream terraces along the western margin of the basin. There are several locations along the range-front where stream terraces appear to be right-laterally displaced. Above the town of Walker, CA at the southwestern edge of the basin is an ~30 m high fault scarp, which displaces sediments dated with Cl-36 to ~50 ka. This suggests a vertical displacement rate of ~0.6 m/yr, about half of

recent geodetic estimates. The majority of the range-front fault in Mason Valley forms an alluvial-bedrock contact, and displays only one site where the active range-front fault has cut and displaced older fan sediments. TCN ages of a ~10 m vertically faulted alluvial-fan surface at this site are >100 ka, suggesting a <0.1 mm/yr vertical slip rate for the range bounding fault, significantly less than geodetic estimates. The new LiDAR data reveal several lineaments in the southernmost portion of the valley that display measurable right-lateral displacements. Analysis of LiDAR in Smith Valley shows a much more active range-front fault than that of Mason Valley, with frequently offset late Quaternary fan surfaces along the northern half of the range, along with two additional previously unmapped northwest-striking fault segments towards the center of the basin that also offset Holocene sediments. The Artesia Fan along the Smith Valley range-front is offset ~10 m, and TCN ages range from 10–30 ka, leading to a vertical slip rate of 0.33–1.0 mm/yr. The rate in this case appears to be in line with geodetic rates of deformation that have been reported by others.

Abstract 7

New estimates on the rate of slip for faults of the central Walker Lane, Nevada

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The Walker Lane shear zone trends northwest along the eastern Sierra Nevada and accommodates a significant portion of North American-Pacific Plate relative transform motion. In the central portion of the Walker Lane, the Benton Springs, Petrified Springs, Gumdrop Hills, and Indian Head faults have been identified as the main Quaternary active strike-slip faults that accommodate some portion of the geodetically observed ~8 mm/yr of northwest directed transtensional dextral shear measured across the region. We place quantitative geologic constraints on the shear and extensional components of slip determined from Quaternary mapping of high-resolution topographic datasets, including LiDAR and structure from motion (SFM) models, and ^{10}Be and Cl^{36} cosmosgenic nuclide dating and soil characterization of offset alluvial fans along each of the main strike-slip faults of the central Walker Lane. Thus far, results yield late-Pleistocene-Holocene strike-slip rates for the Benton Springs, Gumdrop Head, and Indian Head faults of 1.8 ± 0.6 mm/yr, 0.6 ± 0.4 mm/yr, and <0.9 mm/yr, respectively, and we are awaiting results for the Petrified Springs fault. The extensional component of slip appears to be minimal for these faults, with a maximum determined rate of 0.12 mm/yr on the Benton springs fault, assuming a minimum dip of 60^0. Thus far, the horizontal rates agree with prior geologic estimates and are at the high end of rates predicted by others from geodetic block modeling. These observations suggest steady rates of shear across these sets of faults throughout the Quaternary within this portion of the Walker Lane.

Abstract 8

Recent paleoseismicity of the Kings Canyon fault zone between Ash and Vicee canyons, Carson City, Nevada

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[2]U.S. Geological Survey
[3]Soil Tectonics

The 15 km long, north-trending, east-dipping, normal dip-slip Kings Canyon fault zone is part of the Carson Range fault system and is located <5 km from downtown Carson City, Nevada. Previous investigations have documented Holocene faulting on this structure, but lacked absolute age control. To determine the recent rupture history of the Kings Canyon fault zone, we excavated three trenches and a soil pit into a late Quaternary alluvial fan cut by numerous fault traces near Ash Canyon.

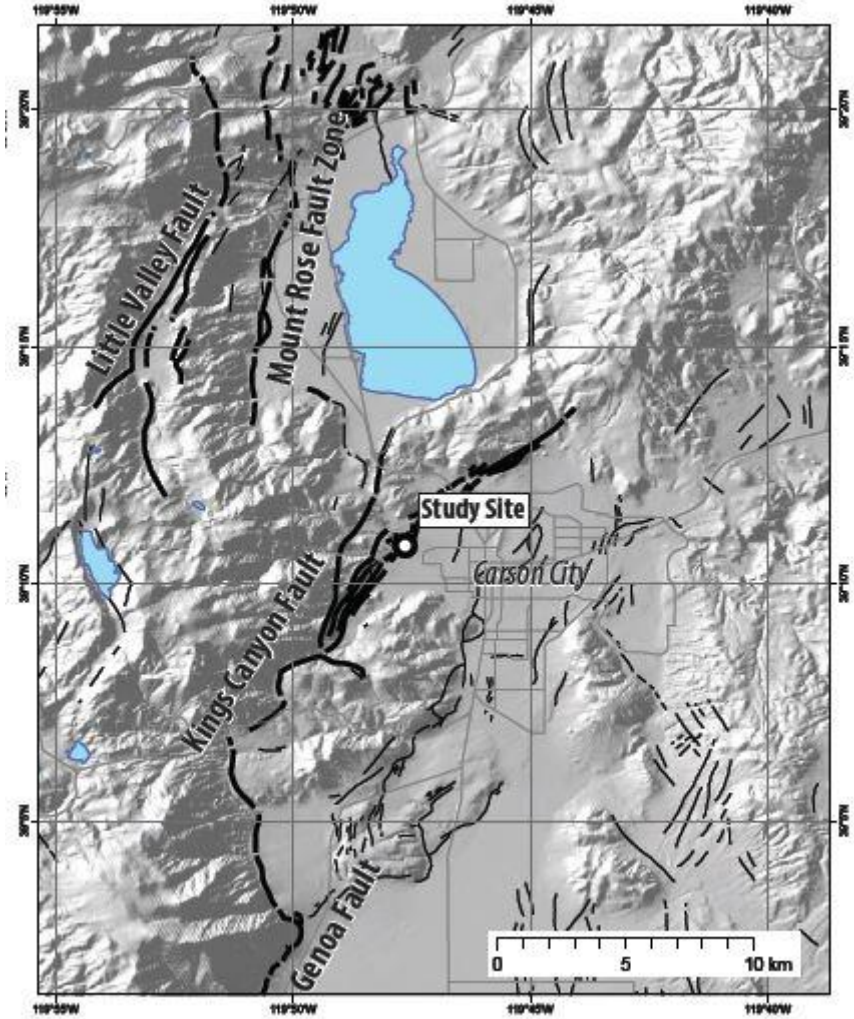

Figure 1. Location map of the Kings Canyon fault zone and the study site.

The alluvial-fan deposits are generally cobbly coarse-and-medium-grained granitic sands, with a few boulders, as much as 60 cm in diameter. Sedimentary structure varied from thin, regular well-bedded sand layers and lenses to massive cobbly coarse sand layers as much as 0.5 m thick. A compound soil was found in at the site consisting from bottom to top of alluvial-fan deposits with thin sub-horizontal clay seams, a silica-cemented Bq horizon, a weakly colored Bw horizon, and an organic rich, fine sand A horizon. This study found that the moderate silica-cement in the Bq horizon appears to have formed during the last ~2000 years.

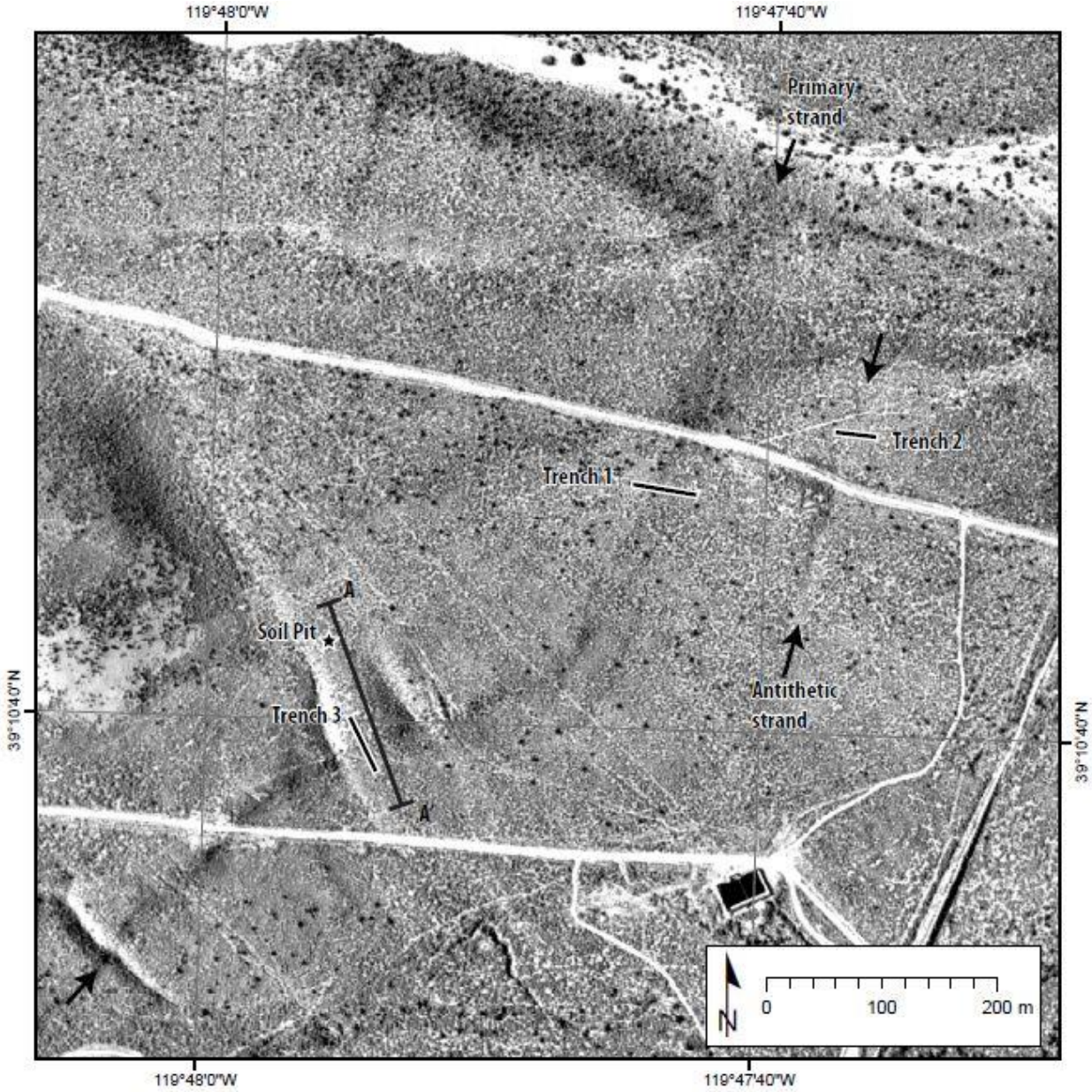

Figure 2. Low-sun-angle photograph flown in 1972 by Dr. David "Burt" Slemmons showing the youngest strands of the Kings Canyon fault zone in fan deposits (a main fault trace and an antithetic fault trace) and the locations of Trenches 1, 2, and 3, the soil pit, and scarp profile A–A' partially shown in figure 4.

Based on the exposure in Trench 3, sited across the base of a large northeast-striking, beveled fault scarp, we document evidence for four surface-faulting earthquakes based on colluvial-wedge stratigraphy, fault terminations, and aligned gravels indicating periods of slope stability between earthquakes. Additional supporting evidence of these events comes from Trenches 1 and 2. Ages from eight AMS radiocarbon and ten optically stimulated luminescence samples provide constraints on the timing of the four paleoearthquakes. Oxcal modeled ages using these dates are Paleoearthquake 1 (PE1) at 1420 ±70 cal. ybp, PE2 at 1630 ±110 cal. ybp, PE3 at 1820 ±140 cal. ybp, and PE4 at 3960 ±820 cal.ybp. These data imply that the three most recent events occurred as a cluster of earthquakes, with short interseismic intervals of approximately 200 to 300 years.

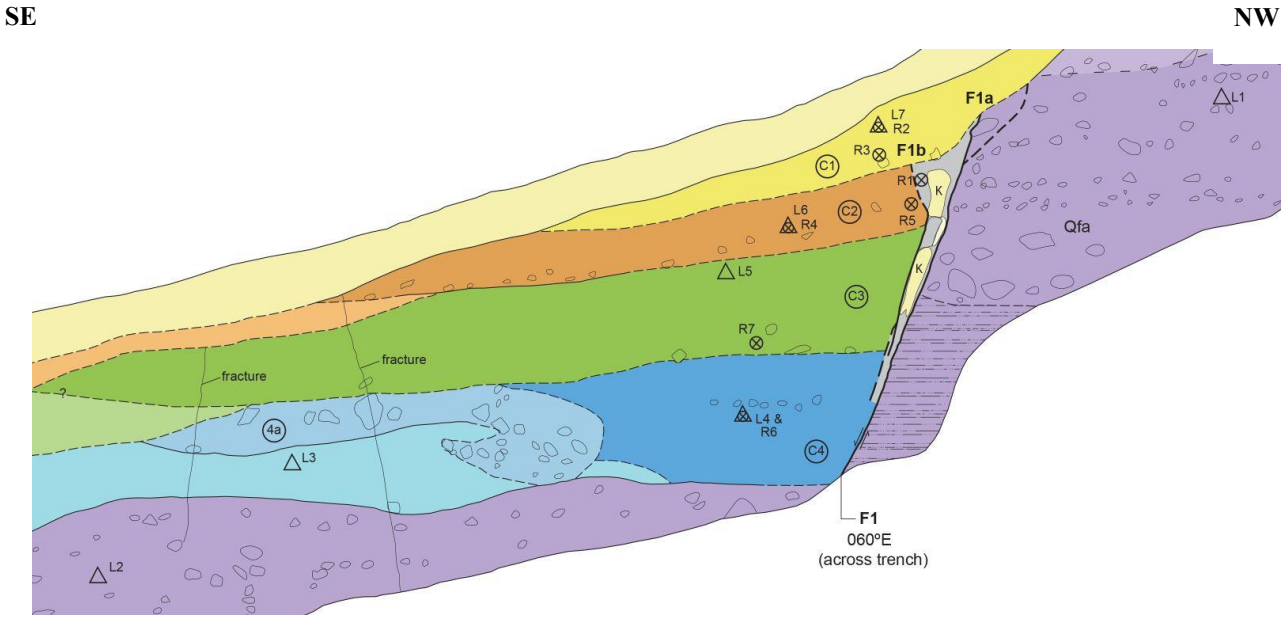

Figure 3. The central part of Trench 3 showing the colluvial wedge stratigraphy (C1 through C4) and the location of radiocarbon dates (circles) and luminescence dates (triangles). Krotovina indicated as "k".

A late Holocene vertical fault slip rate for the Kings Canyon fault of 1.5 to 1.7 m/ky since 5 ka was calculated by combining the vertical surface offset recorded at Trench 3 (8.4 ±0.5 m) with the age of the faulted fan below this surface (~5 ka, based on luminescence dating). During the late Holocene, this fault slipped at a rate comparable to the Genoa fault, south along the range-front.

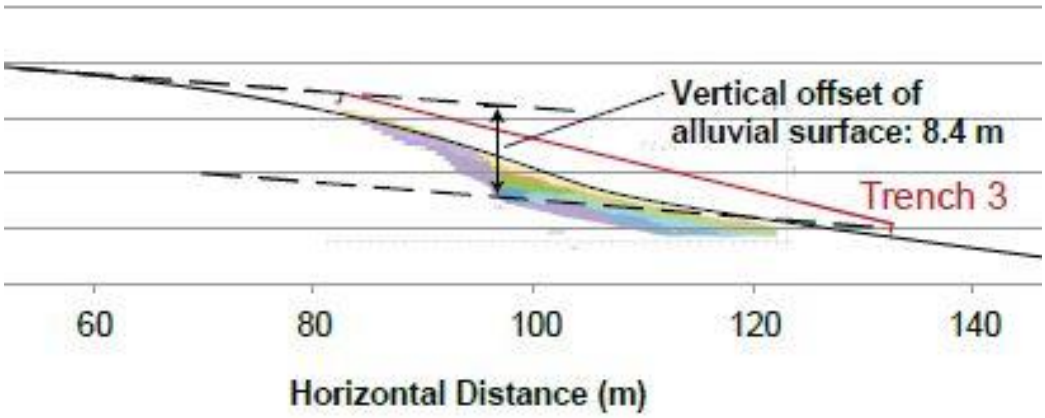

Figure 4. Central part of the scarp profile at Trench 3 illustrating the 8.4 m offset of the alluvial-fan surface. The uncertainty on this estimate is ±0.5 m.

This paleoseismic history allows us to evaluate synchronicity between the Kings Canyon fault and adjacent faults in the Carson Range fault system. Ramelli and Bell (2014) estimate that the two most-recent events along the Genoa fault occurred about 300 ybp and about 1700 ybp.

The Kings Canyon fault did not fail during the most-recent earthquake along the Genoa fault. There are two paleoearthquakes along the Kings Canyon fault (PE2 or PE3) that might correlate with the penultimate event along the Genoa fault. There is a similar paleoseismic relationship between the Kings Canyon fault zone and the Washoe Valley fault zone to the north. However, the youngest event on the Kings Canyon fault zone does not correlate with any adjacent events, and thus was an independent rupture.

Our observations suggest the Kings Canyon fault zone poses a significant seismic hazard to the Reno-Carson City urban corridor and potentially the northern Tahoe basin. The fault zone has produced four surface-rupturing earthquakes during the last half of the Holocene, and the elapsed time since the most recent event is 1400 years. While the Kings Canyon fault zone

fails as an independent source, it also might fail along with adjacent faults along the range-front. Results from this investigation indicate that the Kings Canyon fault zone has produced earthquakes with Mw >6.8.

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Abstract 9

Fault interactions along a N-S belt around 114.75 degrees W longitude in southern Nevada

Wanda J. Taylor[1], Shaimaa Abdelhaleem[1], Alexander Peck[1], Seth Dee[2], and Craig dePolo[2]
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[2] Nevada Bureau of Mines and Geology, University of Nevada, Reno

A series of Quaternary faults that contribute to the regional Quaternary strain budget, but lack detailed study, lie in a N-S belt along 114.75°W longitude in southern Nevada. These faults have spatial relations that suggest structural interactions are probable, and thus, related slip events among them are possible. From S to N the faults are: the Frenchman Mountain (FMF), California Wash (CWF), Arrow Canyon Range, Wildcat Wash, Kane Spring Wash, Coyote Spring, and Maynard Lake faults. We have and are collecting map, paleoseismic, and scarp data as well as information on the related basins to address the histories and inter-relations of these faults. The Frenchman Mountain fault was active in both the Miocene and Quaternary. It has a total of ~7 km of stratigraphic separation based on Triassic units exposed in the footwall and logged in wells in the hanging wall. The maximum hanging wall Miocene-Quaternary basin-fill thickness is ~4.7 km based on gravity data (Langenheim et al., 2001). Kinematic indicators show that the FMF has dip slip near the center, which changes to oblique slip as the fault curves to the N and S. To the north in Nellis Dunes Recreation Area, the slip is normal left-oblique and largely NE-striking left-lateral strands offset structures associated with the, thus, older Las Vegas Valley shear zone. The FMF tip underlaps the CWF tip, which steps toward it thorough a series of right steps. The CWF is a predominantly normal fault and bounds a basin with up to ~2.5 km of Oligocene-Quaternary fill. Where the scarps along the CWF are in older Quaternary deposits, multi-vent scarps are as much as 7 m high, but the youngest scarps in the youngest deposits are a maximum of 1–2 m. Two colluvial wedges exposed in a natural dissection yielded 14C ages of 1825 ± 95 and 1950 ± 80 cal yr BP. The CWF tip overlaps with that of the Arrow Canyon Range fault, another normal fault, with a fault spacing of ~25 km. At the northern end, the Arrow Canyon Range fault forms a gentle relay ramp, exposed in Miocene and Quaternary sediments, with the southern Wildcat Wash fault. A natural dissection along the Wildcat Wash fault exposed two colluvial wedges, one of which yielded a 14C date on charcoal of 1445 ± 85 cal yr BP. Northward the ~N-striking Wildcat Wash fault curves to a NE-strike as it approaches the NE-striking left-lateral Kane Spring Wash fault. The Kane Spring Wash fault lies along the southern edge of the Southern Nevada seismic belt. To the north, the N-striking, normal Coyote Spring fault scarp extends for about 18 km and the maximum width of the associated basin is only ~3 km. The Coyote Spring fault spans most of the gap between the left-lateral Kane Spring Wash fault and the left-lateral NE-striking Maynard Lake fault to the north. The Maynard Lake fault shows left offsets of older Quaternary drainages, offset of a young resurgent fan and the central part contains a transpressional right stepover. In summary, the curves in strikes of some of these faults toward each other near their tips, the relay ramp, and the proximity of these faults to each other suggest that they may work together or in sequence to accommodate regional strain. The NE-striking left-lateral faults and fault sections probably accommodate slip transfer.

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Abstract 10

New paleoseismic data from the Frenchman Mountain fault, Las Vegas

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[3]U.S. Geological Survey

The Frenchman Mountain fault is an 18-km long, north- and northeast-striking, west-dipping, range-bounding normal fault on the eastern side of Las Vegas Valley. The fault is expressed along the western flank of Frenchman and Sunrise Mountains as a zone of sub-parallel scarps in alluvial-fan surfaces, bedrock range-front scarps, and exposed shear planes juxtaposing coarse grained Quaternary sediments against Precambrian and Paleozoic footwall rocks (Matti, et al., 1993; Anderson and O'Connell, 1993; Peck, 1998). The Frenchman Mountain fault is assigned a vertical slip rate of 0.015 mm/yr

in the USGS National Seismic Hazard Map (Peterson et al., 2008, 2014), and geodetic block modeling suggests the fault has a 0.2 mm/yr normal slip rate (Hammond et al., 2014). Evidence for Quaternary paleoearthquakes has previously been presented (Anderson and O'Connell 1993; Rittase, 2007; and Peck, 1998), but these studies did not include detailed documentation of paleoseismic evidence, age dating of deposits, estimates of earthquake recurrence or late-Quaternary slip rate.

A previously excavated exposure of the Frenchman Mountain fault in Quaternary sediments was recently identified and investigated in detail. The excavation was originally part of a fault investigation conducted between 2005 and 2007 by a local consulting company for a planned housing development; the consultant's report remains confidential. The fault exposed in the excavation is buried by late-Pleistocene alluvial-fan deposits, but the exposure is on strike with Quaternary fault scarps to the north and south that are 2–8 m high.

Our new detailed logging of the excavation documents evidence for three paleoearthquakes on an 85° west-dipping fault zone in Quaternary alluvial-fan gravels. Evidence for these events includes offset stratigraphy and three scarp-derived colluvial wedge packages. Optically stimulated luminesce (OSL) dating samples were collected from all colluvial wedge packages, the faulted stratigraphy beneath the wedge and the overlying unfaulted fan gravels; results of the OSL dating are pending. Quaternary units beneath the colluvial wedge packages have an average, total vertical displacement of 1.6 m across the fault zone. The oldest recorded faulting event (E3) has an estimated vertical displacement of 0.8 m. The two youngest events (E1 and E2) have a combined vertical displacement of 0.8 m.

An adjacent excavation, 65 m to the east, exposes a 35° west-dipping fault zone with well-developed fault gouge, placing older Quaternary alluvial-fan gravels (early Pleistocene?) against Precambrian gneiss. The relationship between the two fault zones at depth is unresolved, but it is likely that the high-angle fault soles into the lower angle fault at an estimated intersection depth of 50 m below the ground surface.

A basin depth map of the Las Vegas Valley, inverted from gravity data, shows the deepest part of the basin is parallel to and west of the Frenchman Mountain range-front (Langenheim et al, 2001; Langenheim et al, 2005). The gravity data suggests that the Las Vegas basin is bound on the east by a 60°–65° west-dipping fault that projects to the surface over 800 m west of the logged fault exposure. If the inferred basin-bounding fault at depth connects to the lower angle fault at the range-front, it suggests an active normal fault with a convex-up or anti-listric orientation.

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Rittase, W.M., 2007, Cenozoic extension in the River Mountains and Frenchman Mountain, southern Nevada: University of Nevada, Las Vegas, M.S. thesis, 181 p.

Abstract 11

The Las Vegas Valley fault system—a 2017 progress report

Craig M. dePolo[1], Wanda J. Taylor[2], Seth M. Dee[1], Shaimaa Abdelhaleem[2], James L. Werle[3]
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[2]Department of Geoscience, University of Nevada Las Vegas
[3]Nova Geotechnical

The Las Vegas Valley fault system (LVVFS) is made up of five recognized faults: the Eglington fault, Decatur fault, Valley View fault, Cashman fault zone, and Whitney Mesa fault zone (fig.1). In addition, there are many smaller faults

between and as strands of the larger faults. Faults within the LVVFS are expressed at the surface as fault scarps and warps, springs and spring deposits, and vegetation and tonal lineaments. The faults are closely spaced, subparallel to one another, and have the same sense of displacement, normal dip-slip with a down-to-the-east component. The faults are generally north-south striking in the central part of the basin and northeast striking in the northern part of the basin. Multiple hypotheses have been proposed for the origin of the fault scarps including tectonic movement, differential compaction, spring discharge deposits, salt dissolution, shaking-induced settlement, and various combinations of these. The Nevada Bureau of Mines and Geology, the Department of Geology at the University of Nevada Las Vegas, and the U.S. Geological Survey have launched a multi-year research project to understand the seismic potential of these faults. Evidence that supports a seismic potential in Las Vegas Valley include: recorded earthquake activity (including some small felt earthquakes; fig. 2), documented brittle surface fault offsets, and evidence of potential liquefaction features.

Figure Reference:

Page, W.R., Lundstrom, S.C., Harris, A.G., Langenheim, V.E., Workman, J.B., Mahan, S.A., Paces, J.B., Dixon, G.L., Rowley, P.D., Burchfiel, B.C., Bell, J.W., and Smith, E.I., 2005, Geologic and geophysical maps of the Las Vegas 30′ x 60′quadrangle, Clark and Nye counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, scale 1:100,000.

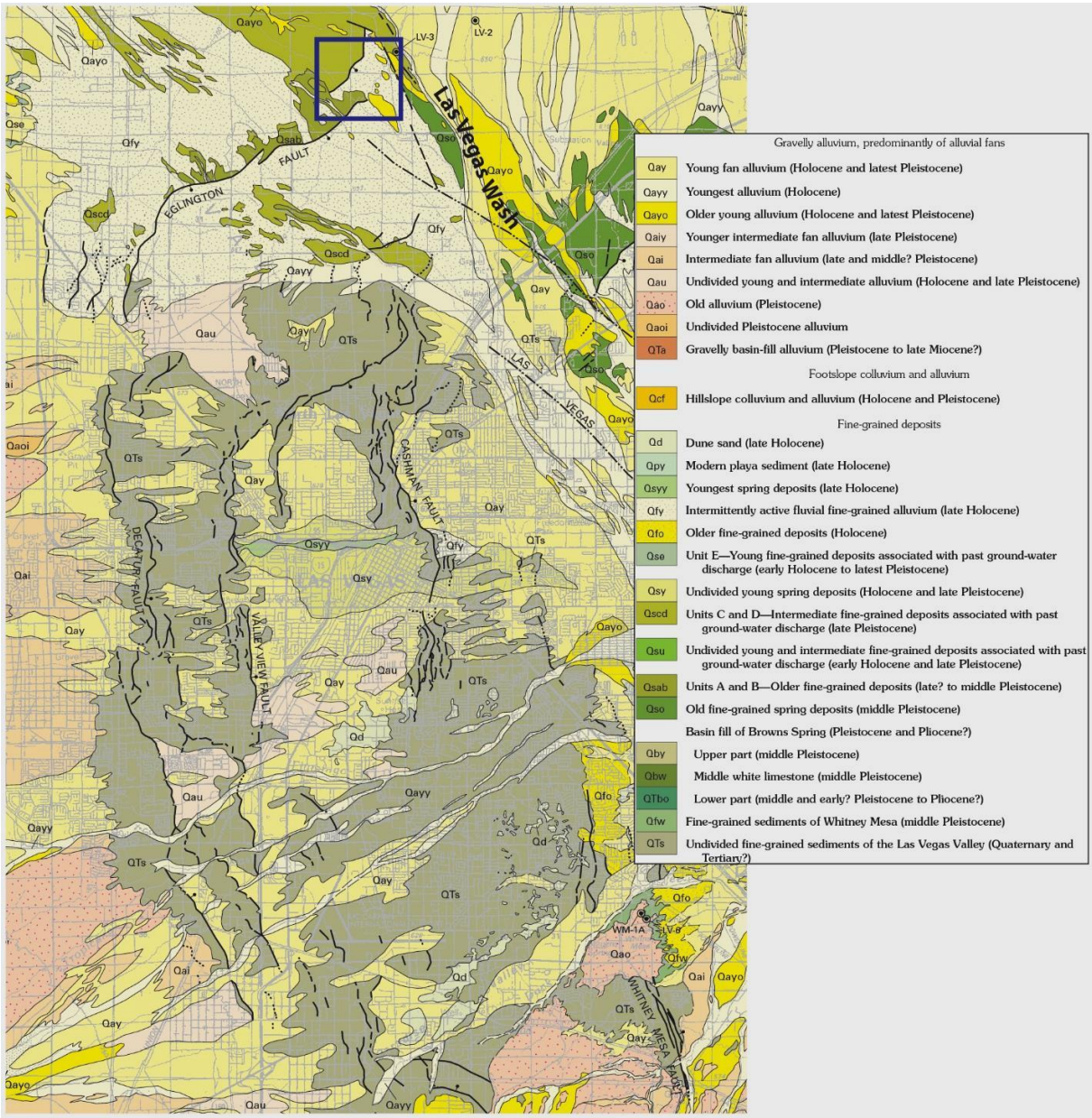

Figure 1. Geologic map and Quaternary faults in the central part of Las Vegas Valley. Blue box denotes an area of future trenching by this project. The map is a part of a larger map created by Page et al. (2005).

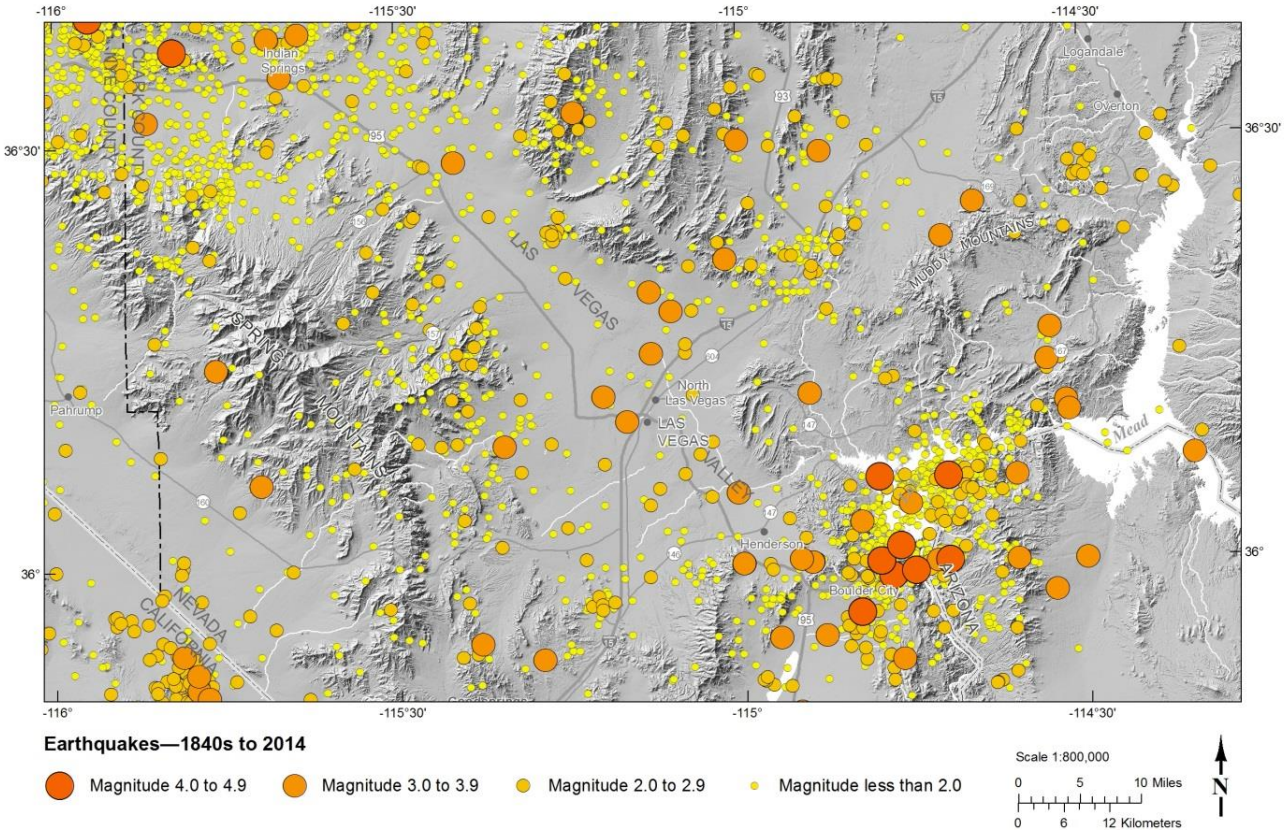

Figure 2. Earthquake activity in the Las Vegas Valley region between the late 1800s and 2014. Las Vegas Valley is in the center of the figure and many micro-earthquakes are located in and around the valley. Post 1970 activity was recorded by the Nevada Seismological Laboratory.

Abstract 12

Seeking input on the inclusion of the Eglington fault, Nevada, in the National Seismic Hazard Map

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[2]Nevada Bureau of Mines and Geology, University of Nevada, Reno

The USGS seeks guidance from the Working Group on Nevada Seismic Hazards on treatment of the Eglington fault and other faults of the Las Vegas Valley fault system (LVVFS), Nevada, in future updates of the National Seismic Hazard Map (NSHM). The Eglington fault was first included as a seismic source in the 2014 update to the NSHM (Petersen et al., 2014), guided largely by a white paper published by the Nevada Bureau of Mines and Geology (dePolo et al., 2013). However, substantial uncertainty remains regarding the seismogenic potential of the LVVFS. Two endmember hypotheses have been proposed regarding the mechanisms responsible for producing the escarpments associated with the LVVFS, including the Eglington fault: 1) tectonic (e.g., coseismic surface rupture) and 2) non-tectonic (e.g., prehistoric differential sediment compaction). In this presentation, we will summarize existing geologic, geodetic, geophysical, and geochronologic data that provide insight into the mechanism(s) responsible for scarp formation within the LVVFS, point out unresolved problems with both endmember tectonic and non-tectonic scenarios, and describe ongoing work to address these problems. We will explore how to represent the Eglington fault within a logic tree framework for future map updates. Our ultimate goal is to seek a recommendation from the Working Group on Nevada Seismic Hazards regarding treatment of the Eglington fault and other faults of the LVVFS in future updates to the NSHM.

dePolo, C.M., Taylor, W.J., and Faulds, J.E., 2013, Evidence for high contemporary slip rates along the Eglington fault, Clark County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 13-12, 8 p.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p.

Day 2, February 6, 2018

Abstract 13

Review of Nevada and eastern California seismicity and the Nevada Seismic Network

Ken Smith, Rachel Hatch, Christine Ruhl, Graham Kent, Annie Kell, Dave Slater, Gabe Plank, Mark Williams, Mickey Cassar, Tom Rennie, John Torrisi, and Ryan Presser
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The Nevada Seismological Laboratory (NSL) provides seismic network coverage and real-time seismic monitoring for the State of Nevada and areas of eastern California. Recent upgrades to the network have improved catalog completeness and the detection threshold throughout most of the state and region. With improvements to the network and processing procedures, NSL is now locating about 15K–18K earthquakes per year; however, most of state remains poorly monitored. Recent instrument installations in the Reno-Carson-City-Lake Tahoe-Truckee areas have improved overall data quality and coverage, greatly improving the ability to conduct detailed studies of local earthquake activity. Also, under support from U.S. Geological Survey's Earthquake Early Warning Program (EEW) the Nevada Seismological Laboratory is installing low-latency strong motion instrumentation along the eastern Sierra, with data incorporated into the west coast 'ShakeAlert' system. Recent station installations in the vicinity of the Nevada National Security Site have improved the catalog in Southern Nevada; whether these remain permanent stations is uncertain. Recent support from the USGS to install free-field broadband/strong motion instrumentation in the Las Vegas area will greatly improve completeness, location accuracy and earthquake response for the Las Vegas basin (site selection and permitting are underway). Other contributions to this meeting will provide details of recent research activities into earthquake processes and ground motion studies. Here we summarize Nevada historical earthquake activity and historical instrumental seismicity, most of which has been incorporated in prior hazard maps, and update the working group on the current state of the monitoring network, earthquake response, existing programs that contribute to seismic hazard evaluations and review the region's most recent earthquake activity.

Abstract 14

Characterizing earthquake sources in the urban Reno-Carson-Lake Tahoe regions

Christine J. Ruhl, Kenneth D. Smith, Rachel E. Abercrombie, Graham M. Kent, Ilya Zaliapin, Rachel L. Hatch

Probabilistic seismic hazard analysis (PSHA) depends on characterizing the potential (size and location) for future damaging earthquakes and then predicting the ground motion from these earthquake sources. In order to obtain the best possible PSHA model, earthquake line sources and areal source regions must be characterized accurately. Because surface faults do not always reflect the active subsurface structures capable of producing moderate to large earthquakes (e.g., 2016 M5.8 Christchurch, NZ earthquake; 2008 M5 Mogul, NV earthquake), seismicity can be useful in characterizing subsurface seismic potential. Network improvements and increased computational techniques have facilitated a surge in advanced seismicity studies in the last decade. In western Nevada, we have leveraged abundant microseismicity and moderate seismic sequences to better characterize earthquake sources using waveform-based earthquake relocation, kinematic and stress field analysis, statistical clustering, and source parameter estimation. We present 15+ years of relocated microseismicity in the Reno-Carson-Lake Tahoe region and discuss proposed seismicity zones including seismicity rates within each, style of faulting, and seismogenic depths. We highlight discrete line sources within the diffuse seismicity zones that have consistent physical properties (e.g., style of faulting). We demonstrate a technique for identifying seismically active line sources within clustered seismicity zones using the highly-clustered Mogul earthquake swarm that occurred in urban Reno, NV in 2008. In future PHSA in Nevada, it may be increasingly important to include line sources capable of producing M5+ magnitude earthquakes identified via relocated microseismicity in place of less-detailed areal source zones.

Abstract 15

Precise relocations, source parameters, and directivity effect for five recent earthquake sequences near Nevada urban areas

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Felt earthquakes within recent sequences and swarms of seismicity in Reno, Nevada and the surrounding urban areas (2010–present) have caught attention of the public and emergency responders. Our objective is to characterize this seismicity and its associated structures, source parameters, and hazard implications. Based on improved seismic network coverage in the Reno area under additional USGS support, we develop high-resolution relocations to the Thomas Creek, NV (2015–2016; largest event = Mw 4.3), Herlong, CA (2016; largest event = Mw 4.5), Virginia City, NV (2014; largest event = ML 3.2), Carson City, NV (2012–2015; largest event = ML 2.9), and Truckee (2017; largest event = Mw 3.8) earthquake sequences. Relocation results for each sequence using the new GrowClust application (Trugman and Shearer, 2017), show well-defined primary fault structures with additional and more complex off-fault structures within the northern and central Walker Lane, with the majority of events occurring on unmapped faults. To assist with hazard analysis, we compile measurements of the source parameters from moment tensors, short-period mechanisms and stress drops of the larger events (M > 2), for each sequence. These help characterize urban seismicity and supplement results from previous studies on stress drop in the area and provide input to ground motion models. Lastly, we attempt to detect evidence for directivity, testing for unilateral and bilateral ruptures for the larger events of each sequence. Directivity effects of even moderate events near urban areas can increase risk. Preliminary results of the stress drop measurements for the sequences tested show moderate to low values for all events tested. Average values for each sequence are: Thomas Creek → 8 MPa; Herlong → 21 MPa; Carson City → 14 MPa; Virginia City → 5 MPa; Truckee → 4 MPa. Preliminary results of our directivity analysis show unilateral rupture components within the Truckee sequence for two of the largest events in the sequence (Mw 3. 6 and Mw 3.8) as well as for several events in the 2014 Virginia City sequence. With this analysis on recent sequences, we hope to gather a better understanding of the source characteristics of sequences and identification of local seismogenic structures in order to contribute to the hazard assessment.

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Abstract 16

Fault-scaling relationships depend on the average fault-slip rate

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This study addresses whether knowing the slip rate on a fault improves estimates of magnitude (Mw) of shallow continental surface-rupturing earthquakes. Based on 43 earthquakes from the database of Wells and Coppersmith (1994), Anderson et al. (1996) previously suggested that the estimates of Mw from rupture length (LE) are improved by incorporating the slip rate of the fault (SF). We re-evaluate this relationship with an expanded database of 80 events, which includes 56 strike-slip, 13 reverse-, and 11 normal-faulting events. When the data are subdivided by fault mechanism, magnitude predictions from rupture length are improved for strike-slip faults when slip rate is included but not for reverse or normal faults. Whether or not the slip-rate term is present, a linear model with Mw ~ log LE over all rupture lengths implies that the stress drop depends on rupture length—an observation that is not supported by teleseismic observations. We consider two other models, including one we prefer because it has constant stress drop over the entire range of LE for any constant value of SF and fits the data as well as the linear model. The dependence on slip rate for strike-slip faults is a persistent feature of all considered models. The observed dependence on SF supports the conclusion that for strike-slip faults of a given length, the static stress drop, on average, tends to decrease as the fault-slip rate increases.

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Abstract 17

Characterization of earthquake ground motions for engineering design in the Reno basin: geotechnical and seismological perspectives

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Current seismic codes for buildings and bridges define the earthquake ground motions used for design on the basis of regional seismic hazard assessment, bedrock characteristics, and adjustment factors for site response (i.e., site coefficients). The site coefficients have been developed from strong motion recordings supplemented with computational results from one-dimensional dynamic soil response analyses. The 1-D nature of the site response assessment precludes consideration of 2-D and 3-D effects on the characteristics of the ground motions. Therefore, the influence of basin effects is not explicitly accounted for in the code-based seismic hazard assessment. While the possible importance of basin effects on design ground motions is mentioned in the commentary of the codes, little guidance is provided for practitioners in regions featuring geologic basins, such as Reno, Las Vegas, Los Angeles, and Seattle. We will present insights gleaned from recent civil engineering projects that have addressed basin effects on strong ground motions, and share observations made in the Reno-area basin using recorded data from earthquakes in the region, and computational models of 3D basin effects. The focus is on the seismological and engineering characterization of earthquake ground motions. The implications for engineering practice in Reno highlight the benefits of integrated project interaction by seismologists, earth scientists, and geotechnical engineers.

Abstract 18

Comprehensive community velocity models for Nevada's urban basins: the key to predicting earthquake ground motions

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In the ten years since the USGS-sponsored Western Basin and Range Community Velocity Model (CVM) Workshop, several groups have collected comprehensive shear-velocity data in Nevada urban areas. Clark County and the City of Henderson set a new global standard for earthquake-hazard mapping by collecting the Clark County Parcel Map. The Parcel Map covers 1500 sq. km of urban and urbanizing parts of the county with over 10,000 shear-velocity measurements. Each measurement resulted in a shear-velocity profile to over 70 m depth, with a spacing of 300 m or less in the covered regions. Used by the County in permitting activities, the Parcel Map provides a detailed picture of velocity variations across an entire urban basin. The Map shows hidden alluvial-fan margins, low-velocity zones along fault traces, and geostatistical metrics compatible with the fractal scales of variation common in velocity logs of wells. Together with work on deeper velocities at UNLV, and gravity analyses of basin thickness by the USGS, the Clark County Parcel Map provides a more comprehensive CVM for Las Vegas than those that exist for any other urban basin in the world.

The last ten years have also seen significant progress toward this standard in the Reno and South Lake Tahoe urban areas. University of Nevada, Reno (UNR) and Optim have completed many hundreds of measured shear-velocity profiles and several generations of gravity analyses in both areas, with USGS sponsorship. UNR students are currently documenting and publicly posting dispersion data for each measured velocity profile, and integrating different generations of gravity analyses for basin thickness. Where Reno-Tahoe leads globally is in the measurement of shear velocity below geotechnical depths, from 30 m to the basin floor at up to 1 km depth. The USGS sponsored multiple deep-basin velocity surveys by Optim across the Reno-area basin from 2012 to 2015. UNR experimented with ultra-deep velocity measurements across Reno in 2016 and achieved velocity definition to depths exceeding 2.5 km.

Community velocity models feed directly into physics-based computation of ground motions from earthquake sources that includes basin and geotechnical effects. The detailed CVMs available for Las Vegas and Reno-Tahoe have enabled comprehensive modeling of shaking across these areas from both scenario events and small recorded earthquakes over the last seven years. Sensitivity tests demonstrate that the geotechnical details in the Parcel Map, for instance, can amplify or de-amplify shaking by a factor of two. The computation of ten rupture scenarios on six faults affecting the Tahoe basin allowed creation of a new methodology, developing a simplified probabilistic hazard map for Tahoe. The new map shows that Stateline could experience "Severe" 30 cm/s levels of ground shaking at a rate exceeding once every 1400 years. This new hazard mapping methodology needs to be developed further and applied to Reno and Las Vegas.

Abstract 19

Development of a community shear-wave velocity profile database in the United States

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We describe a multi-institution effort to develop an open-access shear-wave velocity (VS) profile database (PDB), which will include a public repository for VS profile data in the United States. VS profiles are an essential resource for ground motion modeling, basin velocity structure modeling, and other applications. The minimum requirements for a site to be included in the database are in situ geophysical VS measurements and location metadata. Other information is included as available, including geotechnical logs, penetration resistance, laboratory test data, ground water elevation, and P-wave velocity profiles. The project is currently at the stage of data collection (over 4500 VS profiles in the USA) and prototype data model development. The database will be presented as an online map-based interface with downloadable VS profile and metadata information. While the primary focus of data collection to date has been in California, the Pacific Northwest, and central and Eastern U.S., it is imperative that we eventually lead a data collection effort in Nevada and the rest of the intermountain west (IMW). Access to data comprising the USGS national VS30 compilation has been provided; 814 locations in Nevada and the rest of the IMW are included, but the number of VS profiles is likely lower. We seek to spread awareness about the project and solicit collaborations with VS data owners in Nevada, with the end goal of expanding the geographic coverage of the database for future contributions to reduction of epistemic uncertainties associated with seismic site characterization and seismic hazard evaluations. Funding for this project was provided by the USGS Earthquake Hazards Program under contract number G17AP00018.

Abstract 20

Investigating basin amplification factors for shaking in the Reno-Tahoe and Las Vegas regions for local and regional events

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The impacts of seismic shaking on urban basins outside Nevada have been in the news since the 1985 Michoacán earthquake damaged Mexico City—and with another event this year. Construction projects for tall buildings in Seattle were recently delayed out of concerns that current design standards may not sufficiently account for the shaking amplification that occurs in geologic basins. Building codes in Nevada pertaining to seismic hazard use the USGS National Seismic Hazard Map program, which does not include site or basin amplification factors. NGA-West2 Ground motion prediction equation (GMPE) incorporates basin amplification factors homogeneously in 1-D based on depths to certain shear-velocity values (Z1.0, Z2.5) and on the geotechnical average velocity to 30 m depth (Vs30). We investigate whether such GMPEs may adequately predict amplification in Nevada's urban basins: Reno; Tahoe; and Las Vegas. We are quantifying and comparing basin amplification factors recorded from a series of local and regional events in and around the urban areas. The focus of our analysis lies in the variation of amplification factor with spatially distributed source locations azimuthally and lithologically. Broadband records we are examining include: the 2008 Mogul sequence; 2015 M4.3 Thomas Creek; 2015 3 M ~ 5.5 Nine Mile Ranch; 1992 M 5.7 Little Skull Mountain; 2014 M4.8 Caliente; and 2014 M3.6 Enterprise events. Our initial investigation is only into peak ground velocity (PGV) ratios of basin over bedrock stations; with the intention of including other measures of shaking intensity such as spectra or duration. We have generated 3D physics-based SW4 synthetic seismograms for these events that partially account for basin effects at low frequencies of shaking (<1.0 Hz), and we can examine how well the synthetic PGV ratios predict the recorded ratios.

Abstract 21

GPS constraints on present-day slip rates in the northernmost Walker Lane: Reno, Carson City, and Tahoe region, NV and CA

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We combine observations from the MAGNET GPS network in Nevada and eastern California with data from other western U.S. continuous GPS networks to precisely measure present-day deformation in the northern Walker Lane. We present an updated dense velocity solution (~10 km average station spacing) that spans the Sierra Nevada-Walker Lane-Basin and Range transition, and we use these velocities to infer slip rates on faults in the Reno, Carson City, Lake Tahoe, and eastern Sierra Nevada regions through an elastic block modeling approach. The velocity data show that the deformation budget in the northern Walker Lane decreases northward from ~7 mm/yr in the central part of the region to ~5 mm/yr across the Honey Lake and Mohawk Valley faults as plate boundary deformation is increasingly accommodated on Basin and Range normal faults. Accurately representing the density of active faults in the northern Walker Lane requires a detailed model with

a relatively large number of blocks. This approach allows slip to be distributed among all likely seismic sources rather than concentrating slip on a sub-sample of major faults. A comparison of model predictions between our detailed regional model and western U.S. scale models shows that a detailed fault representation is needed to accurately estimate fault slip rates for seismic hazard products.

Abstract 22

Robust estimation of fault slip rates using GPS imaging in the Walker Lane and western Great Basin

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The Walker Lane belt is a zone of tectonic transition between the Sierra Nevada and Basin and Range in the intermountain western United States. Here, transtensional tectonic strain accumulation is released on many active strike-slip and normal faults that pose a seismic hazard to nearby communities including Reno, Carson City, Mammoth Lakes, Bishop and Las Vegas. Over the past couple of decades, measurements with GPS networks have improved the resolution of crustal strain rates. These measurements have transformed our understanding of the role of shear strain, block rotations, earthquake cycle transients, vertical motions, and the influence of climate conditions on active deformation. Each of these factors influence how geodetic data are compared to longer term measurements of strain release on faults, and how they can be used to improve the robustness of estimates of hazard via incorporation of the data into probabilistic seismic hazard calculations.

To integrate the data into hazard products, we use geodetic velocities to estimate the rate of slip on active faults. In the Walker Lane, estimating slip rates can be challenging for several reasons. For example, geodetically measured strain accumulation is geographically variable, and strain release is known to have occurred on hundreds of dextral, normal, and sinistral faults, folds, anticlines, and oroclinal flexures that accommodate relative motion. Also, fault slip styles can vary over short distances, even within single basins. Not all deformation occurs on large range-bounding faults, and faults can terminate without continuation into other systems. Thus, a significant fraction of the deformation budget may be "off-fault" in the sense that future strain release may not occur on previously identified faults. Moreover, measured strain accumulation is smoothed over several times the locking depths, making the estimated slip rates sensitive to foreknowledge of the location and geometry of active structures. Finally, transient deformation from the earthquake cycle, nearby magmatic systems, or climate-induced hydrological loading changes, may be present in the geodetic velocity field and potentially contaminate the measurements if not properly taken into account.

In this presentation, we will discuss recent progress in addressing these challenges, which fall into three main categories, 1) improvements in measurement of the GPS velocity field, 2) innovation in block modeling to estimate slip rates robustly, 3) better isolating the contribution of transient hydrological loading and time variable deformation from the Long Valley caldera.

Measurement of the geodetic velocity field in the Walker Lane has been refined through extending the precision and geographic coverage of GPS measurements across the western Great Basin, improved integration with regional GPS networks, and innovations in applying robust estimation techniques to the data. Through continued support from the USGS NEHRP Geodetic Networks program, regular surveys have extended the time series to a maximum of nearly ~14 years long. Long time series are absolutely essential when assessing crustal deformation rates to a precision measured in tenths of a mm/yr, and when deformation is time variable, as discussed below. The Nevada Geodetic Laboratory processes the MAGNET data with the GIPSY/OASIS software as a part of its system that includes data from over 16,700 stations on Earth, including all of the continuously operating GPS networks in the United States. From the GPS time series, we robustly solve for station rates with the MIDAS algorithm, and use GPS Imaging to robustly estimate interpolated velocity fields, and MELD for strain rates.

Using geodetic data to estimate slip rates on faults requires knowledge of the location, strike, dip, and locking depth of the active structures, and how they connect to accommodate interseismic strain. Some of these parameters are often only roughly known. By incorporating a new strategy called "spontaneous blocks", we are making progress in objectively and robustly modeling the slip rates, with less analyst bias, by automatically generating models from the data on fault geometries. We derive suites of solutions to quantify the uncertainty in the slip rate solutions that are attributable to the uncertainty in both the data and in prior knowledge of the geometry of fault structures and completeness of that database.

In recent years, our improved attention to the vertical rates, changes and seasonality in those rates have resulted in greater appreciation of the role of climate, drought and their effects on active crustal deformation. Uplift of the Sierra Nevada is now measured at ~1–2 mm/yr between the latitudes of Lake Tahoe and the Garlock fault. We have now detected changes in vertical rates, including a significant increase in uplift rate during the California drought 2011–2016. This signal reveals a sensitivity of uplift to hydrological loading. We show that these changes are correlated with accelerated inflation of the magmatic system at the Long Valley caldera in eastern California, resulting in measurable changes in strain rates, magmatic uplift, and seismicity that are detectable up to 80 km from the magmatic center beneath the resurgent dome.

Abstract 23

Robust estimation of the secular and time-variable strain-rate field in the American southwest

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Strain rate models derived from horizontal GPS velocities have proven to be useful for seismic hazard estimation. For example, seismic source models should ideally satisfy the implied geodetic moment rate. For this reason, the USGS seismic hazard maps have, for instance, added source zones to the Walker Lane to ensure that the geologic shear strain rate equals the geodetic rate. In another example, geodetic strain-rate models can be used to forecast earthquake productivity when appropriate empirical scaling is applied (e.g., Bird et al., 2010, Bird and Kreemer, 2015).

Thus far, most strain rate models have lacked a robust estimation of the model uncertainties. Moreover, the Bayesian approach of the Haines and Holt type models, make the posteriori uncertainties dependent on the assumed priors. We have developed a new algorithm that provides a robust estimation of the strain-rate tensor at a given location as well as the standard deviations that reflect the true scatter in the model estimate. This algorithm (called "MELD"—Median Estimation of Local Deformation) works particularly well to retrieve the long-wavelength strain-rate signal in areas of low deformation, such as intraplate North America. The performance of MELD depends on the station distribution and the amount of spatial variation in the strain-rate signal. However, its robust error estimation provides a useful diagnostic to assess which strain rate features at various wavelengths should be considered significant.

We present the latest interseismic GPS velocity field compilation for the American southwest. We then apply MELD under various assumptions on the wavelength of interest and present uncertainties maps.

Because MELD is better at pulling subtle long-wavelength signals out of noisy data, we also present two time-varying strain models. One is associated with the horizontal seasonal displacements, and another is associated with the decaying postseismic deformation after the 2010 El-Mayor Cucapah (EMC) earthquake. The seasonal model clearly identifies large-scale coherent signals, which can be divided into three domains for which the time of year of maximum deformation is different: northern and southern California, and the Great Basin. The signal is largest and most coherent in northern California, where we see compression and extension in an orientation normal to the coast and Sierra Nevada in the Spring and Fall, respectively.

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Abstract 24

Update on PBR constraints on ground motion from normal faults

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Dates on last rupture on the Genoa fault and the Antelope Valley fault add to the database for constraints on ground motion for normal faults. Also, recent acceptance of the results of foam rubber modeling of thrust faults suggests re-evaluation of the results of modeling of normal faults by both foam rubber and lattice numerical models.